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# Utilisation of Clinical Waste Incineration Fly Ash and Silica Fume as Supplementary Cementitious Materials in Mortar: Performance Evaluation and Environmental Impact Assessment

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ABSTRACT

*The rising production of Clinical Waste Incineration Fly Ash (CWIFA) presents disposal challenges due to high costs, limited land availability, and pollution concerns. However, using CWIFA as a supplementary cementitious material in mortar could help reduce the reliance on Portland cement in construction. Before adopting this approach, it is essential to ensure that CWIFA is adequately solidified and stabilized in the mortar to prevent the leaching of harmful heavy metals into the environment. This study explores the use of CWIFA and silica fume (SF) as supplementary cementitious materials in mortar. Two series of samples were tested: Series 1 and Series 2, incorporating varying percentages of CWIFA (0%, 2.5%, 5%, 10%, and 15%) and SF (0% and 10%), with a constant fine aggregate-to-cementitious ratio of 2.75 by mass and constant water-to-cementitious ratio of 0.485. This study investigated the effect of adding CWIFA and SF on mortar's strength properties. Additionally, the study found that a combination of Portland cement and 10% SF effectively enhances physical encapsulation and minimizes heavy metal leaching (nickel, arsenic, chromium, lead, and selenium) as determined by the Toxicity Characteristic Leaching Procedure (TCLP USEPA Method 1311). These findings suggest that incorporating CWIFA and SF can improve the strength performance of mortar mixtures and offer potential benefits for construction and environmental remediation.*

*Keywords: Clinical Waste; Clinical Waste Incineration Fly Ash; silica fume; leaching; Toxicity Characteristic Leaching Procedure (TCLP); environmental; stabilisation/solidification*

## INTRODUCTION

The global rise in clinical waste (CW) generation and the associated disposal costs have created a need for alternative waste management strategies. In Malaysia, this trend mirrors the global situation, exacerbated by factors such as the COVID-19 pandemic, the rapid expansion of healthcare facilities, and urbanization. The volume of CW disposed of in Malaysia has significantly increased, rising from 30,727.04 metric tonnes per year in 2018 to 49,131.62 metric tonnes per year in 2022 (Department of Environment Malaysia 2019, 2023). Classified as scheduled waste under environmental regulations, CW disposal costs range from RM 1,500 to RM 4,000 per metric tonne (Pariatamby, 2017). The COVID-19 pandemic has further complicated disposal by increasing the volume of challenging CW. Projections indicate that high infection rates will continue to drive CW generation upward through 2023 (Al-Omran et al. 2023).

Clinical waste incineration results in two solid residuals: clinical waste incineration bottom ash (CWIBA) and clinical waste incineration fly ash (CWIFA). If not utilized, these ashes are disposed of in secured landfills. Recently, there has been growing interest in CWIFA due to its potential cementitious and pozzolanic properties, suggesting its viability as a supplementary cementitious material (SCM). To mitigate pollution and recycle waste, there is a need for methods that incorporate CWIFA in construction materials, thereby reducing the energy required to produce cement and treating waste simultaneously. Evaluating the leachate potential of CWIFA is crucial when considering its use in construction to ensure that it meets environmental standards for heavy metal leaching, as determined by the Toxicity Characteristic Leaching Procedure (TCLP USEPA Method 1311).

Silica fume (SF), a by-product of silicon metal or ferrosilicon alloy production, is a highly reactive SCM that enhances the mechanical properties and environmental resistance of construction materials. The combination of SF and CWIFA holds promise for improving compressive strength and reducing heavy metal leaching in mortar. This mixture could be beneficial in various applications, including concrete, mortars, cement-based materials, geotechnical and geo-environmental applications, agriculture, and road construction. Although municipal solid waste incineration fly ashes (MSWIFA) are currently used in commercial composite cement production to reduce environmental impact, the potential of CWIFA combined with SF in mortar has not been extensively explored.

SF, rich in silicon dioxide (SiO2), reacts with calcium hydroxide in mortar to form supplementary cementitious materials due to its high silica content. CWIFA, identified as a potential pozzolanic material with cementitious properties, requires environmental evaluation before use in construction materials to ensure compliance with TCLP USEPA Method 1311 for heavy metals. Adding SF to mortar mixtures can enhance compressive strength while reducing heavy metal leaching, making it a promising approach for sustainable construction practices.

The solidification/stabilisation (S/S) of hazardous or toxic waste using mortar has garnered significant attention in waste management. This process encapsulates waste materials within a mortar matrix to prevent their dispersion and environmental contamination (Zhao et al. 2017). Cement, a primary binder in the S/S technique, is widely used for immobilizing hazardous substances, particularly metals (Grilo et al. 2014). This method is well-established and recognized for its effectiveness in reducing the leachability of heavy metals (Banhart, 2006). Stabilisation offers a cost-effective alternative to hazardous waste landfills, significantly reducing waste volume and replacing raw materials in civil construction (Liddle et al. 2011). The addition of pozzolanic materials like CWIFA to the waste mix results in a solidified material that enhances the S/S of metals (Soltys et al. 2021).

The S/S process, which involves physical and chemical mechanisms such as encapsulation, fixation, or adsorption, is increasingly used to manage combined organic and inorganic industrial waste (Al-Kharabsheh et al. 2022). This technique often involves modifying the waste's physical and chemical composition, allowing pollutants to remain contained within the solidified matrix as it degrades over time (Orazov et al. 2023). Evaluating the leachability of contaminants from fly ash and bottom ash before and after stabilisation demonstrates the effectiveness of the solidification process in reducing the solubility and leachability of harmful substances (Czop & Piekarczyk 2019).

S/S processes are crucial for immobilizing heavy metals, particularly through cement-based techniques. Cement-based solidification creates a durable matrix that traps heavy metals within its porous gel structure (Chen et al. 2009). Cement binds waste compounds, forming insoluble metal hydroxides and improving waste resistance, compressibility, and permeability (Paria & Yuet, 2006). The goal of S/S is to convert contaminants into less mobile and reactive forms, achieving a chemically stable state (Gao et al. 2021). This process lowers the solubility and toxicity of pollutants, resulting in reduced leachate concentrations of heavy metals (Chen et al. 2009). Cement solidification and stabilisation are widely adopted to minimize atmospheric emissions and recycle waste in construction products (Bie et al. 2016). Extensive research has examined the efficiency of S/S techniques and the characteristics of CWIFA, highlighting the positive impact of cement solidification on leaching toxicity. The literature consistently supports the effectiveness of cement-based S/S techniques in immobilizing heavy metals and decreasing leachability, emphasizing their growing importance in waste management. The following section will delve into the use of a cement-based S/S mortar system.

Recent research has increasingly focused on the potential of incineration by-products, particularly ash, as cost-effective building materials in the construction industry (Dry, 2004). Waste incineration technology has evolved over the past century, addressing environmental concerns while creating economic opportunities (Ravishankar, 1990). In Malaysia, traditional mortar has been linked to environmental issues such as resource depletion, excessive energy consumption, and carbon emissions (Marut et al. 2020). Despite ongoing efforts to incorporate ash by-products into mortar production, adoption has been slow due to concerns about practicality, cost, and resistance to change. The rising cost of slags and ashes, along with the recognition of mixed cements as comparable or superior to standard Portland cement, has highlighted the need to explore incineration by-products as alternatives. This approach aims to address long-term environmental issues by using diminishing natural resources more sustainably (Lin et al. 2005). Therefore, utilizing ash from incineration by-products as supplementary cementitious materials (SCM) for mortar represents a significant step towards reducing environmental impact and supporting a circular economy.

Efforts to convert incineration by-products into valuable building materials are gaining momentum. Several studies have shown promising results in using these by-products for mortar production. For instance, Seifi et al. (2019) found that mortars made with wastepaper sludge ash and ground granulated blast furnace slag (GGBS) achieved optimal compressive strength at a specific water-to-binder ratio, with strength improving over time with curing. Bie et al. (2016) investigated the impact of cement quantity and leaching conditions on mortars mixed with municipal solid waste incineration fly ash (MSWIFA), finding that cement reduced the leaching of heavy metals. Tian et al. (2021) explored the use of waste glass as an additive in municipal solid waste incineration fly ash, highlighting its effectiveness in enhancing solidification and immobilizing heavy metals. Viet et al. (2020) examined the potential of fly ash from municipal solid waste incineration as a CO2 sequestrant and SCM for eco-friendly construction materials, demonstrating its effectiveness in stabilizing hazardous elements in mortars. Hamood et al. (2017) investigated the effects of substituting rice straw ash with water in mortar mixtures, noting improvements in strength and density, although flowability and water absorption were reduced. Liu et al. (2019) evaluated mortars containing recycled waste glass powder, GGBS, and fly ash, finding enhanced early reaction intensity, accelerated hydration, and improved chloride migration resistance. Ibrahim et al. (2021) studied mortars with MSWIFA, concluding that an optimal percentage of 5% yielded consistent and acceptable properties.

While numerous global studies have successfully used incineration ash by-products in mortar production, the focus on Clinical Waste Incineration Fly Ash (CWIFA) is notable due to its significant and ongoing production worldwide. The next section will explore the role of CWIFA as an SCM in mortar production. Incineration is a common method for disposing of clinical waste (CW) generated by hospitals and healthcare facilities. The amount and type of CW produced can vary based on factors such as the facility's size and type, as well as the country's standard of living, with larger and more advanced facilities producing more waste. This study aims to develop a safe and efficient method for managing and disposing of CW in compliance with relevant regulations, minimizing risks to public health and the environment.

The CWIFA samples for this study are sourced from Radicare Sdn Bhd's incinerator plant in Teluk Panglima Garang, Selangor. The plant, established in 1997, received an upgrade with a new incinerator in March 2018. The study involved a two-day sampling period of CW processed at the plant (Tri Ecoedge Sdn Bhd 2018). The incinerator's design adheres to the Environmental Quality (Clean Air Regulations, CAR) 2014 to meet local environmental standards (Lai & Law 2019). The plant operates within emission standards, with CW fed into the incinerator in batches. The average CW intake ranges from 1.022 to 2.8 metric tonnes per day, coming from government hospitals, private clinics, and health centers (Tri Ecoedge Sdn Bhd 2018). The efficiency of the air pollution control system, specifically for hydrochloric acid (HCl), improved by at least 97 percent, and particulate emissions after the baghouse filter were below 10 mg/Nm$^3$

One effective method for reducing leachate production is by utilizing Clinical Waste Incineration Fly Ash (CWIFA). CWIFA is the residue remaining after the incineration of clinical waste, such as used syringes and medical equipment (Choi & Jusoh, 2021). Leveraging the chemical properties of CWIFA to minimize leachate can benefit the environment by reducing groundwater and soil contamination and removing pollutants before they are discharged. This approach is widely used for solidification and stabilization prior to landfill disposal due to its ease of implementation and low cost (Liu et al. 2018). Resource recovery—encompassing recycling, composting, and energy recovery—plays a crucial role in reducing the need for new raw materials, saving energy, and mitigating environmental impacts (Zaman, 2016).. It promotes sustainable development by lessening the negative effects of human activities on the environment.

Incorporating CWIFA into mortar presents a sustainable construction solution by diverting waste from landfills and enhancing mortar properties. However, it is essential to ensure that CWIFA is properly treated and processed before its use in construction to ensure safety for human health and the environment. Understanding the qualities of raw CWIFA is crucial, as these characteristics influence the performance, quality, and sustainability of the finished product. Previous studies on CWIFA help identify potential concerns or hazards, design suitable materials, and ensure effective use in various applications. Thus, investigating CWIFA's properties as a supplementary cementitious material (SCM) is necessary for maximizing its potential benefits.

The compressive strength decreases as the percentage of CWIFA increases because it has lower levels of CaO and $SiO_2$ (Ababneh et al. 2020). Municipal Solid Waste Incineration Fly Ash (MSWIFA) has minimal impact on cement hydration, but excessive amounts of MSWIFA can reduce compressive strength (Bie et al. 2016; Tang et al. 2016; Yang et al. 2018). Longer curing times enhance the compressive strength of solidification/stabilization (S/S) products (Lombardi et al. 1998),, and higher ratios of cement/MSWIFA combined with longer curing times improve compressive strength due to pozzolanic reactions and water molecule fixation (Bie et al. 2016; Li et al. 2018;

Tang et al. 2016; Yang et al. 2018). Silica Fume (SF) significantly enhances compressive strength due to its fineness, chemical properties, and pozzolanic reactivity (Bai & Rao, 2015; Imam et al. 2018; Mehta & Ashish, 2020; Roy & Sil, 2012). SF improves concrete strength and is used as a cement additive for high-performance concrete (Neville, 2013; Nochaiya et al. 2010). SF helps create high-performance concrete with lower water-cement ratios and better hydration (Roy & Sil 2012; Saridemir 2013; Yanfei Yue et al. 2018). Combining SF with Nanosilica (NS) results in higher compressive strength, regardless of the dosage (Nattaj & Nematzadeh, 2017; Seifan et al. 2020).. Adding 10% SF to mortar or concrete enhances its properties (Nattaj & Nematzadeh, 2017; Seifan et al. 2020)., and improved compressive strength is observed with increased curing time and age (Amudhavalli & Mathew, 2012; Collepardi et al. 2010; Djezzar et al. 2018; Hanumesh et al. 2015; Neville 2013).

The leaching test is used to identify which components of a solid substance will dissolve and form leachate. This method is crucial for assessing solid waste conditions in landfills, with the TCLP (Toxicity Characteristic Leaching Procedure) USEPA Method 1311 serving as a key evaluation tool to determine if a waste is hazardous. The TCLP method assesses the leaching behavior of cement-based waste to check for toxic elements, making it a widely accepted protocol for confirming non-toxicity. Using low-cost materials is crucial for budget compliance, and these materials must also be non-toxic to prevent environmental and health risks (Firoozi et al. 2022).

Lowenbach & Schlesinger (1979) describe the leaching test process, which involves exposing a solid substance to a leaching solution to identify which components dissolve into the leachate. The test conditions, such as sample preparation, solution composition, contact method, liquid-to-solid ratio (L/S), system control (e.g., pH and temperature), leachate separation, and duration, are adjusted based on the experimental objectives. These tests simulate landfill conditions. Waste in landfills leaches harmful substances like heavy metals and organic contaminants into surface and groundwater, creating a significant environmental burden (Rahman et al. 2023).

According to USEPA SW-846, the TCLP Method 1311 comprises four main phases: sample preparation, extraction, leachate separation, and analysis. Waste that passes this test is classified as non-hazardous, while failing waste is deemed hazardous and subject to stricter regulations. This method is crucial for evaluating the leaching behavior of Clinical Waste Incineration Fly Ash (CWIFA) to ensure that toxic elements do not leach out.

Studies, such as those by Anastasiadou et al. (2012) and Tzanakos et al. (2014) show that cement-based systems containing waste have been extensively researched due to their role in immobilizing metals and contaminants. Heavy metal leaching is often minimal compared to the total metal content in the waste. However, real-world scenarios, like frequent short wetting events, can impact leaching (Al-Akhras et al. 2011). These studies also evaluate binding mechanisms of cement-based composites.

Effective strategies for managing metal-containing waste, such as solidification, have been supported by various studies. Bie et al. (2016) and Tang et al. (2016) demonstrated that cement can significantly reduce heavy metal leaching, with levels falling below USEPA thresholds. Sobiecka et al. (2014) and Anastasiadou et al. (2012) found that the leaching of CWIFA is influenced by the Portland cement ratio. Agamuthu & Chitra (2009) observed that heavy metal concentrations could increase with additives like activated carbon and rice husk.

The TCLP method identifies high concentrations of metals like zinc (Zn) and lead (Pb) in CWIFA, with some exceeding regulatory limits (Ababneh et al. 2020; Anastasiadou et al. 2012). Limited literature exists on CWIFA heavy metals, but studies show that leaching is affected by factors like combustion conditions and particle size (Qian et al. 2008; Yan et al. 2019). The pH of the mortar, which can affect leaching, is also crucial. A decline in pH can lead to mortar damage, and real-life exposure to various water sources can influence this (Al-Akhras et al. 2011).

In conclusion, the leaching test is vital for assessing the potential release of hazardous substances from solid waste into the environment. The TCLP USEPA Method 1311 is the standard protocol for determining non-toxicity and is used to ensure safe disposal and management of CWIFA. Table 1 shows the TCLP constituents, and their regulatory level and Table 2 shows the heavy metal composition of raw CWIFA. Meanwhile, Table 3 presents the heavy metal in cement-based system containing CWIFA by TCLP. The results help evaluate cement-based system's binding mechanisms, with passing waste classified as non-hazardous according to USEPA regulations.

TABLE 1. TCLP constituents and their regulatory levels (IOWA Department of Natural Resources, 2015)

| Constituent | Regulatory level (mg/L) |
|---|---|
| Arsenic | 5.0 |
| Barium | 100.0 |
| Cadmium | 1.0 |
| Chromium | 5.0 |
| Lead | 5.0 |
| Mercury | 0.2 |
| Selenium | 1.0 |
| Silver | 5.0 |

TABLE 2. Heavy metal composition of raw CWIFA based on relevant past studies

| Hazardous waste criteria | * Hazardous waste screening criteria (TCLP) (mg/kg) | Ababneh et al. 2020 | Al-Fares, 2013 | Al-Mutairi et al. 2004 | Genazzini et al. 2003 | Jawaid and Kaushik, 2012 | ** TCLP hazardous waste limit (mg/l) | Tzanakos et al. 2014 | Anastasiadou et al. 2012 | Genazzini et al. 2003 |
|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium (Cd) | (20 mg/kg) | 7 | 5.61 | 14 | 6.2 | 85 | 1.0 (mg/l) | <DL | 0.0171 | 0.04 |
| Lead (Pb) | (100 mg/kg) | 38 | 899.62 | 127 | 490.3 | 964 | 5.0 (mg/l) | - | 5.2162 | 0.9 |
| Zinc (Zn) | - | 44 | 3762.23 | 414 | 2.8 | - | - | 6.0172 | 13.2 | 50 |
| Chromium (Cr) | (100 mg/kg) | - | 58.1 | 43 | 107.6 | 100 | 5.0 (mg/l) | 0.1865 | 0.0855 | 0.2 |
| Copper (Cu) | - | - | 247.7 | 18 | 628.5 | 172 | - | - | 1.03 | 0.1 |
| Nickel (Ni) | - | - | 31.75 | - | - | 45 | - | <DL | 0.0762 | - |
| Barium (Ba) | - | - | - | - | - | - | - | 100 | 1.8404 | - |
| Iron (Fe) | - | - | - | 60000 | - | - | - | - | 0.86 | - |
| Manganese (Mn) | - | - | - | - | - | - | - | - | - | - |
| Aluminium (Al) | - | - | | 643 | - | - | - | - | - | - |
| Mercury (Hg) | - | - | | 9000 | - | - | - | - | - | - |
| Titanium (Ti) | - | - | | | | | | | | |
| pH | - | - | - | - | - | - | - | - | - | - |

* Hazardous Waste Screening Criteria (TCLP) refers to limits allowed in solid waste or soil for disposal in a landfill. Limits developed by the Oregon Department of Environment Quality under authority given by Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, SW-846 Manual, Section 8.4, EPA Office of Solid Waste (USEPA, 2000).

** TCLP is a test to determine contaminants' mobility in solid wastes or soils. These are the limits allowed to leach out of soil or solid waste in a landfill. From 40 CFR 261.24 (IOWA Department of Natural Resources, 2015).

TABLE 3. Heavy metal in cement-based system containing CWIFA by TCLP based on relevant past studies

| Author's | CWIFA in cement-based system | Heavy metal (TCLP hazardous waste limit (mg/l)) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Cd | Pb | Zn | Cr | Cu | Ni |
| | | 1 mg/l | 5 mg/l | - | 5 mg/l | - | - |
| Ababneh et al. 2020 | 20% of O-CWIFA (mg/l) | 0 | 6.72 | 19.8 | - | - | - |
| | 20% of T- CWIFA (mg/l) | 0 | 2.92 | 6.8 | - | - | - |
| Tzanakos et al. 2014 | 20% (75% CWIBA + 25% CWIFA) (mg/l) | <DL | - | 1.2630 | 0.0321 | - | <DL |
| | 30% (75% CWIBA + 25% CWIFA) (mg/l) | <DL | - | 1.3569 | 0.0452 | - | <DL |
| | 50% (75% CWIBA + 25% CWIFA) (mg/l) | <DL | - | 1.5248 | 0.0632 | - | <DL |
| | 20% (50% CWIBA + 50% CWIFA) (mg/l) | <DL | - | 1.9856 | 0.0245 | - | <DL |
| | 30% (50% CWIBA + 50% CWIFA) (mg/l) | <DL | - | 2.0145 | 0.0365 | - | <DL |
| | 50% (50% CWIBA + 50% CWIFA) (mg/l) | <DL | - | 2.1452 | 0.0695 | - | <DL |
| Anastasiadou et al. 2012 | 40% CWIFA (mg/l) | 0.0021 | 0.3368 | 2.3718 | 0.0481 | 0.3012 | 0.0446 |
| | 50% CWIFA (mg/l) | 0.0056 | 0.5244 | 1.7828 | 0.0707 | 0.5507 | 0.0546 |
| | 60% CWIFA (mg/l) | 0.0071 | 0.3861 | 1.52 | 0.0562 | 0.5962 | 0.0469 |
| | 70% CWIFA (mg/l) | 0.0038 | 0.5440 | 2.8 | 0.0419 | 0.4358 | 0.0112 |
| Jawaid & Kaushik, 2012 | Soil + 20% CWIFA (mg/l) | 0.115 | 0.747 | - | 0.07 | 0.579 | 0.379 |
| | Soil + 20% CWIFA + 20% Cement (mg/l) | 0.060 | 0.105 | - | 0.045 | 0.960 | 0.291 |
| Genazzini et al. 2005 | Non-spiked CWIFA (mg/l) | 0.04 | 0.9 | 50 | - | 0.1 | - |
| | 50% CWIFA (non-spiked ash) (mg/l) | <0.02 | 0.4 | 9 | 1.1 | 0.7 | - |
| | 50% CWIFA (0.1% Cd, 1% Cr, 1% Pb and 2.8% Zn) (mg/l) | 5.9 | <0.2 | 136 | 20 | 0.9 | - |
| | 50% CWIFA (5% Pb) (mg/l) | 0.06 | 50 | 9 | 0.9 | 0.7 | - |
| Genazzini et al. 2003 | (w/(c+a) =0.35, 10% CWIFA (mg/l) | Not measured | Not measured | Not measured | Not measured | Not measured | - |
| | (w/(c+a) =0.35, 25% CWIFA (mg/l) | <0.02 | 0.6 | 0.3 | 0.1 | 0.3 | - |
| | (w/(c+a) =0.35, 50% CWIFA (mg/l) | 0.04 | 0.7 | 1.3 | 0.1 | 0.7 | - |
| | (w/(c+a) =0.5, 10% CWIFA (mg/l) | 0.02 | 0.3 | 0.04 | 0.2 | <0.1 | - |
| | (w/(c+a) =0.5, 25% CWIFA (mg/l) | Not measured | Not measured | Not measured | Not measured | Not measured | - |
| | (w/(c+a) =0.5, 50% CWIFA (mg/l) | 0.03 | 0.3 | 0.15 | 0.4 | 0.1 | - |

Note: ** <DL = below detection limit

# METHODOLOGY

## EXPERIMENT DESIGN AND PROCEDURE

The pH test measures the acidity or alkalinity of a substance by quantifying hydrogen ions in a solution. It determines if a substance is acidic (pH < 7), neutral (pH = 7), or alkaline (pH > 7). In mortar production, pH testing is essential for assessing the suitability of raw materials, as it affects rheological properties, chemical reactions, and environmental impact. Accurate pH measurements ensure that mortar meets performance standards and minimises environmental impact, especially when dealing with waste materials such as CWIFA. Measurements were conducted in accordance with ASTM standards D4980 and D1293, using a pH meter and electrode that were calibrated daily. For the raw materials (CWIFA, silica fume, Portland cement, fine aggregate, and tap water), 10 g of material was mixed with 100 mL of water in a beaker. The pH meter recorded readings once the pH values had stabilised within a range of 0.1 units. Figure 1 shows the testing conducted using a pH meter.

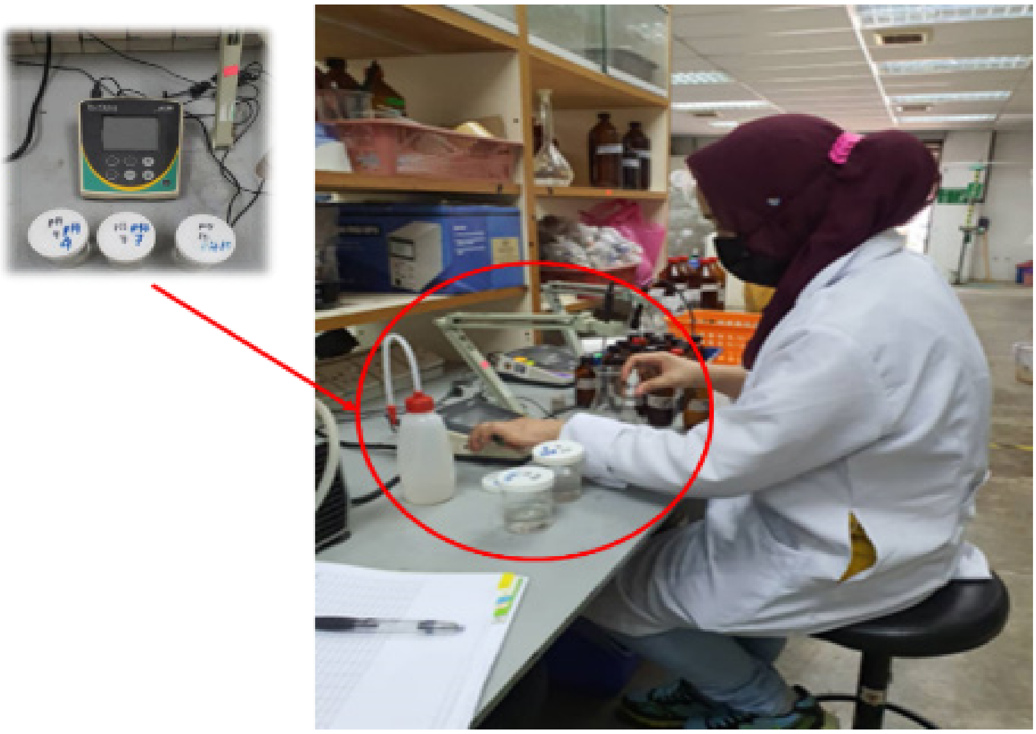

FIGURE 1. Testing by pH meter

# DESIGN MIX

This study carefully selected various percentages of CWIFA for evaluation, including 0%, 2.5%, 5%, 10%, and 15% by weight of the cementitious material. The maximum CWIFA content was capped at 15% due to regulatory and control restrictions. CWIFA is classified as scheduled waste under the Environmental Quality (Scheduled Wastes) Regulations (2005), specifically code SW406, which imposes limits on its use. This regulatory constraint made it impractical to use higher quantities of CWIFA. The study aimed to examine the effects of different CWIFA percentages on mortar properties, including compressive strength and leaching characteristics.

In addition, the study investigated the impact of SF at 0% and 10% by weight of the cementitious material. SF is known for its ability to enhance mortar performance, and the chosen percentages were based on its proven benefits. The experimental study was divided into two series: Series 1, which included mortar mixtures with CWIFA and SF at 0%, and Series 2, which included CWIFA and SF at 10%. These series were further divided into different mixing proportions, as detailed in Tables 4 and 5. In these tables, C0, C2.5, C5, C10, and C15 denote the weight percentages of CWIFA (0%, 2.5%, 5%, 10%, and 15%, respectively), while SF0 and SF10 represent the weight percentages of SF (0% and 10%, respectively) in the mortar mixtures. In this study, three hundred (300) mortar cubes with dimensions of 50 mm x 50 mm x 50 mm x 50 mm were used. Figure 2 illustrates the batching of materials, which is determined by the mortar proportion.

FIGURE 2. Batching of materials according to mortar proportion

TABLE 4. Mortar mixtures properties for Series 1

| Series | Mortar mixtures | Fine aggregate-to-cementitious ratio | Water-to-cementitious ratio | CWIFA (%) | SF (%) |
|---|---|---|---|---|---|
| 1 | C0SF0 | 2.75 | 0.485 | 0 | 0 |
| | C2.5SF0 | 2.75 | 0.485 | 2.5 | 0 |
| | C5SF0 | 2.75 | 0.485 | 5 | 0 |
| | C10SF0 | 2.75 | 0.485 | 10 | 0 |
| | C15SF0 | 2.75 | 0.485 | 15 | 0 |

*Note: *Example: C0SF0 is 0% CWIFA and 0% SF by weight percentage of the total cementitious material.*

TABLE 5. Mortar mixtures properties for Series 2

| Series | Mortar mixtures | Fine aggregate-to-cementitious ratio | Water-to-cementitious ratio | CWIFA (%) | SF (%) |
|---|---|---|---|---|---|
| 2 | C0SF10 | 2.75 | 0.485 | 0 | 10 |
| | C2.5SF10 | 2.75 | 0.485 | 2.5 | 10 |
| | C5SF10 | 2.75 | 0.485 | 5 | 10 |
| | C10SF10 | 2.75 | 0.485 | 10 | 10 |
| | C15SF10 | 2.75 | 0.485 | 15 | 10 |

Note: * Example: C0SF10 is 0% CWIFA and 10% SF by weight percentage of the total cementitious material

## COMPRESSIVE STRENGTH TEST

The compressive strength of mortar was tested using ASTM C109. Mortar cubes (50 mm³) were tested at 3, 7, 28, 90, and 180 days in triplicate. The maximum load applied was recorded, and compressive strength was calculated based on this load and the cube's cross-sectional area. Testing was conducted with an NL Eco Smart automatic compression machine, with a maximum capacity of 2,000 kN and a steady loading rate of 1.8 kN/s as shown in Figure 3. Results were displayed in kN and N/mm².

FIGURE 3. The set up of the compressive strength testing of the mortar cube

## TOXICITY CHARACTERISTIC LEACHING PROCEDURE (TCLP)

Solidified/stabilised mortar refers to a mortar mixture that has been treated to improve its properties. Solidification involves encasing waste materials, such as CWIFA, within the mortar matrix, while stabilisation chemically alters hazardous components to less toxic forms. The purpose of solidified/stabilised mortars is to minimise the leaching of harmful substances, such as heavy metals.

To assess the effectiveness of this process, the leachability of toxic metals from the mortar was tested using the Toxicity Characteristic Leaching Procedure (TCLP) as outlined in Method 1311 of the U.S. Environmental Protection Agency's SW-846 (Fallis, 1992). The TCLP test, conducted at the Environmental Laboratory, School of Civil Engineering, USM in Nibong Tebal, Pulau Pinang, measured the concentration of metals leached from the mortar into the leaching solution.

Given concerns about heavy metals in CWIFA and their potential for environmental contamination, mortar cubes used in compressive strength tests were subjected to TCLP analysis at 3, 7, 28, 90, and 180 days. The mortar cubes were crushed, sieved through a 9.5 mm screen, and then mixed with an extraction fluid. The extraction fluid was prepared by diluting 5.7 mL of glacial acetic acid (CH3CH2OOH) with deionized water to a final volume of 1 liter, resulting in a pH of 2.88 ± 0.05. Mortar particles (10 g) were combined with 200 mL of the extraction fluid in bottles, creating a liquid-to-solid ratio of 20:1 (mL/g). These bottles were rotated on a rotary agitation apparatus at 30 ± 2 rpm for 18 ± 2 hours. Afterward, the bottles were filtered through a 0.45 µm glass fiber filter to separate the solid and liquid phases. The pH of the filtered liquid was recorded, and the concentration of heavy metals was analysed using a Varian 710-ES inductively coupled plasma-optical emission spectrometry (ICP-OES) machine illustrated in Figure 4. The Results were compared to the TCLP tolerable limits specified in 40 CFR 266 (2020) Appendix VII, which sets concentration limits for regulated heavy metals including arsenic, nickel, chromium, lead, and selenium.


FIGURE 4. Heavy metal elements measurement done by ICP - OES machine

## RESULTS AND DISCUSSION

### COMPRESSIVE STRENGTH

Portland cement significantly enhances the compressive strength of mortar, especially in solidification/stabilization (S/S) processes used to treat hazardous waste like CWIFA. The effectiveness of this treatment is evaluated by the compressive strength of the S/S mortar, which directly correlates with the amount of Portland cement used. Table 6 presents the compressive strength results for Series 1 mortar with 0%, 2.5%, 5%, 10%, and 15% CWIFA as supplementary cementitious materials (SCM). Mortar with 5% CWIFA (C5SF0) shows the highest strength (37.84 MPa at 180 days), while 15% CWIFA (C15SF0) has the lowest strength (19.03 MPa at 3 days). Mixes with 2.5% and 5% CWIFA outperform the control mortar due to the filler effect (Memon et al. 2013), but strength decreases with more than 10% CWIFA due to slower pozzolanic reactions (Ababneh et al. 2020; Al-Akhras et al. 2011; Bie et al. 2016; Tang et al. 2016; Yang Yue et al. 2019). Meanwhile, Series 2 mortar with 5% CWIFA and 10% SF (C5SF10) achieved the highest compressive strength of 44.92 MPa at 180 days. The addition of 10% SF enhances strength, with a maximum improvement at 5% CWIFA, while higher CWIFA percentages (10% and 15%) show reduced strength. This increase is due to SF's fineness and pozzolanic reactivity and aligns with findings that SF significantly boosts compressive strength (Ahmad et al. 2022).

The use of CWIFA in mortar improves compressive strength up to 5%, due to its micro-filling ability and pozzolanic activity, but decreases beyond this percentage due to lower strength compared to cement. SF enhances compressive strength significantly due to its greater pozzolanic reactivity and fine particle size, improving density and structure. Longer curing times further increase strength by allowing complete hydration and filling of voids, though the rate of strength gain decreases over time. The optimal curing time and requirements for different mortar mixtures need further study.

TABLE 6. The average Compressive Strength of mortar mixtures at different ages

| Series | Mortar Mixtures | Compressive Strength (MPa) | | | | |
|---|---|---|---|---|---|---|
| | | 3 days | 7 days | 28 days | 90 days | 180 days |
| Series 1 | C0SF0 | 20.03 | 23.98 | 27.13 | 34.22 | 36.52 |
| | C2.5SF0 | 20.21 | 24.90 | 28.60 | 35.49 | 36.49 |
| | C5SF0 | 21.13 | 25.26 | 29.58 | 35.04 | 37.84 |
| | C10SF0 | 19.57 | 23.74 | 27.43 | 33.76 | 35.51 |
| | C15SF0 | 19.03 | 22.74 | 26.62 | 32.46 | 34.51 |
| Series 2 | C0SF10 | 26.54 | 31.34 | 40.01 | 42.76 | 43.76 |
| | C2.5SF10 | 27.28 | 32.35 | 39.94 | 43.42 | 44.42 |
| | C5SF10 | 28.78 | 33.13 | 41.513 | 43.92 | 44.92 |
| | C10SF10 | 26.49 | 30.67 | 38.61 | 42.21 | 42.97 |
| | C15SF10 | 25.39 | 29.23 | 36.53 | 41.128 | 40.88 |

## TCLP USEPA METHOD 1311 (1992) OF MATERIAL CHARACTERISATION

The TCLP USEPA Method 1311 (1992) evaluates the leaching potential of contaminants from solid waste like CWIFA by extracting samples with an acidic solution and analyzing the leachate for pollutants. The results are compared to USEPA regulatory limits to determine if the CWIFA is hazardous. TCLP testing of CWIFA revealed it to be hazardous due to high concentrations of several heavy metals, as shown in Table 7. For example, zinc (Zn) was the most prevalent, with a concentration of 0.0052 mg/L, while chromium (Cr) was found at a relatively high concentration of 6.0704 mg/L. Arsenic (As), cadmium (Cd), and lead (Pb) were below detectable limits, which are 5.0 mg/L, 1.0 mg/L, and 5.0 mg/L, respectively. Copper (Cu), iron (Fe), nickel (Ni), magnesium (Mg), and calcium (Ca) were also present in significant amounts, with concentrations of 6.0704 mg/L, 0.0450 mg/L, 0.1221 mg/L, 6.2784 mg/L, and 164.4730 mg/L, respectively.

The results indicate that the leachate from CWIFA contains heavy metals, especially chromium, at levels exceeding USEPA's threshold limits. High chromium levels in CWIFA are attributed to sources in clinical waste such as orthopedic implants, prostheses, laboratory waste (e.g., histological preparations), and certain pharmaceuticals used in healthcare (Dey, 2022; Iacob et al. 2020; Jin &

Chu, 2019; Kiernan, 2015; Pires et al. 2023) noted that elevated calcium concentrations in CWIFA come from bone cement and orthopedic implants.

The high concentration of heavy metals in CWIFA results from two processes: metal vaporisation during combustion, which condenses into ash particles, and the adsorption of metals from flue gases onto ash particles. These processes lead to elevated metal levels, causing leaching and potential environmental harm if not managed properly.

TABLE 7. Metal composition of CWIFA

| Material (mg/l) | As | Ca | Cd | Cr | Cu | Fe |
|---|---|---|---|---|---|---|
| CWIFA | UD | 164.473 | UD | 6.0704 | 0.0067 | 0.0450 |
| USEPA Limit (mg/l) | 5.0 | - | 1.0 | 5.0 | - | - |
| Material (mg/l) | Mg | Ni | Pb | Zn | Se | |
| CWIFA | 6.2784 | 0.1221 | UD | 0.0052 | UD | |
| USEPA Limit (mg/l) | - | - | 5.0 | - | 1.0 | |

Note: *UD = below the detected limit of ICP testing

To assess the leaching potential of building materials like mortar, the TCLP USEPA Method 1311 (1992) was used to evaluate Silica Fume (SF), Portland cement, and fine aggregate, helping to understand their potential environmental and health impacts. Table 8 lists contaminant concentrations in SF, Portland cement, and fine aggregate as measured by the TCLP USEPA Method 1311 (1992) and ICP test. SF had notable levels of arsenic (0.2412 mg/L) and magnesium (18.5919 mg/L), higher than CWIFA, Portland cement, and fine aggregate. Portland cement showed elevated selenium (0.5123 mg/L) and high calcium (636.3110 mg/L), with other metals like cadmium, copper, iron, nickel, and zinc below detection limits. Fine aggregate had lower concentrations overall, with calcium at 9.4835 mg/L and selenium at 0.2580 mg/L. Arsenic, cadmium, and nickel in fine aggregate were below detection limits. Water tested had a calcium concentration of 2.1386 mg/L.

Identifying the elemental content of CWIFA helps in determining the specific compounds, including harmful heavy metals, that may pose environmental risks. XRD analysis reveals the presence of chloride (37.0%), sodium (23.2%), and calcium (11.2%) in CWIFA, along with other elements such as oxygen, aluminum, silicon, carbon, and sulfur. The variation in elemental composition is due to the diverse materials incinerated, such as plastics, paper, and metals, reflecting the heterogeneous nature of CWIFA.

TABLE 8. Metal composition of SF, Portland cement, fine aggregate, and water

| Material (mg/l) | As | Ca | Cd | Cr | Cu | Fe |
|---|---|---|---|---|---|---|
| SF | 0.2412 | 103.9300 | 0.0070 | 0.0162 | 0.0391 | 0.0712 |
| Portland cement | 0.1434 | 636.3110 | UD | 0.2047 | UD | UD |
| Fine aggregate | UD | 9.4835 | UD | 0.0104 | 0.0036 | 0.0839 |
| Water | 0.008534 | 2.13860 | UD | UD | UD | UD |
| USEPA Limit (mg/l) | 5.0 | - | 1.0 | 5.0 | - | - |
| Material (mg/l) | Mg | Ni | Pb | Zn | Se | |
| SF | 18.5919 | 0.4472 | 0.3027 | 1.7366 | 0.1495 | |
| Portland cement | 0.2111 | UD | 0.0876 | UD | 0.5123 | |
| Fine aggregate | 0.5027 | UD | 0.0533 | 0.2740 | 0.2580 | |
| Water | UD | UD | UD | UD | UD | |
| USEPA Limit (mg/l) | - | - | 5.0 | - | 1.0 | |

Note: *UD = below the detected limit of ICP testing

The form of mineral contained exists in CWIFA by XRD analysis, especially sodium chloride (NaCl). This chloride is known to have a high solubility in water and, therefore, is easily leachable. Hence, the presence of chlorides in CWIFA indicates that the metal content in CWIFA is also likely to be leachable. This was due to chemicals dosed during incineration, such as sodium bicarbonate and activated carbon scrubber in the air pollution control system. Sodium bicarbonate and activated carbon remove acidic gases (HCl), particulate matter, trace organics, and heavy metals from the flue gas, thus resulting in a high chloride content remaining in CWIFA after the air pollution control system. While removing HCl, sodium bicarbonate and activated carbon scrubbers convert HCl to NaCl and carbon dioxide ($CO_2$). As a result, a high concentration of chloride ions is left behind in the CWIFA after the air pollution control system as shown in Table 9. Moreover, XRD analysis has confirmed that CWIFA exists in the form of compounds, particularly chlorides (NaCl), which can also contribute to the presence of chloride ions in CWIFA.

TABLE 9. Element of CWIFA by XRD analysis

| Material (%) | Chloride (Cl) | Natrium (Na) | Oxygen (O) | Calcium (Ca) | Total (%) |
|---|---|---|---|---|---|
| CWIFA | 37.0 | 23.2 | 17.9 | 11.2 | 100 |
| Material (%) | Aluminium (Al) | Silicon (Si) | Carbon (C) | Sulfur (S) | |
| CWIFA | 6.4 | 2.4 | 1.5 | 0.4 | |

The TCLP USEPA Method 1311 effectively assesses the leaching potential of contaminants in solid waste materials like CWIFA, which was found hazardous due to high heavy metal concentrations, particularly chromium at 6.0704 mg/L. Elevated calcium levels in CWIFA stem from bone cement and orthopedic implants. Heavy metal concentrations in CWIFA are heightened by metal vaporization and adsorption during combustion. While SF showed higher arsenic and magnesium levels compared to CWIFA, Portland cement, and fine aggregate, these were within USEPA limits. XRD analysis identified Cl, Na, O, Ca, Al, Si, C, and S in CWIFA, highlighting potential environmental risks if not properly managed. Proper treatment of CWIFA and other clinical wastes is essential to prevent environmental contamination and protect human health.

## TCLP USEPA METHOD 1311 (1992) OF SERIES 1 MORTAR MIXTURES

This study examined how curing duration and supplementary cementitious materials (SCMs) influence mortar's ability to treat hazardous wastes, such as clinical waste incineration fly ash (CWIFA). The results show that mortars effectively immobilize heavy metals through solidification/stabilisation process. Extended curing times and optimized mortar composition enhance stability and strength.

In Series 1, TCLP testing assessed the impact of CWIFA as a supplementary cementitious material (SCM) on heavy metal concentrations in mortar. At 3 days, arsenic (As) was highest in C0SF0 (0.116 mg/L) and lowest in C15SF0 (0.081 mg/L). By 7 days, As concentrations decreased with increased CWIFA content, eventually falling below detection limits. Chromium (Cr) levels were highest in C15SF0 (0.468 mg/L) at 3 days and decreased over time, with no mixture achieving detection limits by 180 days. Lead (Pb) levels were highest in C0SF0 (0.080 mg/L) at 3 days but dropped below detection limits in all mixtures by 7 days. Selenium (Se) was highest in C0SF0 (0.254 mg/L) at 3 days and decreased with CWIFA content, becoming undetectable by 28 days. Nickel (Ni) was highest in C15SF0 (0.112 mg/L) at 3 days, with levels decreasing over time. Heavy metal concentrations were influenced by the interaction between CWIFA and Portland cement, with overall trends showing improved immobilization of metals with increased CWIFA content. The heavy metal concentrations in Series 1 mixtures are summarised in Table 10.

TABLE 10. The concentration of heavy metal of Series 1 mortar mixtures at different testing ages (mg/l)

| Heavy metal | Mortar mixtures | 3 days | 7 days | 28 days | 90 days | 180 days |
|---|---|---|---|---|---|---|
| Arsenic (As) | C0SF0 | 0.116238 | 0.109824 | 0.093201 | UD | UD |
| | C2.5SF0 | 0.112967 | 0.109177 | 0.090002 | UD | UD |
| | C5SF0 | 0.108040 | 0.095782 | 0.073030 | UD | UD |
| | C10SF0 | 0.104258 | 0.067284 | 0.066494 | UD | UD |
| | C15SF0 | 0.081434 | UD | UD | UD | UD |

*continue ...*

... *cont.*

| Heavy metal | Mortar mixtures | 3 days | 7 days | 28 days | 90 days | 180 days |
|---|---|---|---|---|---|---|
| Chromium (Cr) | C0SF0 | 0.221441 | 0.072421 | 0.054796 | 0.048055 | 0.021199 |
| | C2.5SF0 | 0.335525 | 0.110513 | 0.080475 | 0.035222 | 0.029944 |
| | C5SF0 | 0.348412 | 0.275011 | 0.202227 | 0.066784 | 0.052842 |
| | C10SF0 | 0.364804 | 0.236391 | 0.260064 | 0.115512 | 0.058138 |
| | C15SF0 | 0.468077 | 0.332559 | 0.312379 | 0.168168 | 0.075621 |
| Lead (Pb) | C0SF0 | 0.080303 | 0.034809 | UD | UD | UD |
| | C2.5SF0 | 0.078451 | 0.027781 | UD | UD | UD |
| | C5SF0 | 0.065658 | UD | UD | UD | UD |
| | C10SF0 | 0.059980 | UD | UD | UD | UD |
| | C15SF0 | 0.040741 | UD | UD | UD | UD |
| Selenium (Se) | C0SF0 | 0.254274 | 0.185851 | UD | UD | UD |
| | C2.5SF0 | 0.242620 | 0.157858 | UD | UD | UD |
| | C5SF0 | 0.226051 | 0.071684 | UD | UD | UD |
| | C10SF0 | 0.187660 | 0.045974 | UD | UD | UD |
| | C15SF0 | 0.130777 | UD | UD | UD | UD |
| Nickel (Ni) | C0SF0 | 0.001877 | 0.001706 | UD | UD | UD |
| | C2.5SF0 | 0.099826 | 0.039979 | UD | UD | UD |
| | C5SF0 | 0.102055 | 0.089855 | 0.024583 | 0.018046 | UD |
| | C10SF0 | 0.111892 | 0.106690 | 0.050991 | 0.025714 | 0.015072 |
| | C15SF0 | 0.112214 | 0.109907 | 0.070046 | 0.046900 | 0.030440 |

Heavy metal concentrations in mortars are reduced primarily through physical encapsulation within the matrix. Chemical reactions between heavy metals (e.g., As, Cr, Pb, Se, Ni) and Portland cement form a solid matrix that prevents leaching. Portland cement reacts with water to produce calcium silicate hydrate (CSH) gel, which binds the metals through interactions with calcium oxide (CaO), forming stable, insoluble compounds that trap the metals. Extending the curing duration enhances this process by allowing more time for the stabilisation/solidification (S/S) process, leading to a more stable matrix and reduced leaching of these metals. Studies show that longer curing times significantly decrease heavy metal concentrations, including $Pb^{2+}$, due to more complete chemical reactions and improved encapsulation (Chen et al. 2004; Kumpiene et al. 2008; Li et al. 2021; Wang et al. 2020).

The results showed all mixtures maintained heavy metal concentrations below USEPA leaching thresholds. Longer curing periods led to lower metal concentrations. Portland cement played a key role in encapsulating these metals, and the stabilisation/solidification technique effectively treated the waste materials, reducing environmental and health risks.

## TCLP USEPA METHOD 1311 (1992) OF SERIES 2 MORTAR MIXTURES

Series 2 examines As, Cr, Pb, Se, and Ni concentrations in mortars with varying CWIFA contents (0%, 2.5%, 5%, 10%, 15%) and 10% silica fume at different ages (3, 7, 28, 90, 180 days). Heavy metal reduction is due to their physical encapsulation within the mortar matrix via chemical reactions with Portland cement, which forms a solid matrix that traps the metals. The study also evaluates how curing duration and SCMs affect the treatment of hazardous wastes like CWIFA. Results show that extended curing and optimised mortar composition improve stability, strength, and heavy metal immobilisation, with silica fume enhancing these effects, offering sustainable methods for hazardous waste treatment and protection of environmental and human health.

In the study, arsenic (As) concentrations were highest in C0SF10 (0.1496 mg/l) and lowest in C15SF10 (0.0556 mg/l) at 3 days. By 7 days, As levels dropped to below detection limits in C15SF10, with other mixtures showing reduced concentrations. At 90 and 180 days, all mixtures had As below detection limits. Higher CWIFA content reduced As, but detectable levels were mainly from Portland cement.

For chromium (Cr), C0SF10 had the lowest concentration (0.1638 mg/l) at 3 days, while C15SF10 had the highest (0.4676 mg/l). Cr levels decreased significantly by 7 days and continued to drop, with C15SF10 consistently showing the highest concentrations. Cr concentrations from raw CWIFA exceeded USEPA limits, while those from fine aggregate and Portland cement were within limits. Increasing CWIFA content led to higher Cr levels, with no mixture reaching below detection limits.

Lead (Pb) levels were highest in C0SF10 (0.0604 mg/l) and below detection limits in C15SF10 at 3 days. Pb remained below detection limits throughout the study. C15SF10 had the lowest Pb concentration at 3 days, with Pb linked to Portland cement and fine aggregate.

Selenium (Se) concentrations were highest in C0SF10 (0.2322 mg/l) and lowest in C15SF10 (0.0813 mg/l) at 3 days. By 7 days, Se levels in C15SF10 were below detection limits, and remained so throughout the study. Increasing CWIFA content reduced Se concentrations, with stabilized compounds forming from Portland cement reactions. The heavy metal concentrations in Series 1 mixtures are summarised in Table 11.

Increasing curing duration in Series 2 lowers As, Cr, Pb, Se, and Ni concentrations due to improved hydration and chemical reactions that form stable compounds and enhance encapsulation within the mortar matrix. Extended curing creates a denser matrix that reduces leaching potential. Despite these benefits, Cr concentrations did not fall below detection limits even after 180 days, indicating equilibrium in the Portland cement-CWIFA reaction.

TABLE 11. The concentrations of heavy metals in Series 2 mortars are summarised

| Series | Mortar mixtures | 3 days | 7 days | 28 days | 90 days | 180 days |
|---|---|---|---|---|---|---|
| Arsenic (As) | C0SF10 | 0.149607 | 0.037315 | UD | UD | UD |
| | C2.5SF10 | 0.114212 | UD | UD | UD | UD |
| | C5SF10 | 0.080524 | UD | UD | UD | UD |
| | C10SF10 | 0.079289 | UD | UD | UD | UD |
| | C15SF10 | 0.05563 | UD | UD | UD | UD |
| Chromium (Cr) | C0SF10 | 0.163822 | 0.086913 | 0.065084 | 0.038467 | 0.026348 |
| | C2.5SF10 | 0.206030 | 0.199580 | 0.103185 | 0.053978 | 0.045604 |
| | C5SF10 | 0.278707 | 0.232516 | 0.129376 | 0.078850 | 0.074448 |
| | C10SF10 | 0.386121 | 0.299121 | 0.199658 | 0.162538 | 0.047991 |
| | C15SF10 | 0.467586 | 0.308230 | 0.236061 | 0.167617 | 0.095531 |
| Lead (Pb) | C0SF10 | 0.060448 | UD | UD | UD | UD |
| | C2.5SF10 | 0.052086 | UD | UD | UD | UD |
| | C5SF10 | 0.034604 | UD | UD | UD | UD |
| | C10SF10 | 0.02161 | UD | UD | UD | UD |
| | C15SF10 | UD | UD | UD | UD | UD |
| Selenium (Se) | C0SF10 | 0.232157 | 0.086183 | UD | UD | UD |
| | C2.5SF10 | 0.228385 | 0.008964 | UD | UD | UD |
| | C5SF10 | 0.183471 | UD | UD | UD | UD |
| | C10SF10 | 0.155265 | UD | UD | UD | UD |
| | C15SF10 | 0.081319 | UD | UD | UD | UD |
| Nickel (Ni) | C0SF10 | 0.046034 | UD | UD | UD | UD |
| | C2.5SF10 | 0.051840 | UD | UD | UD | UD |
| | C5SF10 | 0.055121 | 0.026148 | UD | UD | UD |
| | C10SF10 | 0.056027 | 0.026887 | 0.010593 | UD | UD |
| | C15SF10 | 0.078626 | 0.031893 | 0.026038 | 0.019236 | 0.015695 |

Adding 10% silica fume (SF) improves encapsulation by reacting with calcium hydroxide ($Ca(OH)_2$) to form additional calcium silicate hydrate (CSH) gel. This extra gel fills voids, increases density, reduces permeability, and limits heavy metal mobility, enhancing the mortar's stability and reducing leaching. Using CWIFA and SF as SCMs in mortars effectively immobilises heavy metals, with extended curing and SF contributing to reduced concentrations and improved matrix stability. All mixtures met USEPA leaching limits, demonstrating effective heavy metal stabilisation and reduced environmental and health impacts.

## CONCLUSION

The impact of solidification/stabilization (S/S) with Portland cement and supplementary cementitious materials (SCMs) like CWIFA and SF on mortar compressive strength reveals that extended curing times improve strength across all mixtures. CWIFA enhances compressive strength up to 5%, but higher amounts reduce strength, whereas SF significantly boosts compressive strength by increasing CSH gel formation. This improvement underscores the importance of optimal curing times and material proportions for reducing leaching, which contributes to better environmental and structural performance.

This study evaluates the leaching behavior of mortars using the TCLP USEPA Method 1311, focusing on the treatment of CWIFA. The method showed CWIFA's hazardous risk due to high heavy metal levels, particularly chromium at 6.0704 mg/l, resulting from metal vaporisation and adsorption during combustion. The research assesses how curing duration and SCMs, such as SF, affect mortar's ability to treat hazardous wastes like CWIFA. Findings indicate that extending curing times and using SCMs improve strength, and heavy metal immobilisation. Mortars with CWIFA and SF effectively keep heavy metal concentrations below USEPA leaching thresholds, with SF enhancing encapsulation by forming additional calcium silicate hydrate (CSH) gel.

In summary, the study highlights CWIFA's hazardous nature and the effectiveness of mortars in immobilising heavy metals through solidification/stabilisation process. Extended curing and SCMs like SF reduce leaching potential, offering insights into sustainable waste treatment and safer construction practices.

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## DECLARATION OF COMPETING INTEREST

None.

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