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OPTIMIZATION OF MINERAL RESIDUE-BASED COMPLEX ADDITIVES FOR MECHANICAL AND HYDRATION PERFORMANCE IN CEMENT BINDER MATERIALS

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Abstract- The continuous growth of municipal solid waste incineration ash (MSWIA) poses significant environmental challenges while offering potential opportunities for sustainable construction materials. This study investigates the feasibility of using MSWIA as a mineral additive in Portland cement, both individually and in combination with natural zeolite, aiming to improve resource efficiency and reduce environmental impact. Portland cement CEM I-52.5N was partially replaced with MSWIA at different dosages (1-30%), and selected compositions were modified using zeolite to neutralize undesirable components and stabilize heavy metals. The compositional properties of the ash obtained from the incineration of solid household waste have shown that it has a composition characteristic of mineral additives. Standard mechanical tests were conducted to evaluate setting time, normal consistency, flexural strength, and compressive strength determined at curing ages of 1, 7, and 28 days. The results indicate that low MSWIA contents (1-5%) slightly accelerate early hydration and enhance early-age strength due to the presence of soluble salts acting as hydration activators. Raising replacement levels results in a gradual reduction in mechanical strength, primarily associated with dilution effects and unreacted ash particles. The combined use of MSWIA and zeolite mitigates strength loss and promotes the formation of a denser, modified cement matrix through enhanced pozzolanic reactions. XRD and SEM analyses confirm a reduction in portlandite content and increased formation of calcium silicate hydrates. The findings demonstrate that MSWIA can be safely and effectively utilized as a mineral or complex additive in Portland cement, contributing to sustainable waste management and eco-efficient cement production.

Keywords: Municipal Solid Waste Incineration Ash, Portland Cement, Mineral Additives, Zeolite, Hydration Mechanism, Sustainable Construction Materials.

1. INTRODUCTION

The global surge in urbanization and population has resulted in a marked rise in the generation of municipal solid waste (MSW) [1-3]. One of the most widely used methods for the disposal of municipal solid waste is waste incineration. However, the incineration of municipal solid waste produces a large amount of ash, the disposal of which is an important issue from both an ecological and economic point of view [4-6]. Landfilling of MSWIA poses serious environmental risks due to the potential leaching of heavy metals and soluble salts, motivating the search for sustainable utilization pathways [7-10].

The cement and concrete sector are one of the biggest consumers of natural mineral resources and is responsible for considerable energy consumption and CO_2 emissions [11]. The use of supplementary cementitious (SCMs) materials to partially replace Portland cement clinker and mineral additives has become a key strategy for improving the environmental performance of cement-based materials [12]. Despite the widespread use of many wastes and by-products generated during manufacturing and industrial processes, materials derived from the incineration of municipal solid waste are almost completely unused [13-16]. Municipal solid waste incineration ash represents a complex technogenic material containing calcium-rich phases, amorphous aluminosilicates, soluble salts, and trace amounts of heavy metals [17]. Previous studies have demonstrated that MSWIA can be incorporated into cement systems as a mineral additive or raw material for clinker production; however, its application is often limited by high chloride content, variable chemical composition, and potential negative effects on mechanical performance at higher replacement levels [1-3]. Recent research has emphasized the need for combined or modified approaches to mitigate these drawbacks and enhance the reactivity of MSWIA in cementitious matrices [18, 19].

Natural zeolites are aluminosilicate minerals characterized by high specific surface area, ion-exchange capacity, and pozzolanic activity [20-23]. Their ability to

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immobilize heavy metals and interact with calcium hydroxide makes them promising candidates for improving the performance and environmental safety of waste-containing cement systems. Despite this potential, limited studies have systematically investigated the combined use of MSWIA and natural zeolite as a complex mineral additive in Portland cement, particularly with respect to hydration mechanisms, microstructural evolution, and strength development.

A clear mechanistic understanding of how municipal solid waste incineration ash (MSWIA) and natural zeolite jointly modify the hydration and strengthening processes of Portland cement is currently missing from the literature. This study bridges this gap by providing a detailed analysis of the kinetics, phase development, and mechanical performance of cement pastes incorporating MSWIA-zeolite blends, thereby offering, a scientific basis for their effective use as sustainable binder components.

This work moves beyond merely reporting the effect of MSWIA on cement properties. The experimental novelty and key demonstrated contributions are:

1. Qualification of Performance Limits: We experimentally define and compare the safe replacement windows for WSWIA used alone versus in a complex with natural zeolite, based on compressive strength retention thresholds relevant to practical applications.
2. Mechanistic Proof of Strength Recovery: We demonstrate and provide microstructural evidence (via XRD/Cem) that co-adding zeolite with WSWIA mitigates strength loss not merely by dilution but through a pozzolanic compensation mechanism, consuming portlandite and forming additional C-S-H gel.
3. Development of an Empirical Performance Model: We derive simple, data-driven correlations between replacement level and strength retention, providing a predictive tool for estimating the mechanical performance of blends within the studied range.
4. Engineering Application Mapping: We translate the laboratory results into actionable guidelines by mapping optimal mix designs to specific, realistic engineering use-case scenarios (e.g., non-structural vs. Structural applications).

The novelty of this work consists in the combined application of MSWIA and natural zeolite to neutralize undesirable components, stabilize heavy metals, and promote the formation of a denser, modified cement matrix suitable for sustainable construction applications.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1. Materials

The experimental work utilized Portland cement CEM I-52.5N, which served as the principal binder the principal binder throughout this study. This cement was sourced from the Holcim production facility located in Garadagh, Azerbaijan. The chemical and mineralogical characteristics of the cement were investigated using advanced physicochemical analysis techniques. The cement exhibited a typical clinker mineral composition dominated by alite (C_3S) and belite (C_2S), ensuring high early and long-term strength (Tables 1 and 2).

Table 1. Number of oxides included in CEM I-52.5N cement

Chemical composition of cement, %						
CaO	MgO	Fe_2O_3	SiO_2	Al_2O_3	R_2O	Loss on Ignition %
65.22	1.4	4.4	22.9	4.8	0.62	0.2

Table 2. Mineralogical composition of CEM I-52.5N cement

Amount of minerals %			
C_3A	C_3S	C_2S	C_4AF
5.5	70.7	9.4	11.5

A large amount of waste is generated at the Solid Waste Incineration Plant located in the Balakhani settlement of Baku City. Fuel ash generated as waste at the plant was used in the research work. First, the ash was dried in a laboratory drying cabinet to 1% moisture content and ground to cement fineness in a laboratory ball mill. The percentage of oxides included in the ground powder was determined (Table 3).

Table 3. The number of oxides included in the waste generated from the burning of household garbage

Sodium oxide	Magnesium oxide	Aluminum oxide	Silicon oxide	Phosphorus oxide	Sulfur oxide	Potassium oxide	Calcium oxide	Ferrium oxide	Chlorine	Loss on Ignition %
6.47	1.32	1.50	5.64	7.01	1.49	6.40	34.25	0.65	0.60	13.99

Note: Loss on ignition indicates the number of volatile components at a temperature of 950 °C

Natural zeolite rock was sourced from the Aydag deposit (Tovuz region, Azerbaijan). The material was crushed, dried, and ground to cement fineness. Its high SiO_2 and Al_2O_3 content and low CaO content indicate pronounced pozzolanic activity. Limestone powder obtained from the Gulbakh quarry (Garadagh region) was used in selected compositions as an inert mineral component for comparative analysis.

Table 4. Chemical composition of zeolite rock

No.	Mineral-active supplement	Al_2O_3	SiO_2	Fe_2O_3	CaO	MgO	SO_3	R_2O
1	Zeolite rock	13.6	69.42	1.55	3.18	0.89	0.14	7.9

Table 5. Chemical composition of limestone

No.	Mineral supplement	CaO	Al_2O_3	Fe_2O_3	SiO_2	MgO	SO_3	R_2O
1	Limestone	49.25	0.36	0.21	8.42	0.61	0.24	-

The chemical composition of the zeolite rock brought from the Aydagh deposit of the Touz region is given in Table 4 limestone powder brought from the Gulbakh quarry in the Garadagh region was also used in the studies as a mineral additive (Table 5). Standard quartz sand from the Imishli river was used as fine aggregate for mortar preparation in accordance with EN 196-1 requirements.

2.2. Chemical and Mineralogical Characterization

X-ray fluorescence (XRF) served as the primary method for chemical analysis of the starting materials. Concurrently, the phase assemblage and crystal structure of these materials were investigated by X-ray diffraction (XRD, CuK radiation), collecting data across a 20 interval of 5-60°. Phase identification was carried out using standard reference patterns. Microstructural observations of hardened cement paste were performed using scanning electron microscopy (SEM). Samples cured for 28 days were dried, gold-coated, and examined to evaluate hydration products, morphology, and pore structure.

2.3. Mixture Design and Sample Preparation

Portland cement was partially replaced with MSWIA at replacement levels ranging from 1 to 30 wt.%. For complex additive systems, MSWIA was combined with natural zeolite at equal proportions, with total replacement levels varying from 5 to 30%. Reference samples containing only Portland cement were prepared for comparison. Cement pastes were mixed with water to achieve normal consistency as determined by the Vicat apparatus. Setting times were measured according to EN 196-3 [24]. Cement pastes specimens with dimensions of 20×20×20 mm were cast and cured under standard conditions. Mortar specimens with a cement-to-sand ratio of 1:3 was prepared for mechanical testing.

2.4. Mechanical Testing

Flexural and compressive strengths of mortar specimens (40×40×160 mm) were measured at curing ages of 1, 7, and 28 days in accordance with EN 196-1. Compression tests were conducted using a hydraulic testing machine, and average values were reported based on at least three specimens for each mixture [25].

2.5. Evaluation of Mineral Activity

The mineral activity of MSWIA and zeolite was evaluated based on lime absorption and water resistance tests. The interaction between lime and mineral additives was used to evaluate putty reactivity and suitability for cementitious systems.

3. RESULTS

In accordance with the requirements of the standard, the setting time, water resistance and the degree of saturation of the liquid phase with calcium oxide of samples prepared from zeolite rock brought from the Aydag deposit and ash obtained from the incineration of household waste were determined [26]. For this, one part of the samples obtained from mixing air-hardening lime and ash was used to determine the setting time, and the other part was used to check the water resistance (Table 6).

Table 6. Zeolite rock and ash activities

No.	Test name	Unit of measure	Standard requirement	Zeolite rock	MSWIA
				Test results	
1	End of setting of the dough sample	day	7 should be too many	4	3.5
2	Water resistance of dough samples	day	Must be less than 3	17	12
3	The amount of lime absorbed from the solution after 30 days	mq/q		80	50

As can be seen from the table, both samples fully meet the requirements for mineral active additives, but zeolite rock gives better results than MSWIA. The results of the study show that both additives can be used as mineral additives in the production of Portland cement. It is worth noting that both additives can be used in the production of clinker-free adhesives and, accordingly, in the production of low-grade lime-slaked compositions. Comparative tests were conducted with natural mineral additives to study the feasibility of using MSWIA obtained as a result of household waste incineration in the production of Portland cement, which is one of the main directions of utilization.

In order to determine the role of MSWIA from the Baku household waste incineration plant as a mineral active additive in Portland cement, zeolite rock was used in parallel as a mineral additive, and Garadagh limestone was used as a mineral additive. To study the effect of zeolite rock on cement, both separately and in combination with limestone, CEM I-52.5N cement from the HOCIM plant was used. From the point of view of both normal consistency (NC) and strength, zeolite meets the requirements for mineral active additives (Table 7).

Table 7. The effect of zeolite rock on Portland cement

No.	Composition %		NC, %	Compressive strength limit, (day), MPa			
	CEM I-2.5N	Zeolite rock		1	2	7	28
1	100	0	28	26.0	37.2	49.1	62.5
2	93	7	29.7	16.3	28.2	39.8	54.6
3	80	20	31.4	12.3	27.5	33.0	51.8
4	75	25	32	11.4	19.5	30.1	40.8
5	70	30	32.1	11.3	18.7	29.0	39.9
6	65	35	32.8	6.3	13.8	25.1	35.2

As shown in Table 7, increasing the zeolite rock content from 7% to 35% raises the normal consistency of Portland cement from 28% to 32.8%. With the addition of 7% zeolite rock, the normal consistency of Portland cement increases by 12%, while the cement grade decreases by 12.6%. With an increase in the zeolite rock content to 30%, the compressive strength of cement stone decreases from 26 MPa to 11.3 MPa; a further increase in the zeolite content to 35% leads to a sharp decrease in strength to 6.3 MPa. At a zeolite rock content of 7%, the Portland cement exhibits a strength grade of 54.6 MPa. Increasing the zeolite content to 20% reduces the cement grade strength to 51.8 MPa, corresponding to a decrease of 17.1%. When the zeolite rock content reaches 35%, the cement brand strength declines to 43.7%.

Garadagh limestone powder was used as a mineral additive to replace a certain amount of zeolite rock. 4-17% of the zeolite rock content was replaced with limestone powder [27]. The characteristics of the cement obtained as a result of the complex addition of zeolite rock and limestone are given in table 8. In Table 8, ZR is zeolite rock; *L* is limestone. When adding limestone, the normal density of cement decreases slightly. When adding zaolite rock and 17-23% of limestone together, the strength is 53.3-45.4 MPa. This shows a good result compared to zeolite alone. However, when adding 30-35% of compels additives, the brand strength of cement decreases significantly and is 30.5-34.1 MPa.

Table 8. Effect of zeolite rock and limestone complex additive on cement properties

No.	Composition %			NC, %	Compressive strength limit, (day), MPa			
	CEM I-52.5N	*ZR*	*L*		1	2	7	28
1	83	13	4	27.6	11.9	23.2	34.6	46.3
2	77	15	8	26.4	9.1	20.1	31.6	43.4
3	70	17	13	27.0	6.9	15.4	24.9	34.1
4	65	18	17	27.4	5.9	14.3	22.7	30.5

The effect of MSWIA obtained from the incineration of household waste on the properties of Portland cement is given in Table 9.

Table 9. Effect of ash from municipal waste incineration on cement properties

No.	Composition %		NC, %	Strength limit, (day), MPa			
				bending		compression	
	CEM I-52.5N	MSWIA, %		1	28	1	28
1	100	0	28.5	4.00	14.55	44.28	67.27
2	99	1	28.5	3.96	10.27	49.56	60.52
3	98	2	28.5	3.54	6.27	46.36	58.00
4	97	3	28.5	3.44	6.27	36.22	53.61
5	95	5	29.0	3.12	6.01	30.15	51.21
6	90	10	29.0	3.74	5.37	24.08	46.34
7	85	15	29.0	3.87	5.76	22.22	45.29
8	80	20	29.0	3.23	5.39	17.72	41.58
9	70	30	29.0	2.94	4.03	13.01	35.71

As can be seen from Table 9, when MSWIA is added to cement as a mineral additive in an amount of up to 3%, the normal consistency does not change. However, when the ash content increases above 5%, the normal consistency increases slightly. When adding 1-5% MSWIA to the composition of Portland cement, the 28-day strength decreases by 10.4-23.87%. When increasing the MSWIA content to 20%, the decrease in strength is 31.11-38.19%.

However, when increasing the MSWIA content to 30%, the strength decreases by about 2 times. When adding 1-2% MSWIA, the 1-day strength of cement increases by 5-10%. This is due to the presence of electrolytes in the ash that accelerate setting. Comparison of MSWIA with zeolite rock showed that at low doses, both components act as mineral additives, and their effects on the strength of cement are close to each other. When the amount of MSWIA is increased, the various admixtures in it negatively affect the strength of the cement, so the results are lower than in the case of zeolite rock.

In order to neutralize the heavy metals contained in the MSWIA and mitigate its effect on strength, the effect of both components on Portland cement in composite form was studied using the zeolite-containing component, which is the rock of the Aydag deposit. The results of the effect of MSWIA obtained from the incineration of household waste on the properties of Portland cement in a complex form are given in Table 10.

As can be seen from Table 10, when the components are added in a complex form up to 15%, the bending strength of Portland cement decreases by 16.48 - 23.28%. When the components are added by 20-30%, the 28-day strength limit of Portland cement decreases by 31.52-36.16%. Comparison of table 9 and table 10 showed that the decrease in the strength of Portland cement (PC) decreases somewhat when the MSWIA is added together with zeolite rock. This is explained by the formation of additional cementing compounds as a result of the activating effect of the electrolytes included in the MSWIA on the zeolite.

Table 10. Effect of MSWIA and zeolite complex additive on cement properties

No.	Composition %			NC, %	Compression strength limit, (day), MPa	
	CEM I-52.5N	MSWIA, %	Zeolite rock		1	28
1	100	-	-	28.5	48.07	75.76
2	95	2.5	2.5	28.5	40.56	63.27
3	90	5	5	28.5	41.42	61.63
4	85	7.5	7.5	29.0	40.03	58.12
5	80	10	10	29.5	53.42	57.59
6	70	15	15	30.5	28.60	58.26

To synthesize the mechanical properties and empirically model the data from Tables 7-10 and create a predictive tool for engineering practice the 28-day compressive strength test results were normalized as strength retention (%) relative to the reference sample (100% PC). A semi-empirical model was developed by fitting the data with trend lines. Figure 1 plots the strength retention against the total replacement level for MSWIA-Zeolite complex (1:1 ratio).

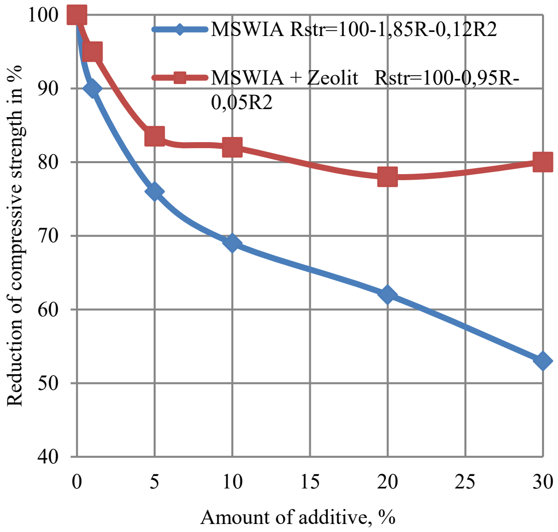


Figure 1. Strength retention versus the total replacement level for pure MSWIA and the MSWIA-zeolite complex

The obtained data were fitted with quadratic polynomial curves, yielding the following predictive equations:

- MSWIA alone: Strength retention (%)

$R_{str} = 100 - 1.85R - 0.12R^2 \quad (R^2=0.98)$

- MSWIA-zeolite complex: Strength retention (%)

$R_{str} = 100 - 0.95R - 0.05R^2 \quad (R^2=0.96)$

where, R is the total substitution percentage (0-30%). these equations clearly demonstrate that the rate of strength loss significantly lower for the compels additive. The model allows one to estimate the substitution level required to maintain strength above a certain threshold (e.g., 75% or

60%). For example, to maintain strength >75%, the maximum allowable substitution is approximately 5% for pure MSWIA and 15% for the MSWIA-zeolite compels. This quantitative analysis serves as the basis for determining performance ranges.

Table 11. Summary of performance limits and recommended replacement windows

System	Max Recommended Replacement	Expected 28-day Strength Retention*	Primary Limiting Factor
MSWIA Alone	≤5%	≥85%	Clinker dilution and limited pozzolan city
MSWIA-Zeolite Complex	≤15%	≥75%	Combined dilution and reactivity balance
MSWIA-Zeolite Complex	≤15%	≥75%	Combined dilution and reactivity balance

*Based on empirical model and experimental data

During the research, samples hardened for 28 days were taken and the changes in the microstructure of the cement stone were determined using modern testing methods in the central testing laboratory of the Azerbaijan National Academy of Sciences. To investigate the microstructural and phase evolution of cement paste induced by MSWIA incorporation, X-ray diffraction (XRD) and scanning electron microscopy (SEM) were employed. During the research, X-ray phase (Figures 2-5) and microscopic (Figure 6) analyses of cement stones prepared without additives, with 10%, 20%, 30% MSWIA addition were conducted. X-ray diffraction analysis of the reference cement stone indicates the main clinker phases, alite (C_3S) and belite (C_2S), are present, reflecting incomplete hydration of the cement (Figure 2).

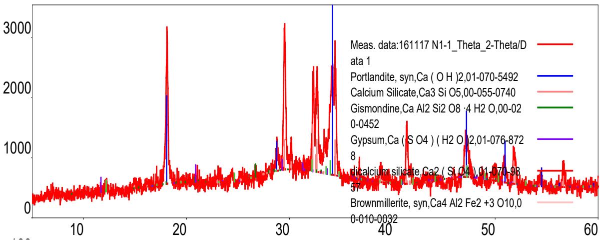


Figure 2. X-ray diffraction (XRD) analysis of cement stone without additives

Distinct diffraction peaks of portlandite (CH, Ca $(OH)_2$) demonstrate the advancement of the cement hydration process. The Calcium silicate hydrate (C-S-H) phase, predominantly amorphous, is observed as a broad diffuse halo rather than sharp peaks. Minor calcite ($CaCO_3$) reflection is also present, indicating partial carbonation of the cement matrix. This phase assemblage is characteristic of hydrated Portland cement and serves as the reference system. For cement stone with 10% MSWIA, the CH peaks exhibit a significant reduction in intensity, reflecting the pozzolanic activity of MSWIA (Figure 3)

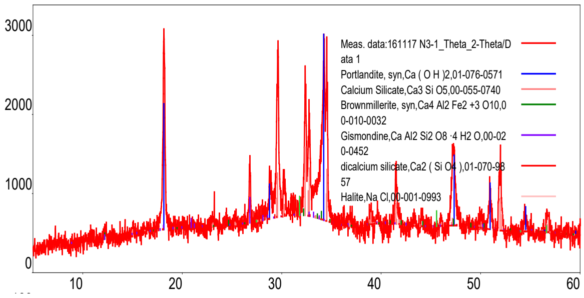


Figure 3. X-ray diffraction (XRD) analysis of cement stone with 10% MSWIA

The interaction of silicate and aluminate compounds in MSWIA with portlandite leads to the formation of secondary hydration phases such as calcium hydro silicate and calcium hydro aluminate. This reaction contributes to CH depletion and improved hydration of C_3S and C_2S, which increases the amorphous phase content an refines the cement matrix. When the MSWIA content is increased to 20%, the pozzolanic reaction becomes more pronounced, as evidenced by the further decrease in CH peak intensity (Figure 4).

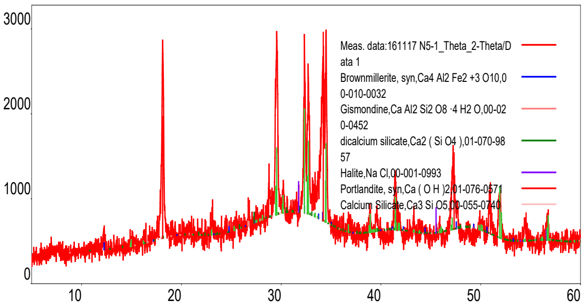


Figure 4. X-ray diffraction (XRD) analysis of cement stone with 20% MSWIA

The amorphous halo corresponding to the C-S-H phase becomes more pronounced, reflecting enhanced formation of hydration products. The diminished intensities of the C_3S and C_2S peaks indicate a higher degree of clinker hydration. Furthermore, crystalline phases derived from MSWIA, such as quartz, may function as micro-fillers, promoting a denser microstructure. This phase composition can be regarded as optimal with respect to phase development and microstructural densification. At a 30% MSWIA replacement level, the intensities of the C_3S and C_2S peaks are markedly reduced, reflecting the decreased clinker content in the system (Figure 5).

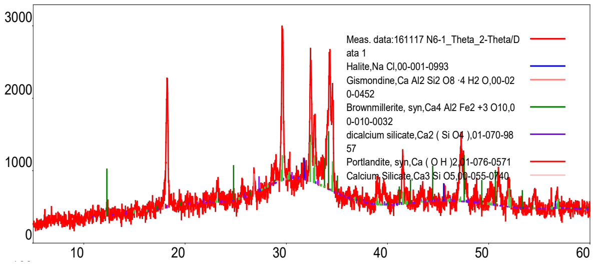


Figure 5. X-ray diffraction (XRD) analysis of cement stone with 30% MSWIA

Although the CH peaks continue to diminish, the formation of new hydration products becomes restricted. Such behavior arises from excessive MSWIA incorporation, which limits the availability of reactive clinker phases in the system. As a result, the fraction of inert or poorly reactive clinker phases increases, potentially leading to less efficient hydration and a decline in the mechanical performance of the cement matrix.

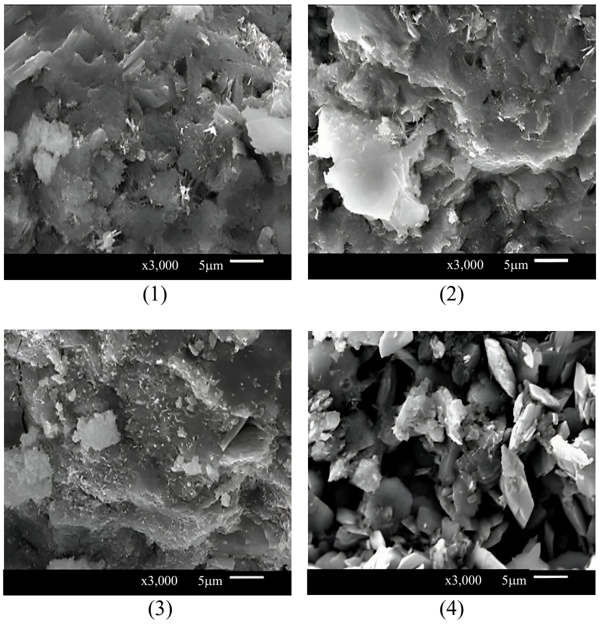
To quantitatively link microstructural changes to mechanical performance, the relative intensity of the primary portlandite (CH) peak (near 18-20°) was estimated for each sample and normalized to the reference (0% MSWIA) intensity. The results are summarized in Table 12. The progressive reduction in CH content correlates directly with the observed strength retention: up to 20% replacement, CH consumption indicates active pozzolanic reaction contributing to matrix densification. At 30% replacement, while CH is further reduced, the drastic drop in clinker (C_3S/C_2S) peaks signifies excessive dilution, explaining the significant strength loss. This quantifies the transition from a pozzolanic activity-dominated regime to a clinker dilution-dominated regime.

Table 12. Semi-quantitative XRD analysis linking CH reduction to strength retention

MSWIA Replacement (%)	Normalized CH Peak Intensity (arb. units)	28-day Strength Retention (%) (from Model) 28-day	Dominant Mechanism
0 (Ref.)	1.00	100	Baseline hydration
10	0.65	~69	Active pozzolanic reaction
20	0.45	~52	Pozzolanic reaction + Mico filling
30	0.30	~35	Excessive dilution + limited reactivity

The results of studies involving MSWIA addition indicate a significant alteration in the cement structure. Microstructural analysis of the samples showed that the nature of the newly formed hydrate compounds is different. Portlandite crystals are clearly visible in cement stone without additives.

The SEM images (Figure 6) directly support the mechanistic claims. Image (1) for the reference shows abundant, well-defined Portlandite (CH) plates alongside C-S-H gel. With 10% MSWIA (Image 2), the CH plates are less distinct, and the matrix appears denser with more uniform C-S-H, corroborating the active pozzolanic reaction indicated by XRD. At 20% MSWIA (Image 3), the microstructure shows further refinement with fewer pores, but also the beginning of unreacted, angular ash particles (micro-fillers). At 30% MSWIA (Image 4), the matrix contains a significant fraction of unreacted or partially reacted ash particles, creating weak interfaces and explaining the strength decline despite ongoing CH consumption. This visual evidence confirms the shift from a strength-enhancing pozzolanic regime to a strength-limiting filler-dilution regime as replacement increases.



(1) (2)

(3) (4)

Figure 6. Microstructural feature of cement stone, 1) Microstructural feature of cement stone without additives, 2) Microstructural feature of cement stone with 10% MSWIA, 3) Microstructural feature of cement stone with 20% MSWIA, 4) Microstructural feature of cement stone with 30% MSWIA

4. DISCUSSION

The experimental results demonstrate that MSWIA can function both as a hydration activator at low dosages and as a mineral additive at higher replacement levels. The early-age strength enhancement observed at 1-2 % MSWIA is primarily attributed to soluble alkali salts and chlorides present in the ash, which accelerate dissolution of clinker minerals and promote early C-S-H formation [28]. At highest replacement levels, the reduction in mechanical strength is mainly governed by dilution effects and limited reactivity of ash particles. Although MSWIA contains amorphous aluminosilicate phases, its pozzolanic activity is lower than that of mineral-active additives [29]. As a result, excessive clinker replacement reduces the availability of calcium silicates required for strength development.

The incorporation of natural zeolite plays a critical role in mitigating these negative effects. Zeolite's high specific surface area and ion-exchange capacity facilitate the adsorption of alkali ions and heavy metals, reducing their detrimental influence on cement hydration. Furthermore, the pozzolanic reaction between zeolite and calcium hydroxide lead leading to the formation of additional C-S-H gel, which refines pore structure and enhances matrix densification [26, 30]. The observed reduction in portlandite content and modification of microstructure in MSWIA-zeolite systems are consistent with findings reported in international studies on waste-derived mineral additives. The synergistic interaction between MSWIA and zeolite enables partial compensation for clinker dilution, resulting in improved mechanical performance and enhanced environmental safety.

The quantified performance limits (Section 3, Table 11) can be directly translated into practical engineering guidelines. We define three representative application scenarios based on typical strength requirements:

- Non-structural/Masonry Mortar: Target 28-day compressive strength ≥ 25 MPa. Focus is on sustainability and cost reduction. High replacement levels are acceptable.
- General Structural Concrete: Target 28-day compressive strength ≥ 40 MPa, with strength retention >60% relative to reference PC. Requires a balance between sustainability and guaranteed mechanical performance.
- High-Performance/Sustainability-Driven: Target is maximum waste velarization while maintaining strength retention > 75% for eco-label compliance or specific green building codes.

Table 13 maps the experimental results to these scenarios, providing actionable mix design recommendations.

Table 13. Recommended mix windows by application scenario

Application Scope	Performance	Recommended System/Recommended quarticity	Justification (Based on Results)
Non-structural	≥25 MPa	MSWIA Alone/Up to 20-30%	Strength meets target (35.7-41.6 MPa at 20-30% repl., Table 9)
General Structural	≥40 MPa, Retention >60%	MSWIA-Zeolite Complex/10 - 15%	Strength 45.3-58.1 MPa (Tables 9,10). Retention >60%. Optimal balance.
High-Performance Green	Retention >75%	MSWIA-Zeolite Complex/≤15%	Model predicts ~75% retention at 15% (Fig.6). Zeolite ensures environmental safety and microstructural density.
High-Performance Green	Retention >85%, minor strength loss	MSWIA Alone/≤5%	Strength retention ~85-90% (Table 9, Model). Simple, effective low-dose activation.

From a practical perspective, the results suggest that MSWIA can be safely utilized in Portland cement at low replacement levels (up to 5 %) without significant loss of performance. The combined use of MSWIA and zeolite allows higher replacement levels (up to 15 %) while maintaining acceptable strength, offering a promising pathway for sustainable cement production and waste valorization.

5. CONCLUSIONS

Based on the experimental investigation of municipal solid waste incineration ash (MSWIA) as a mineral and complex additive in Portland cement systems, the following conclusions can be drawn:

1. Municipal solid waste incineration ash exhibits dual behavior in cement systems: at low replacement levels (1-2%), it acts as a hydration activator due to the presence of soluble salts, leading to a slight acceleration of setting and an increase in early-age strength of up to 10%.
2. When used as a mineral additive at higher replacement levels, MSWIA causes a gradual reduction in mechanical strength, primarily due to clinker dilution and the limited pozzolanic reactivity of ash particles. At replacement levels up to 5%, the reduction in 28-day compressive strength remains within an acceptable range for many practical applications.
3. Excessive replacement of Portland cement with MSWIA (≥20%) results in a significant decrease in both compressive and flexural strength, which is associated with the presence of unreacted ash particles acting mainly as inert fillers.
4. The combined use of MSWIA and natural zeolite as a complex mineral additive effectively mitigates the negative effects observed when MSWIA is used alone. Zeolite enhances pozzolanic reactions, consumes calcium hydroxide and allows to additionally obtain low-base calcium hydro silicates.
5. XRD and SEM analyses confirmed a reduction in portlandite content and the development of a denser, modified cement matrix in systems containing MSWIA-zeolite complexes, indicating improved microstructural characteristics.
6. From both technical and environmental perspectives, MSWIA can be safely and effectively utilized as a mineral or complex additive in Portland cement systems. The optimal application ranges are up to 5 % for MSWIA alone and up to 15% when combined with natural zeolite, contributing to sustainable cement production and efficient waste valorization.
7. Novelty and Engineering Contribution: This work provides a decision-ready framework for using MSWIA in cement. It defines quantifies, experimentally supported replacement windows (≤5% for MSWIA alone; ≤15% for MSWIA-Zeolite complex), provides a simple empirical model for strength prediction, and maps these findings to practical engineering scenarios. The microstructural evidence quantitatively links portlandite consumption and matrix evolution to the observed strength behavior, validating the proposed pozzolanic compensation mechanism when zeolite is co-added.

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