Optimizing Fly Ash and Cement Ratios for Immobilizing Lead and Arsenic in Liquid Hazardous Waste

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ABSTRACT

Improper handling of hazardous and toxic industrial wastes can directly impact human health and the environment. To overcome this problem, the PT Prasadha Pamunah Limbah Industri (PPLI) provides industrial waste processing services including Stabilization and Solidification (S/S) treatment using cement and fly ash mixtures. This research evaluated the efficiency of S/S in reducing the heavy metal content of lead (Pb) and arsenic (As) in liquid hazardous waste, using waste, fly ash, and cement ratios of 1:1:1, 1.5:1:0.5, and 2:0.5:0.5, tested with the Toxicity Characteristic Leaching Procedure (TCLP). The results demonstrated that the 1:1:1 and 1.5:1:0.5 ratios effectively reduced the Pb and As content, achieving reduction efficiencies of 99.50% and 99.34% for the 1:1:1 ratio, and 99.36% and 99.19% for the 1.5:1:0.5 ratio, respectively. However, the 2:0.5:0.5 ratio produced a brittle mixture prone to leachate formation and it is not recommended. According to the TCLP results, the 1:1:1 and 1.5:1:0.5 ratios met the environmental quality standards outlined in Government Regulation No. 22 of 2021 on Environmental Protection and Management. The statistical analysis using an independent T-test indicated no significant difference in the reduction efficiency between the two effective ratios, suggesting that either can be reliably used. This study addresses existing research gaps by applying the S/S method to liquid hazardous waste, an area previously focused on soil applications. Besides, it demonstrates that high immobilization rates exceeding 99% can also be achieved for Pb and As using cement and fly ash. This study provides a novel perspective on S/S applications, enhancing the efficiency and applicability of hazardous waste treatment processes.

Keywords-hazardous waste management; heavy metal immobilization; leachability reduction; solid waste treatment; toxicity characteristic leaching procedure

I. INTRODUCTION

The rapid growth of industries in Indonesia has led to an increased waste generation, including hazardous and toxic waste. This type of waste encompasses substances, energy, or other components that can directly or indirectly pollute, damage, and endanger the environment, human health, and the survival of other living beings [1]. Heavy metals, such as Lead (Pb) and Arsenic (As), are particularly concerning due to their toxicity and persistence [1]. According to data from the Indonesian Ministry of Environment and Forestry (KLHK), Indonesia generates over 10 million tons of hazardous and toxic waste annually, with around 60% originating from industrial activities [2].

PPLI is a key player in Indonesia's industrial waste management sector, holding permits to handle hazardous and toxic waste. One of its primary methods is S/S. This process is designed to chemically and physically stabilize waste, making it safer for disposal. Stabilization involves pre-treating waste with reactive agents, whereas solidification incorporates materials, such as Portland cement, fly ash, and absorbent clay to give waste a solid, stable form [3, 4]. This method is particularly effective in handling waste with heavy metals, such as Pb and As, reducing their concentrations to meet the environmental quality standards.

Heavy metals, such as Pb, pose significant health risks. For example, Pb can cause cardiovascular diseases and even death if it enters the human bloodstream [5]. This makes the S/S of such metals critical for the environmental and public health. At PPLI, Pb and As are frequently treated using a mixture of fly ash and cement to reduce their concentrations to safe levels.

Fly ash, a byproduct of coal combustion and waste incineration, is generated in significant quantities during the operation of the PPLI's high-capacity incinerator (50 tons per day). This fly ash, categorized as hazardous due to the presence of neurotoxic metals, also possesses valuable pozzolanic properties. These properties, similar to those of cement, make fly ash an effective filler and binder in construction materials, and a promising additive in the S/S process for binding heavy metals in hazardous waste [6, 7].

Previously, PPLI relied solely on cement as an additive in the S/S process. However, this approach proved suboptimal due to the high material costs and excessive cement requirements [8]. To improve the cost efficiency and performance, PPLI has begun exploring the use of fly ash as a partial replacement for cement. Although promising, the specific potential of fly ash derived from PPLI incinerators remains underexplored.

Previous studies on S/S methods have largely concentrated on contaminated soils, often using materials, such as quicklime (CaO) and fly ash, to immobilize heavy metals [9, 10]. While these studies achieved high immobilization rates, their applicability to liquid hazardous waste remains underexplored. Additionally, alternative binding agents, such as coal fly ash-based geopolymers, have demonstrated high immobilization efficiencies (exceeding 99%) for metals, like Pb, Zn, and Cd. However, limited research has focused on applying these methods to both Pb and As in liquid waste [11]. Furthermore, there has been little comparative research on the efficiency of different material ratios in S/S for liquid hazardous waste.

The scope of this study is to evaluate the effectiveness of fly ash sourced from PPLI incinerators in stabilizing and solidifying hazardous liquid waste. Specifically, this research examines artificial waste containing Pb and As at concentrations of 10 mg/L, which is representative of typical unprocessed waste received at PPLI and processed for landfill disposal. Laboratory-scale tests include initial Pb and As concentration analyses, S/S procedures using fly ash and cement at varying ratios, and TCLP tests to assess the environmental safety of the treated waste.

This study aimed to address these gaps by evaluating the performance of fly ash from PPLI incinerators in S/S hazardous liquid waste. By optimizing the ratios of fly ash and cement, this study seeks to enhance the sustainability and cost-effectiveness of hazardous waste management while ensuring compliance with environmental safety standards.

II. METHODS

This quantitative study employed an experimental method to determine the efficiency of reducing heavy metals (Pb and As) in hazardous toxic waste by adding fly ash from an incinerator and Portland cement via the S/S process. The experiment was conducted on a laboratory scale for three months. This research was designed to examine the type of fly ash that provides the highest efficiency in reducing the levels of Pb and As during this process.

Quantitative experimental methods have the advantage of being designed to describe the cause-and-effect (causal) relationship between variables (e.g., variables X and Y) [12]. The conceptual framework of this research is illustrated in Figure 1.

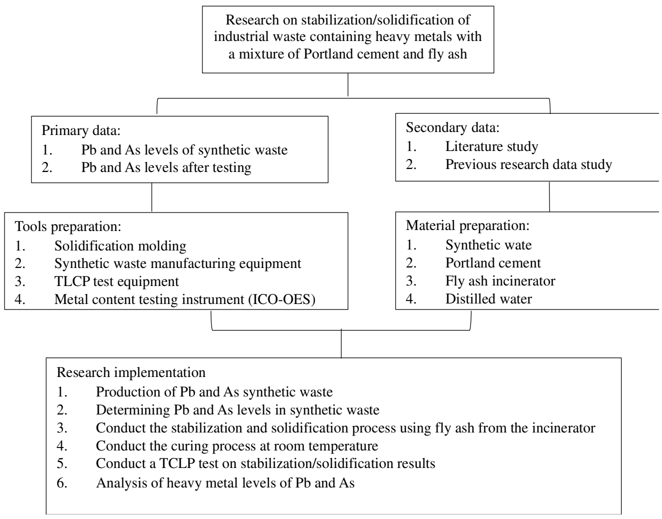

Fig. 1. Research framework.

A. *Observed Variables*

The observed variables included the initial concentration of the liquid hazardous toxic waste containing 10 mg/L of Pb and 10 mg/L of As, and the analysis of the S/S products through TCLP tests. In addition to measuring the mobility of the pollutants in liquids, solids, or mixed waste and determining the toxic properties of the waste [13], the TCLP test can be used to assess the results of the S/S products. According to PP Number 22 of 2021 on Environmental Protection and Management, Appendix XII TCLP-A, the Pb content should not exceed 3 mg/L, and the As content should not exceed 3 mg/L [1].

B. *Experimental Tools and Materials*

The experiments utilized several tools, such as a cylindrical solidification mold with a volume of 500 ml, laboratory glassware, TCLP test equipment, and heavy metal concentration test equipment deploying Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). The studied materials used were Pb and As synthetic waste from Certified Reference Materials (CRM), fly ash from incinerators, Portland cement, and distilled water.

C. Generation of Synthetic Waste and Initial Concentration Analysis

In this study, a synthetic waste concentration of 10 mg/L was utilized to represent the midpoint of the actual waste concentration, as the average levels of Pb and As processed by PPLI typically range between 5 and 20 mg/L. This synthetic waste simulates the concentration of waste received by the PPLI before processing and disposal in a Category 1 landfill. The synthetic waste was then analyzed to measure the actual concentrations of Pb and As using ICP-OES.

D. Preparation of Test Specimens

Once the concentrations of heavy metals Pb and As in the synthetic waste were determined, the S/S process was carried out using a mixture of cement and fly ash from the incinerator. The stabilization phase involves adjusting the pH of the waste to a neutral to weakly alkaline range (pH 7-9), which is optimal for the metal compounds in liquid waste to bind with cement and fly ash [14]. In this pH range, the metal compounds form precipitated salts, resulting in solid formations.

Three different ratios (g/g) of hazardous and toxic waste to fly ash and cement were tested: 1:1:1, 1.5:1:0.5, and 2:0.5:0.5. The resulting test specimens were molded into cylindrical shapes using 500 ml molds. After the S/S processes, the specimens were left to cure for 14 days at room temperature. This curing period was essential to ensure that the compressive strength of the specimens met the required standards because the compressive strength tended to increase with longer curing durations.

E. Toxicity Characteristic Leaching Procedure Test

The product of the S/S process was then subjected to a TCLP test using an extraction solution with a pH ranging from 2.83 to 2.93. According to the Indonesian National Standard number 8808 of 2019 on TCLP, the TCLP test is used to measure the mobility of pollutants in liquids, solids, or mixed waste. It can be also utilized to determine the toxic nature of the waste. In addition, the TCLP test can be used to assess the results of the S/S procedure [13].

TCLP testing was conducted following the method 1311 from EPA [15]. The extraction was performed by stirring at a speed of 30 ± 2 rpm for 18 ± 2 h. The extraction solution was filtered and the Pb and As concentrations in the filtrate were estimated using ICP-OES. The samples were prepared and extracted from the PPLI Laboratory. Hazardous and toxic waste was classified based on the TCLP results, and was deemed hazardous if the results exceeded the existing quality standards.

F. Data Analysis

The experimental results were analyzed using the efficiency calculation formula (1) and compared with the quality standards. The efficiency of reducing the Pb and As metal levels can be calculated by subtracting the concentration after processing from the concentration before processing, dividing the result by the initial concentration, and then multiplying by 100% to obtain the reduction efficiency as a percentage.

$$Efficiency\ (\%) = \frac{Initial\ concentration - Final\ concentration}{Initial\ concentration} \times 100\% \quad (1)$$

Following the metal concentration tests of the samples, a statistical test for the significant differences was conducted to determine whether the test formulations differed significantly and were considered acceptable. The significance test was performed using an independent T-test. Both the F-test and T-test calculations and data processing were performed utilizing Microsoft Excel. The data used were from Pb and As metal concentration tests after processing. The F-test assessed the homogeneity of the sample repetitions, whereas the T-test evaluated the effect of reducing the heavy metal levels in the formulations.

In the previous stabilization process, PPLI used cement as the metal binder. Cement has demonstrated excellent stabilization results and effectively absorbs the heavy metals contained in hazardous and toxic waste. Since then, PPLI has innovated its stabilization process by utilizing the abundant supply of fly ash from incinerators and coal. Fly ash, which has properties similar to those of cement, is now used as a substitute material in the stabilization process to reduce the cement usage and cost. Based on previous experiments conducted before fly ash was introduced, PPLI achieved Pb and As reduction efficiencies ranging from 80% to 90 %. This efficiency range served as the reference standard for the research conducted in this study.

III. RESULTS

A. Initial Waste Characteristics

An initial analysis of synthetic waste was conducted to verify the concentrations of Pb and As. Using ICP-OES, the average concentrations were found to be 9.75 mg/L and 9.72 mg/mL for Pb and As, respectively, which are close to the nominal value of 10 mg/L. The measured concentrations of Pb and As, outlined in Table I, confirmed the accuracy of the waste preparation process and provided a reliable baseline for the subsequent S/S experiments.

TABLE I. INITIAL CONCENTRATION OF WASTE BEFORE PROCESSING

Test	Pb (mg/L)	As (mg/L)	*EQS Pb and As
1	9.73	9.62	<0.5 mg/L
2	9.75	9.70	
3	9.66	9.60	
4	9.64	9.80	
5	9.87	9.75	
6	9.79	9.79	
7	9.78	9.81	
Average	9.75	9.72	

* EQS: Environmental Quality Standards Appendix XII of Government Regulation Number 22 of 2021 concerning the Implementation of Environmental Protection and Management.

B. Stabilization and Solidification Process

The S/S process was tested using three different ratios of hazardous waste, fly ash, and cement, as listed in Table II.

TABLE II. SAMPLE SPECIFICATIONS

Sample No.	Waste: fly ash: cement weight ratio
1	1:1:1
2	1.5:1:0.5
3	2:0.5:0.5

The samples obtained after S/S are shown in Figure 2. The samples with ratios of 1:1:1 and 1.5:1:0.5 produced solid mixtures with a hard, dry texture and no residual leachate, indicating a successful S/S. The samples with a 2:0.5:0.5 ratio exhibited a brittle texture and the presence of residual leachate, signifying failure in the solidification process. These findings suggest that both the 1:1:1 and 1.5:1:0.5 ratios are effective for achieving proper S/S results. However, the 2:0.5:0.5 ratio is unsuitable for long-term containment.

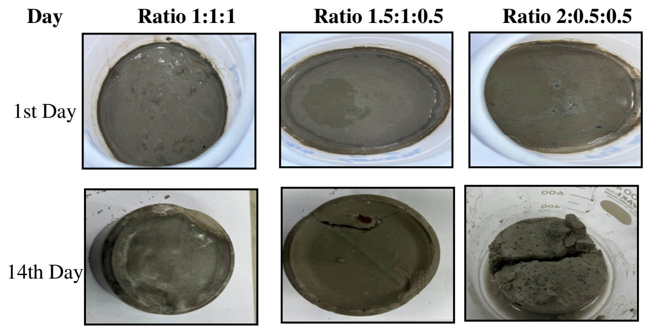

Fig. 2. The samples after the S/S process and after 14 days of curing.

C. Toxicity Characteristic Leaching Procedure Test Results

1) Toxicity Characteristic Leaching Procedure Tests for Pb

The average concentration of Pb was estimated at around 0.06 mg/L in the 1:1:1 and 1.5:1:0.5 ratio samples. Both ratio samples, displayed in Table III, exhibited significant reduction in Pb concentration compared to the initial values and met the environmental quality standards for hazardous waste disposal.

TABLE III. LEAD CONCENTRATION AFTER S/S PROCESSING

Test	Pb metal (mg/L)		*EQS Pb
	Ratio (1:1:1)	Ratio (1.5:1:0.5)	
1	0.03	0.07	<0.5 mg/L
2	0.02	0.08	
3	0.04	0.05	
4	0.04	0.09	
5	0.06	0.05	
6	0.09	0.03	
7	0.06	0.07	
Average	0.05	0.06	

*EQS: Environmental Quality Standards Appendix XII of Government Regulation Number 22 of 2021 concerning the Implementation of Environmental Protection and Management.

2) Toxicity Characteristic Leaching Procedure Tests for As

The TCLP test results for As showed that the concentration of As was 0.06 mg/L and 0.08 mg/L for the 1:1:1 and 1.5:1:0.5 ratio samples, respectively. Both samples, as can be seen in Table IV, had an As concentration below the environmental quality standard limits, ensuring their safe disposal in landfill facilities.

TABLE IV. ARSENIC CONCENTRATION AFTER S/S PROCESSING

Test	As metal (mg/L)		*EQS As
	Ratio (1:1:1)	Ratio (1.5:1:0.5)	
1	0.05	0.09	<0.5 mg/L
2	0.05	0.06	
3	0.06	0.08	
4	0.05	0.10	
5	0.07	0.07	
6	0.08	0.09	
7	0.09	0.06	
Average	0.06	0.08	

*EQS: Environmental Quality Standards Appendix XII of Government Regulation Number 22 of 2021 concerning the Implementation of Environmental Protection and Management.

D. Efficiency in Reducing Pb and As Concentration

The efficiency of the Pb and As reduction for the two samples' ratios was calculated at 99%. As shown in Table V, both proposed ratios (1:1:1 and 1.5:1:0.5) were highly efficient in reducing heavy metal concentrations in the treated waste.

TABLE V. THE EFFICIENCY OF PB AND AS HEAVY METAL REDUCTION

Ratio	The efficiency of Pb (%)	The efficiency of As (%)
1:1:1	99.50	99.34
1.5:1:0.5	99.36	99.19

E. Statistical Analysis

To determine whether there was a statistically significant difference in the reduction of Pb and As between the two ratios, independent F- and T-tests were performed using data from seven experimental repetitions for each ratio.

TABLE VI. INDEPENDENT T-TEST STATISTICAL RESULTS OF PB AND AS

Test statistics	Test F		Test T	
	F Calculation	F Table	T Calculation	T Table
Pb	0.774	4.284	-1.213	2.179
As	1.058	4.284	-1.674	2.179
Conclusion	F Calculation < F Table, where the data from both test results were declared homogeneous		T Calculation < T Table, where both test results stated that there was no difference and were acceptable.	

The Homogeneity of Variance (F-test) results indicated that both datasets exhibited homogeneity of variance. Meanwhile, the T-test results showed that there was no statistically significant difference in the reduction of Pb and As between the 1:1:1 and 1.5:1:0.5 ratios , as evidenced in Table VI.

The initial synthetic waste concentrations of Pb and As were close to the target values, measuring 9.75 mg/L and 9.72 mg/L, respectively. The S/S process using ratios of 1:1:1 and 1.5:1:0.5 successfully produced a dry, solid texture without any residual leachate. The TCLP tests confirmed that the concentrations of Pb and As were reduced to levels below the environmental quality standards, with the reduction efficiencies exceeding 99% for both metals. The statistical analysis revealed no significant differences in the performance between the two effective ratios. These findings demonstrate that both the 1:1:1 and 1.5:1:0.5 ratios are reliable for stabilizing and solidifying hazardous waste containing Pb and As.

IV. DISCUSSION

The PPLI incinerator burns a wide range of hazardous and toxic waste, including infectious waste, hazardous chemicals, and other toxic substances. One byproduct of this combustion process is fly ash, which consists of small particles carried by the flue gas. Fly ash is primarily composed of silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), calcium oxide (CaO), and magnesium oxide (MgO) [16]. Due to its chemical composition, fly ash possesses cementitious properties, meaning that it can act as an adhesive material similar to cement when mixed with water [17].

The addition of fly ash during the S/S process can significantly influence the compressive strength of the resulting material. The key advantages of using fly ash include [18]:

- Minimizing water separation or "bleeding" in the mixture.
- Reducing the heat of hydration during the curing process.
- Decreasing the amount of water needed for mixing.

In this study, fly ash from the incinerator was utilized as a filler in the mixture of hazardous and toxic waste and cement. During the S/S process, fly ash plays a crucial role in forming a solid mass that aids in the absorption and immobilization of the heavy metals present in waste [19]. The interaction between hazardous and toxic waste, fly ash, cement, and heavy metals involves complex chemical reactions. These reactions are influenced by several factors, including the chemical and physical properties of fly ash, the type of heavy metal in the waste, and the environmental conditions during the process.

Several previous studies have focused on the use of fly ash, especially for reducing the concentration of heavy metals in hazardous and toxic waste and have served as valuable reference materials for this research. In 2018, a study explored the reuse of fly ash as an adsorbent to reduce the Fe metal concentrations in liquid waste [20]. These findings demonstrate that fly ash is effective in lowering the iron levels. The performance of the adsorbent was tested by varying its weight, contact time, and activator concentration. The fly ash activated with 6 M NaOH exhibited the highest absorption rate. The experimental results showed that the absorption effectiveness reached 99.42%. Another study examined the efficiency of fly ash in reducing Pb and Cd concentrations during the S/S processes [21]. This study also showed the effect of reducing the content of the heavy metals Pb and Cd in hazardous and toxic waste in the S/S process, where the efficiency of reducing Cd was 99.98%.

Authors in [22] determined the optimal composition of cement and fly ash for stabilizing industrial waste containing heavy metals, such as Cu, Cr (VI), and Pb. The results exhibited that the optimum composition obtained was 90 cement : 10 fly ash. This was determined after obtaining the TCLP results for the three heavy metals that met the quality standards with small values. It was found that hydrocarbons significantly affected the TCLP values of Cu, Cr (VI), and Pb.

A further exploration of the potential of fly ash as an adsorbent material for reducing Fe metal concentrations in liquid waste is required [23]. According to [23], the higher the concentration of the NaOH solution is, the larger is the pore structure of fly ash, and thus, the higher is the absorption process of iron metal. In [24], the elemental properties of fly ash and bottom ash from coal combustion in boilers were used by the fertilizer industry, assessing the opportunities for heavy metal capture in solid waste. The dominant oxides carrying heavy metals, such as Fe_2O_3, were 3.658% in fly ash and 2.237% in bottom ash. The Ag_2O content was 0.143% in fly ash and 0.015% in bottom ash. MnO contained 0.036% in fly ash and 0.015% in bottom ash.

These studies offered valuable insights and guided the development of the present study. The primary distinction of this study lies in the use of incinerator fly ash from PPLI, specifically aimed at reducing the concentrations of heavy metals, Pb and As, in hazardous and toxic waste through the S/S process. The experiment involved varying the mixture ratios of hazardous and toxic waste, fly ash, and cement (1:1:1, 1.5:1:0.5, and 2:0.5:0.5) to determine the most efficient formula for reducing the heavy metal concentrations. By comparing these different formulations, this study aimed to assess the effectiveness of incinerator fly ash in stabilizing heavy metals during waste treatment. Fly ash acts as both a binding agent and stabilizer for heavy metals, helping to reduce their solubility, and consequently, their potential for environmental pollution [25]. The fine particles in fly ash can absorb or bind to the metal ions in the solution, lowering the concentration of heavy metals in the treated waste. Additionally, fly ash can participate in chemical reactions that form insoluble compounds with certain heavy metals, thereby reducing their mobility and toxicity.

Moreover, fly ash components can influence the pH of the waste mixture, and changes in the pH can directly affect the solubility of metals [26]. In an alkaline environment, metals like Pb and As tend to form less soluble compounds, reducing their potential to leach into the environment. However, under more acidic conditions, these metals become more soluble and likely to leach [27].

By using fly ash in the S/S process, the treatment not only addresses the reduction of hazardous metal concentrations, but also offers a cost-effective alternative to using large quantities of cement alone. This dual functionality highlights the potential of fly ash as an effective additive for hazardous waste management.

A. Initial Waste

The initial concentrations of heavy metals in the synthetic waste were determined to be 9.75 mg/L for Pb and 9.72 mg/L for As, which are very close to the nominal values of 10 mg/L. This small discrepancy could be attributed to minor errors during the waste preparation or slight variations in the sensitivity of the ICP-OES instrument. Despite these minor differences, the results confirm that the produced synthetic waste accurately represents real-world hazardous waste conditions, with metal concentrations at levels that pose significant environmental risks.

Based on these values, this synthetic waste is classified as category 1 hazardous and toxic waste, according to the Indonesian regulations. Specifically, it exceeds the TCLP A limits outlined in Attachment XII of Government Regulation Number 22 of 2021 regarding Environmental Protection and Management [1]. This classification underscores the need for effective treatments, such as S/S, to mitigate the environmental hazards posed by waste.

B. Stabilization and Solidification

The purpose of varying the ratios in this study was to assess the effectiveness of fly ash and cement in reducing heavy metal concentrations, while minimizing the use of cement to lower costs. The main objective was to maximize the ability of fly ash to reduce heavy metal concentrations, ensuring that the solidified mixture met the required compressive strength standards during the solidification process.

The results demonstrated that the 1:1:1 and 1.5:1:0.5 ratios were successful in the S/S of hazardous and toxic waste. These mixtures produced samples with a hard, dry texture with no leachate remaining, indicating effective solidification. The absence of leachate and the firm texture suggest that the balance of fly ash, cement, and waste allowed for sufficient chemical interactions to occur, ensuring that the waste was immobilized and the heavy metals were effectively stabilized.

In contrast, the 2:0.5:0.5 ratio produced a sample that displayed a brittle texture and left residual leachate, indicating an unbalanced composition. The disproportionate amount of hazardous and toxic waste relative to the binding agents (fly ash and cement) likely hinders the stabilization process. The lack of homogeneity in this mixture prevents a proper interaction between the waste and stabilizing agents, resulting in inadequate solidification. Employing mechanical mixing techniques, such as high-shear or rotary mixers can ensure a more uniform distribution of fly ash and cement throughout the hazardous waste. Proper mixing can facilitate better interactions between the stabilizing agents and contaminants, resulting in improved structural integrity. Additionally, increasing the curing time under controlled conditions (e.g., temperature and humidity) allows for a more thorough hydration of cement and pozzolanic reactions, enhancing the strength and durability of the solidified waste.

The presence of leachate and brittle texture suggest that the fly ash and cement were insufficient to absorb and immobilize hazardous waste at this ratio, rendering it unsuitable for further testing or environmental applications. Incorporating supplementary binding materials, such as lime (CaO), bentonite, or pozzolanic additives, could improve the chemical and physical properties of the mixture.

This 2:0.5:0.5 ratio was excluded from the TCLP test, as it did not meet the solidification standards required for a further analysis. The waste still contained pollutant substances exceeding the TCLP-A limits, as outlined in Attachment XII of Government Regulation Number 22 of 2021 regarding Environmental Protection and Management [1]. This regulation sets strict limits for the pollutant levels in solidified waste to ensure environmental safety, further affirming that the 2:0.5:0.5 ratio failed to meet these standards.

C. Toxicity Characteristic Leaching Procedure Tests

According to Government Regulation Number 22 of 2021 on the Implementation of Environmental Protection and Management, the TCLP test is a laboratory method used to estimate the potential of hazardous materials to leach from waste. This test is essential for determining whether the hazardous and toxic waste meets the criteria for a safe disposal, as outlined in Appendix XII of the regulations [1].

The results of the TCLP test for Pb in this study indicated that the metal concentration met the toxicity characteristic standards, confirming the suitability of the waste for disposal in a final landfill facility. The reduction in heavy metals in the waste during the S/S processes can be attributed to the binding properties of fly ash. Fly ash acts as a pozzolanic absorbent material, physically binding the heavy metals through its cementitious properties, which enhance the long-term stability.

In addition to fly ash, cement plays a critical role in the stabilization process. Acting as a binder, cement immobilizes the contaminants by forming a calcium silicate layer around the heavy metal particles. This layer prevents hydration and limits the mobility of contaminants, such as Pb. Once encapsulated in the cement matrix, the heavy metals become more physically and chemically stable. The chemical reactions responsible for immobilizing Pb in the solidified waste are:

$$Pb^{2+} + OH^{-} \rightarrow Pb(OH)_2 \text{ (precipitate)}$$

$$Pb^{2+} + CO_3^{2-} \rightarrow PbCO_3 \text{ (precipitate)}$$

These reactions result in the precipitation of the Pb compounds trapped within the cement structure, effectively reducing their potential to leach into the environment.

The behavior of As in waste is influenced by the environmental conditions. In aquatic environments, arsenic can exist in both pentavalent (As(V)) and trivalent (As(III)) forms depending on the level of oxidation or reduction. The mobility and absorption of As are affected by its interaction with clay, sediment, and soil minerals. Under anoxic conditions, microbial activity can methylate As, altering its form. Arsenic can also volatilize in its solid state and enter the atmosphere under certain conditions.

D. Efficiency and Independent T-Test

The results from the independent T-test showed an efficiency rate above 99%, indicating that this study provides promising outcomes and presents a viable alternative for hazardous and toxic waste treatment using S/S. Among the tested ratios, the 1:1:1 ratio demonstrated the highest efficiency. This is attributed to the balanced use of fly ash and cement, which optimizes their combined ability to absorb heavy metals compared to the 1.5:1:0.5 ratio. The balanced composition of the 1:1:1 ratio enabled a better stabilization of the heavy metals, contributing to its superior performance.

This study achieved an efficiency rate of over 90% in reducing Pb and As concentrations, surpassing the 80-90% efficiency achieved when only cement was used in previous treatments. The inclusion of fly ash significantly enhanced the stabilization process, improving both performance and cost-effectiveness by reducing the amount of cement required.

The statistical analysis was conducted employing two methods: F-test and T-test. The F-test was used to evaluate the homogeneity of the data from repeated experiments, whereas the independent sample T-test assessed whether there were significant differences between the outcomes of the different ratios. The T-test was utilized to determine whether the difference in the mean values between the two groups was statistically significant.

In this study's experiment, the data were homogeneous, indicating that the variations between the repeated experiments were consistent. Based on the T-test results, there was no significant difference between the 1:1:1 and 1.5:1:0.5 ratios in terms of efficiency. Therefore, both ratios can be considered viable for use in the S/S process because they provide similar levels of effectiveness in reducing heavy metal concentrations.

V. CONCLUSIONS

In conclusion, a mixture of fly ash from incinerators and cement has proven to be an effective solution for reducing the concentrations of lead (Pb) and arsenic (As) in hazardous and toxic waste. This combination offers an optimal and viable alternative for waste processing, particularly for Stabilization and Solidification (S/S) processes. The reduction efficiencies for Pb using the 1:1:1 and 1.5:1:0.5 ratios (waste: fly ash: cement) reached 99.69% and 99.28%, respectively, while for As, the reduction efficiencies were 99.48% and 99.17%, respectively, for the same ratios. However, the 2:0.5:0.5 ratio is not recommended, as it does not meet the requirements for further processing.

The statistical analysis using independent F- and T-tests revealed no significant differences in the performance of the 1:1:1 and 1.5:1:0.5 ratios for both Pb and As, underscoring the reliability of these formulations. These findings align with prior research, indicating the potential of S/S methods for immobilizing heavy metals. However, this study advances the current knowledge by demonstrating the high reduction efficiencies achieved with specific fly ash and cement ratios, offering practical guidance for optimizing hazardous waste treatment processes.

Previous studies have primarily applied S/S methods to contaminated soils, often using quicklime (CaO) and fly ash to immobilize Pb. Although these approaches have shown promise for soil remediation, the effectiveness of S/S techniques for treating hazardous liquid waste remains largely unexplored. Additionally, while some studies have investigated alternative binding agents, such as coal fly ash-based geopolymers, achieving high immobilization rates (exceeding 99%) for heavy metals, such as Pb, Zn, and Cd, limited studies have extended these methods to target both Pb and As in liquid waste. This study addresses this research gap by offering a novel perspective on stabilization techniques for liquid hazardous waste treatment. By optimizing specific mixture ratios and validating their effectiveness through statistical analysis, this study not only confirms the utility of fly ash and cement mixtures, but also emphasizes the importance of tailored approaches for different waste types.

These findings are particularly relevant for industrial applications dealing with liquid hazardous and toxic waste, as they provide actionable recommendations for minimizing the environmental impact of such waste.

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