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Effect of Incinerator Fly Ash on the Properties of Slag-Based Geopolymer Mortar

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Abstract - This study investigates the feasibility of incorporating incineration fly ash (IFA) into slag-based geopolymer mortar (GM) as an alternative sustainable method for IFA treatment. The influence of IFA content on the fresh and hardened properties of GM is examined, aiming to enhance waste utilization while mitigating environmental concerns. A blend of slag and IFA was employed as the aluminosilicate binder and activated using a sodium-based alkaline activator solution. Based on the Toxicity Characteristic Leaching Procedure (TCLP) results, the raw IFA can be classified as a non-hazardous material. Additionally, flow test results indicated that increasing IFA content negatively affected the workability of GM, with a flow reduction of up to 37% observed when 50% IFA was used. Similarly, the incorporation of 50% IFA adversely impacted compressive strength at all curing ages, leading to reductions of 41, 73, and 75% at 1, 7, and 28 days, respectively. Despite these reductions, all mixes met the standard requirements for masonry cement, rendering them suitable for various masonry applications.

Keywords**:** Incineration fly ash, slag, geopolymer, mortar, compressive strength.

1. Introduction

Municipal solid waste incineration (MSWI) for power generation is regarded as a favourable solution for treating municipal solid waste, as it produces energy while significantly reducing waste volume. Such an option has been increasingly accepted in countries with large populations like China. In fact, the National Bureau of Statistics reported an annual MSW yield of 254 million tons in China in 2023 [1]. Incineration bottom ash (IBA) and incineration fly ash (IFA) constitute the main by-products of the MSWI generated in waste-to-energy facilities. These by-products collectively make up approximately 30–35% of the total municipal solid waste [2]. Meanwhile, the disposal of large amounts of MSWI fly ash in landfills poses various environmental and health concerns. This is mainly due to the leachable soluble salts and heavy metals in the IFA that could potentially contaminate soils and/or groundwater [3]. Therefore, different treatment methods are being utilized to ensure proper disposal or potential reuse of IFA. Among these methods, solidification/stabilization is one of the most efficient treatment technologies that works on immobilizing hazardous substances in IFA during the physical encapsulation and chemical fixing processes [4]. Indeed, heavy metals such as arsenic (As) and lead (Pb) were immobilized during their reaction with hydrated $Ca(OH)_2$ from cement to produce $Ca_3(AsO_4)24H_2O$ and $Pb_3(NO_3)(OH)_5$ [3].

Meanwhile, cement-based solidification matrix showed poor durability due to the presence of sulphate and chloride salts in IFA, resulting in its degradation [5]. In addition, cement production is associated with high carbon dioxide emissions (CO_2), contributing to global warming and major environmental issues [6], [7]. On the other hand, using geopolymers in IFA solidification has been successfully adopted in different studies [4], [8]. The dense three-dimensional amorphous matrix of geopolymers can encapsulate the heavy metals existing in the IFA [8]. As such, large quantities of IFA can be recycled into construction products, resulting in lower CO_2 emissions. Past literature recommended incorporating 5-15% IFA in geopolymers without negatively impacting the compressive strength and durability of concrete [9]. Yet, the high soluble heavy metal content combined with the low aluminium and silicon contents renders IFA an unsuitable construction material for geopolymeric composites when used in high proportions [10]. Similarly, Zhan and Kirkelund [11] claimed that the optimal pulverized fly ash (PFA): IFA ratio was 80:20 for geopolymer binder with a 28-day compressive strength of 15.3 MPa, heat cured at 80°C for 24 hours.

This study investigates the utilization of IFA as a partial replacement of slag in geopolymer mortar manufacturing. The main purpose is to maximize the replacement rate of IFA with minimal loss in performance, leading to the promotion of sustainable construction. The effect of different IFA mass percentages (0, 25, 40, and 50%) on the fresh and mechanical properties of GM was explored. The fresh performance was characterized by the initial flow, whereas the mechanical performance included the 1-, 7-, and 28-day compressive strength.

2. Experimental Program

2.1. Materials

Ground granulated blast furnace slag (or simply slag) and IFA were used in this study as aluminosilicate precursors to produce geopolymer mortar (GM) mixes. The chemical composition of the raw materials used in this study is summarized in Table 1. The particle size distribution of slag and IFA in Figure 1 indicates particle size ranges of 3.6-84.9 µm and 0.6-1738.9 µm for slag and IFA, respectively. Natural crushed limestone sand (CS) with a maximum size of 2.36 mm served as fine aggregates in GM. The specific gravity of slag, IFA, and CS were identified as 2.50, 2.12, and 2.69, respectively. Finally, the alkaline activator solution (AAS) used herein was a combination of sodium hydroxide (SH) solution with Grade N sodium silicate (SS). The SS-to-SH ratio was set at 1.5, and the SH molarity was set at 8 M to achieve GM with acceptable workability and setting times [12].

Table 1: Chemical composition of slag and IFA.

Oxide	Slag	IFA
Al_2O_3	7.5	3.5
SiO_2	27.0	5.4
SO_3	2.5	9.5
CaO	59.7	44.8
Fe_2O_3	1.2	1.6
MgO	1.0	29.9
K_2O	1.1	5.3

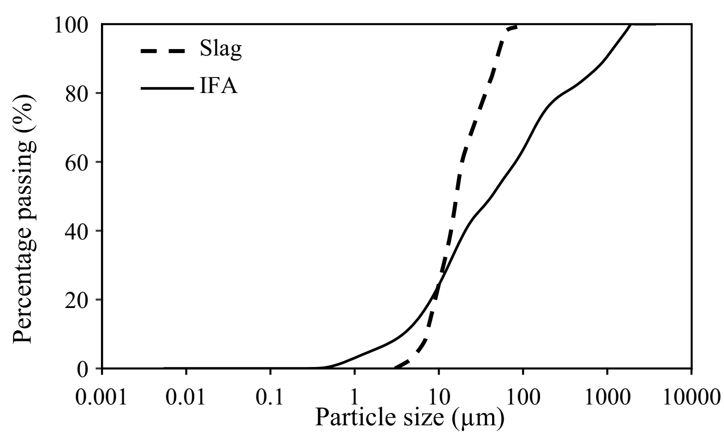

Figure 1: Particle size distribution of slag and IFA

2.2. Mixture Proportioning

In this study, four GM mixes were designed based on the ASTM C91 requirements for masonry cement [13]. Table 2 illustrates the GM mixture proportions. Mixes were labelled as slag-X-IFA-Y, where X and Y denote the mass percentages of slag and IFA, respectively. For instance, mix slag-60-IFA-40 was a GM made with a blend of 60% slag and 40% IFA. All mixes were produced with fixed ratios of binder-to-aggregates at 1:2.75, AAS-to-binder at 0.485, and additional water-to-binder at 0.3. These ratios were selected as per the requirements of the ASTM standard and previous studies [12], [14]. Slag was substituted with IFA at 0, 25, 40, and 50% rates to examine the impact of IFA content on the fresh and hardened properties of GM as well as the classification of the developed mortar mixes.

Table 2: Mix proportions of GM mixes (kg/m^3).

Mix ID	Crushed sand (CS)	Binder materials		Alkaline Activator Solution (AAS)		Water
		Slag	IFA	SS	$SH_{(aq)}$	
Slag-100-IFA-0	1200	436	0	127	85	131
Slag-75-IFA-25	1189	324	108	126	84	130
Slag-60-IFA-40	1183	258	172	125	83	129
Slag-50-IFA-50	1179	214	214	125	83	129

2.3. Sample Preparation and Testing

GM samples were produced under ambient conditions with a temperature and relative humidity of 25±2°C and 50±5%, respectively. The production of GM mixes started by preparing the AAS 24 hours prior to mixing to ensure the dissipation of heat generated during the exothermic reactions occurring during the combination of SH flakes with water and the SH solution with the SS solution. The dry ingredients, including the binders and crushed sand, were mixed for 2-3 minutes. Subsequently, the AAS and additional water were added and mixed for another 2 minutes. After determining the flow, the fresh GM was cast in 50 mm cubic molds, wrapped with plastic sheets for a day, demolded, and ambient cured until testing.

The Toxicity Characteristic Leaching Procedure (TCLP) of IFA was performed according to the SW 846–1311 [15]. One gram of IFA was mixed with glacial acetic acid (pH = 2.88) at a liquid-to-solid ratio of 20:1. The mixture was placed in polypropylene bottles and rotated at 30±2 rpm for 18±2 hours. Afterward, the leachates were filtered through 0.45 μm membrane filters, and their pH was measured. The leachates were digested with concentrated nitric acid. The concentrations of various heavy metals were then determined using inductively coupled plasma optical emission spectroscopy (ICP-OES).

The flowability of GM was measured using a mini-slump cone and a flow table, as per ASTM C1437 [16]. The flow was determined by averaging four diametrical readings. The compressive strength (f_c) of GM was assessed using 50 mm cubes at 1, 7, and 28 days of age according to ASTM C109 [14]. For each mix, three samples were tested to obtain an average.

3. Results and Discussion

3.1. TCLP

Before being utilized in GM, IFA underwent testing for heavy metal content using TCLP. The results are summarized in Table 3. This test was conducted to verify that the IFA qualifies as non-hazardous waste, thereby determining its suitability for application. The TCLP results confirmed that IFA is non-toxic, as the detected heavy metals (Cu, Cr, Cd, Pb, Ni, and Zn) were present only in trace amounts and well below the nationally established hazardous waste thresholds [15]. Consequently, the IFA examined herein can be safely incorporated into the production of GM.

Table 3: Toxicity characteristics of IFA.

Material	Level of toxicity leached of heavy metals (mg/L)								
	Zn	Pb	Cd	Ni	Co	Cr	Cu	Ag	Ba
IFA	0.1695	0.3995	<0.0001	<0.0001	<0.0001	0.3805	0.0160	<0.0001	1.5485
Allowable limit U.S. EPA	100	100	20	20	20	100	20	100	2000

3.2. Flow

The effect of the IFA content on the workability, i.e., the initial flow, of GM was investigated. Figure 2 depicts the flowability of the mortar mixes utilizing IFA. The flow ranged between 13.5 and 21.5 cm. Firstly, the initial flow decreased from 21.5 to 18.0 cm when 25% IFA was incorporated. Similarly, using 40 and 50% IFA in slag-60-IFA-40 and slag-50-IFA-50 mixes led to 21 and 37% reductions in flow, respectively. Such a decline in flow is mainly ascribed to the porous nature and the high specific surface area of IFA, leading to the adsorption of the mixing liquid (AAS or additional water) on the surface of IFA and reduced workability [5]. Another potential reason for this reduction could be attributed to the accelerated setting time caused by the reaction of the excess calcium in IFA. This is in line with results reported by Lu et al. on the use of MSWI fly ash in GM manufacturing [4].

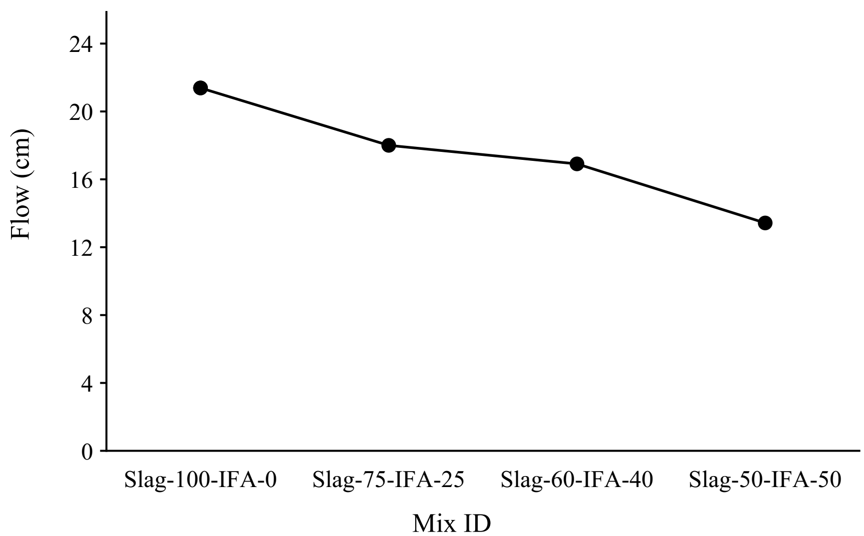

Figure 2: Flow results of GM mixes.

3.3. Compressive Strength

Figure 3 presents the 1-, 7-, and 28-day compressive strengths (f_c) of GM mixes. The 1-, 7-, and 28-day f_c were in respective ranges of 3.35-9.29 MPa, 7.60-28.51 MPa, and 9.41- 37.86 MPa. While the slag-based GM (Slag-100-IFA0 mix) had the highest 7- and 28-day f_c, it showed a low 1-day f_c, as it was not fully hardened after 24 hours. On the other hand, the GM produced with equal quantities of slag and IFA (Slag-50-IFA50 mix) exhibited the lowest f_c at all ages. Since a similar pattern was observed at all ages, the analysis focuses on the 28-day compressive strength values. The manufactured GM mixes were classified as N, S, or M, as per the requirements of ASTM C91 [13]. As such, the slag-based GM was classified as an M-type mortar. The GM incorporating 25% IFA satisfied the requirements of S-type mortar, while the remaining mixes fall under the category of N-type mortar.

According to the results, it was observed that increasing the IFA content compared to slag in the mix led to lower f_c for GM. For example, utilizing IFA at 25, 40, and 50% mass percentages resulted in 53, 73, and 75% strength reductions, respectively. On a similar note, previous studies reported a strength reduction upon incorporating MSWI fly ash in geopolymer mortar [8], [17]. Such a reduction is mainly owed to the lower contents of calcium silicate aluminate (C-A-S-H) and sodium silicate aluminate (N-A-S-H) gels in IFA compared to slag. In fact, slag, which was partially replaced with IFA, is composed of 35% SiO_2 and Al_2O_3. On the contrary, IFA contains only 9% total SiO_2 and Al_2O_3 contents. Moreover, the lower reactivity and higher specific surface area of IFA caused the mixing liquid to be adsorbed on the surface of IFA instead of taking part in the reaction. This excess water eventually evaporated, leading to an increase in porosity and negatively impacting the strength of the GM. In the past, few studies reported an improvement in the compressive strength, followed by a drop upon increasing MSWI fly ash content due to differences in the active substances (CaO and SiO_2) contents existing in the IFA [18], [19]. The results also indicate that f_c increased with curing due to the geopolymerization reaction. Mixes made with 25, 40, and 50% IFA experienced improvements in f_c from 1 to 7 days of 84, 62, and 127% compared to 3, 12, and 42% enhancements in f_c from 7 to 28 days, respectively. This significant strength development is due to the creation of calcium-based gel during the activation process of calcium-rich binders [20].

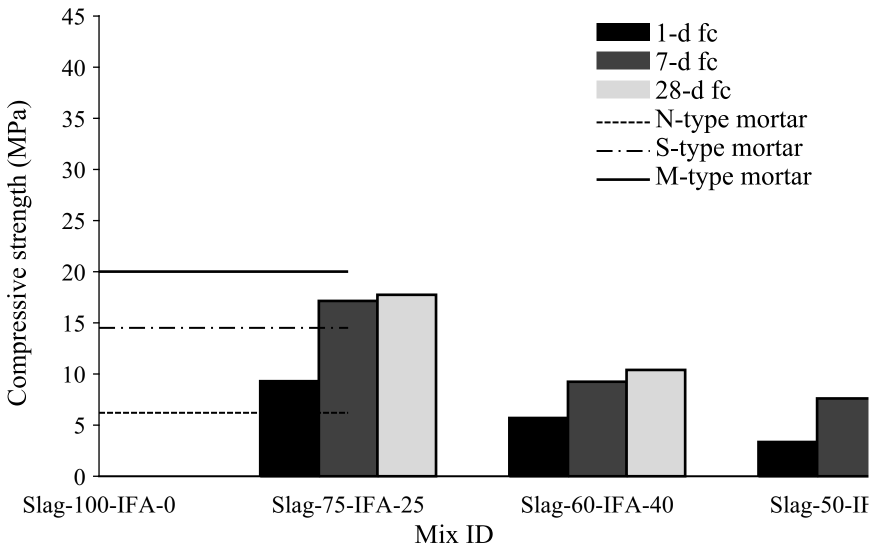

Figure 3: Compressive strength results of GM mixes.

4. Conclusions

This study offers significant insights into the performance of slag-IFA blended GM. The experimental results provide an understanding of the impact of varying the IFA content on the fresh and mechanical properties of GM. According to the TCLP results, the raw IFA could be characterized as a non-hazardous material as all heavy metal concentrations were below the U.S. EPA limits. Moreover, the flow results revealed a negative impact of IFA content on the workability of GM, where a flow reduction of up to 37% was noted with the use of 50% IFA. Similarly, incorporating IFA had a detrimental effect on the compressive strength at all ages. In fact, the 1-, 7-, and 28-day compressive strengths decreased by 41, 73, and 75%, respectively, upon incorporating 50% IFA. Nevertheless, all mixes complied with ASTM C91 requirements for masonry cement and thus can be used for the different masonry applications.

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References

[1] National Bureau of Statistics of China, "China Statistical Yearbook," 2024.

[2] P. Ren, H. Mehdizadeh, and T.-C. Ling, "Performance investigation of the artificial aggregate by integrally recycling incineration bottom ash and fly ash," *Cem. Concr. Compos.*, vol. 152, p. 105678, Sep. 2024, doi: 10.1016/j.cemconcomp.2024.105678.

[3] L. Wang, L. Chen, D. Tsang, Y. Zhou, J. Rinklebe, H. Song, E. Kwon, K. Baek, and Y. Ok, "Mechanistic insights into red mud, blast furnace slag, or metakaolin-assisted stabilization/solidification of arsenic-contaminated sediment," *Environ. Int.*, vol. 133, p. 105247, Dec. 2019, doi: 10.1016/j.envint.2019.105247.

[4] N. Lu, X. Ran, Z. Pan, and A. H. Korayem, "Use of Municipal Solid Waste Incineration Fly Ash in Geopolymer mortar Manufacturing," *Materials*, vol. 15, no. 23, p. 8689, Dec. 2022, doi: 10.3390/ma15238689.
[5] L. Kan, R. Shi, Y. Zhao, X. Duan, and M. Wu, "Feasibility study on using incineration fly ash from municipal solid waste to develop high ductile alkali-activated composites," *J. Clean. Prod.*, vol. 254, p. 120168, May 2020, doi: 10.1016/j.jclepro.2020.120168.
[6] E. Abuowda, H. El-Hassan, and T. El-Maaddawy, "Synergistic impact of geopolymer binder and recycled coarse aggregates on the performance of concrete masonry units," *Clean. Mater.*, vol. 14, p. 100272, Dec. 2024, doi: 10.1016/j.clema.2024.100272.
[7] J. Bawab, H. El-Hassan, A. El-Dieb, and J. Khatib, "Synergetic impact of volcanic ash and calcium carbide residue on the properties and microstructure of cementitious composites," *Constr. Build. Mater.*, vol. 439, p. 137390, Aug. 2024, doi: 10.1016/j.conbuildmat.2024.137390.
[8] P. Zhang, X. Han, J. Guo, and H. Zhang, "Fractal Characteristics of Geopolymer Mortar Containing Municipal Solid Waste Incineration Fly Ash and Its Correlations to Pore Structure and Strength," *Fractal Fract.*, vol. 6, no. 11, Art. no. 11, Nov. 2022, doi: 10.3390/fractalfract6110676.
[9] I. Lancellotti, E. Kamseu, M. Michelazzi, L. Barbieri, A. Corradi, and C. Leonelli, "Chemical stability of geopolymers containing municipal solid waste incinerator fly ash," *Waste Manag.*, vol. 30, no. 4, pp. 673–679, Apr. 2010, doi: 10.1016/j.wasman.2009.09.032.
[10] L. Zheng, C. Wang, W. Wang, Y. Shi, and X. Gao, "Immobilization of MSWI fly ash through geopolymerization: Effects of water-wash," *Waste Manag.*, vol. 31, no. 2, pp. 311–317, Feb. 2011, doi: 10.1016/j.wasman.2010.05.015.
[11] X. Zhan and G. M. Kirkelund, "Electrodialytic remediation of municipal solid waste incineration fly ash as pre-treatment before geopolymerisation with coal fly ash," *J. Hazard. Mater.*, vol. 412, p. 125220, Jun. 2021, doi: 10.1016/j.jhazmat.2021.125220.
[12] E. Abuowda, H. El-Hassan, and T. El-Maaddawy, "Characterization of Geopolymer mortars Incorporating Recycled Fine Aggregates," *Sustainability*, vol. 16, no. 18, Art. no. 18, Jan. 2024, doi: 10.3390/su16188147.
[13] ASTM C91/C91M−23, *Standard Specification for Masonry Cement*, ASTM International: West Conshohocken, PA, USA., 2023.
[14] ASTM C109/C109M−21, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens)*, ASTM International: West Conshohocken, PA, USA., 2021.
[15] SW 846-1311, *Toxicity characteristics leaching procedure*, US., 1992.
[16] ASTM C1437-20, *Standard Test Method for Flow of Hydraulic Cement Mortar*, ASTM International: West Conshohocken, PA, USA., 2020.
[17] S. Casanova, R. V. Silva, J. de Brito, and M. F. C. Pereira, "Mortars with alkali-activated municipal solid waste incinerator bottom ash and fine recycled aggregates," *J. Clean. Prod.*, vol. 289, p. 125707, Mar. 2021, doi: 10.1016/j.jclepro.2020.125707.
[18] Y. Bai, W. Guo, X. Wang, H. Pan, Q. Zhao, and D. Wang, "Utilization of municipal solid waste incineration fly ash with red mud-carbide slag for eco-friendly geopolymer preparation," *J. Clean. Prod.*, vol. 340, p. 130820, Mar. 2022, doi: 10.1016/j.jclepro.2022.130820.
[19] C. Fan, B. Wang, H. Ai, Y. Qi, and Z. Liu, "A comparative study on solidification/stabilization characteristics of coal fly ash-based geopolymer and Portland cement on heavy metals in MSWI fly ash," *J. Clean. Prod.*, vol. 319, p. 128790, Oct. 2021, doi: 10.1016/j.jclepro.2021.128790.
[20] J. Hwalla, H. El-Hassan, A. El-Mir, J. J. Assaad, and T. El-Maaddawy, "Development of geopolymer and cement-based shotcrete mortar: Impact of mix design parameters and spraying process," *Constr. Build. Mater.*, vol. 449, p. 138457, Oct. 2024, doi: 10.1016/j.conbuildmat.2024.138457.