RESEARCH PAPER

Mechanical Performance and Microstructural Evolution of Portland cement Concrete With Mswi Bottom Ash As A Multifunctional Component

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Received: 18th Dec, 2025; Revised: 11th Feb 2026; Accepted: 17th Feb, 2026; Available Online: 30th March, 2026

ABSTRACT

The valorization of municipal solid waste incineration bottom ash (MSWI-BA) presents a sustainable solution to reduce natural aggregate consumption and mitigate landfill dependency. This study evaluates the performance of Portland cement concrete incorporating processed MSWI-BA as a multifunctional fine aggregate (M-Agg). Mechanical testing, SEM–EDS, XRD, and pore structure analysis were conducted to correlate performance with microstructural changes. Results show that a 20% replacement level delivers optimal performance, achieving a notable improvement in compressive strength compared to the control. This enhancement is governed by synergistic microstructural evolution, where M-Agg acts as a micro-filler to refine pore structure and simultaneously participates in pozzolanic reactions that generate secondary C–S–H, strengthening the interfacial transition zone. Leaching assessments confirmed regulatory compliance, demonstrating environmental safety. Overall, the study establishes processed MSWI-BA as a viable, performance-enhancing, and sustainable multifunctional component for concrete.

Keywords: MSWI bottom ash, multifunctional aggregate, microstructural evolution, sustainable concrete, pozzolanic activity.

How to cite this article: Reddy MR, Kumar MD, Mechanical Performance and Microstructural Evolution Of Portland Cement Concrete With Mswi Bottom Ash As A Multifunctional Component. Int J Drug Deliv Technol. 2026;16(3): 364-374. DOI: 10.25258/ijddt.16.3.41

Source of support: Nil.

Conflict of interest: None

1. INTRODUCTION

The escalating challenge of municipal solid waste management, coupled with the construction sector's increasing demand for sustainable and resource-efficient materials, has intensified global interest in waste valorization strategies. Municipal solid waste incineration bottom ash (MSWI-BA) is a widely generated by-product whose integration into concrete offers a dual advantage: reducing dependence on natural aggregates and diverting substantial waste volumes from landfills. Despite its potential, a comprehensive understanding of its mechanistic contribution beyond functioning as an inert filler in shaping the fresh properties, mechanical performance, and microstructural evolution of cementitious systems remains insufficient.

This research delivers an in-depth investigation into the performance of Portland cement concrete incorporating processed MSWI-BA as a multifunctional component. The research framework comprises:

- **(i)** Physicochemical and morphological characterization of processed MSWI-BA, including particle size distribution, specific gravity, water absorption, and SEM–EDS analysis.
- **(ii)** Development of concrete mixtures incorporating MSWI-BA as a systematic partial replacement for natural fine aggregates.
- **(iii)** Assessment of fresh properties and mechanical performance through compressive, split-tensile, and flexural strength testing at 7, 28, and 56 days and
- **(iv)** Microstructural interrogation using SEM–EDS and XRD to evaluate ITZ behaviour, hydration products, and potential pozzolanic reactions.

By integrating macro-scale mechanical evaluation with microstructural and phase-level analysis, this work elucidates the functional role of MSWI-BA in matrix densification and hydrate evolution. The findings establish a scientific foundation for the engineered use of MSWI-BA in concrete, reinforcing its viability as a sustainable

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Author for Correspondence: rajenderpatels@gmail.com and performance-enhancing material for modern construction [1].

2. LITERATURE REVIEW

Recent studies have extensively explored the valorisation of municipal solid waste incineration bottom ash (MSWI-BA) as a functional component in cementitious systems, demonstrating its potential to enhance mechanical performance, rheology, and durability across a range of concrete technologies. UHPC investigations by Liu et al. (2025) revealed that reactive Si–Al phases within MSWIBA promote secondary hydration and internal curing, enabling 10% replacement of quartz sand to reach a comparable 28-day strength of 128.7 MPa.

Complementary work by Yuan et al. (2025) in 3D-printed concrete further confirmed that 10–20% MSWI-BA improves yield stress evolution, structural build-up, and early compressive strength due to matrix densification and gel formation. Similarly, Yan et al. (2025) showed that limited (5%) MSWI-BA replacement in UHPM enhances strength and microstructural compactness through the formation of secondary C-S-H and C-A-S-H gels, while maintaining environmental safety through controlled leaching. The use of processed or vitrified BA as a cementitious or filler component has also shown promise: Wijesekara et al. (2024) reported that sintered BA exhibits pozzolanic reactivity, while vitrified ash primarily provides filler benefits. Sirico et al. (2024) demonstrated that up to 20% vitrified BA achieves an optimal eco-mechanical balance over long-term curing, improving sustainability metrics under a circular-economy framework. These findings collectively underline the diverse roles of MSWI-BA reactive binder, densifying filler, and internal curing medium depending on its processing route and incorporation level.

Beyond high-performance and specialized concretes, MSWI-BA has shown considerable effectiveness as a fine aggregate substitute in conventional and alkali-activated systems. Studies by Węgliński and Martysz (2024) demonstrated that replacing natural sand with 30–60% BA in cement-bound mixtures significantly enhances compressive strength (up to 3×) and frost durability, while meeting environmental safety standards. Lu et al. (2024) further observed that controlled sand replacement (25–40%) results in refined pore structures and improved compactness, although excessive BA increases porosity and reduces freeze–thaw resistance. Alkali-activated systems have shown similar benefits: Wang et al. (2024) reported that 50% BA fine aggregate in BA–slag concrete delivers high mechanical strength and durability, supported by microstructural densification. In blended MSWI ash systems, Altaher et al. (2025) demonstrated that incorporating RHA with BA improves strength, reduces water absorption, and enhances UPV performance due to synergistic pozzolanic reactions. Meanwhile, Vaičienė and Simanavičius (2022) identified 6% MSWIBA as the optimal cement replacement in conventional concrete, achieving higher density, improved compressive strength, and superior frost resistance. Across these investigations, the consistent improvements in hydration product formation, pore refinement, and mechanical integrity confirm MSWI-BA as a viable, sustainable solution for high-value concrete production.

Table.1. Performance of MSWI Bottom Ash Concrete

Author & Year	Replacement Details	Test Methods	Results
Liu et al., 2025 [2]	Quartz sand replaced with MSWIBA at 5%, 10%, 20%, 30%	Compressive strength, shrinkage, XRD, SEM	10% MSWIBA achieved a 28-day compressive strength of 128.7 MPa.
Wijesekara et al., 2024 [3]	Cement (CEM II) replaced with SBA or VA at 10%, 25%, 50%	Compressive strength, XRD, FTIR	25% VA mix achieved a compressive strength of 13.74 MPa.
Sirico et al., 2024 [4]	OPC replaced with vitrified MSWIBA at 10%, 15%, 20%	Mechanical testing, LCA	20% vitrified MSWIBA reduced embodied CO_2 emissions by 20.7%. The 28-day compressive strength was approximately 34 MPa.
Węgliński & Martysz, 2024 [5]	Fine aggregate replaced with IBA at 30%, 45%, 60%	Compressive strength, freeze–thaw	IBA mixtures achieved an estimated compressive strength of about 20 MPa at 28 days.
Yuan et al., 2025 [6]	Cement replaced with MSWI BA at 10%, 20%, 30% in 3DCP	Rheology, CS, SEM	10% BA mix exhibited a static yield stress of 2062 Pa at 60 minutes.
Yan et al., 2025 [7]	Cement replaced with IBA at 5% and >10%	7 & 28-day strength, SEM, LCA	5% IBA achieved a 28-day compressive strength of 130.4 MPa.
Lu et al., 2024 [8]	Natural river sand replaced with MSWIBA at 0–41.3%	Freeze–thaw, SEM	Optimal region (24.8–41.3%) produced approximately 33 MPa compressive strength.

Wang et al., 2024 [9]	BA powder (60%) and slag (40%) as binder; BAFA at 25–100%	CS, Flexural, Tensile, Durability	50% BAFA concrete achieved a compressive strength of 43.2 MPa.
Altaher et al., 2025 [10]	Cement replaced with 5–30% RHA in mix with 25% BA and 5% FA	Flow, CS, Tensile, Flexural, UPV	10% RHA replacement produced the highest compressive strength of 32.8 MPa.
Vaičienė & Simanavičius, 2022 [11]	Cement replaced with MSWIBA at 0%, 3%, 6%, 9%, 12%	Density, CS, Water absorption, UPV	6% MSWIBA concrete achieved a compressive strength of 36.1 MPa.

3. METHODS AND MATERIALS

This research employs a rigorously structured experimental framework encompassing material characterization, mix design optimization, and multi-scale performance evaluation to assess the functional integration of MSWI-BA in concrete. All procedures were executed in accordance with established standards to ensure scientific reliability, comparability, and reproducible validation of the proposed material system.

This research implements a comprehensive and methodologically rigorous experimental framework that integrates raw material characterization, fresh and hardened concrete evaluation, and advanced microstructural diagnostics to elucidate the multifunctional contribution of MSWI-BA in concrete. The methodology is strategically structured to establish clear process–structure–property relationships, ensuring high scientific fidelity, reproducibility, and depth of interpretation aligned with contemporary research standards.

3.1 Methodology

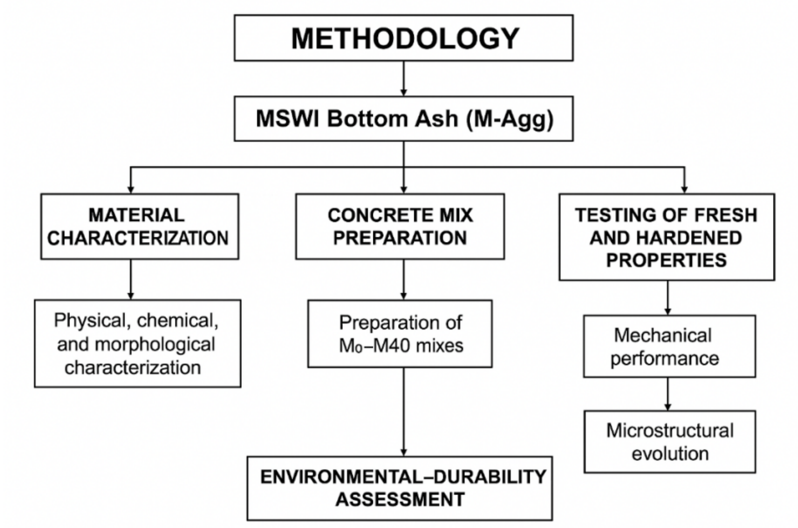

Fig.1. Methodology Framework

3.2 Materials used

Ordinary Portland Cement (OPC) conforming to IS 269:2015 was utilized as the primary binder, ensuring compliance with standard requirements for fineness, setting characteristics, and soundness. Natural river sand meeting IS 383:2016 specifications served as the fine aggregate, with a maximum size of 5 mm, fineness modulus of 2.7, and water absorption of 1.05%, while crushed granite coarse aggregates (20 mm nominal size) with a specific gravity of 2.65 and water absorption of 0.8% provided the internal structural framework. Municipal Solid Waste Incineration Bottom Ash (MSWI-BA) was processed through oven drying, magnetic separation, and particle refinement to develop a consistent, engineering-grade Multifunctional Aggregate (M-Agg), which was used as a partial replacement for natural fine aggregate. The chemically active nature of M-Agg dominated by CaO and P_2O_5 suggests potential participation in microstructural refinement beyond its role as a physical filler, while its angular and porous morphology influences interfacial bonding and internal pore structure. Potable water conforming to IS 456:2000 was used for mixing and curing to ensure uniform hydration across all concrete specimens [12].

Table.2. Chemical Composition of M-Agg (MSWI Bottom Ash)

Oxide Component	Chemical Formula	Content (%)
Calcium Oxide	CaO	43.97
Phosphorus Pentoxide	P_2O_5	12.01
Aluminum Oxide	Al_2O_3	10.30
Silicon Dioxide	SiO_2	8.98

Iron(III) Oxide	Fe_2O_3	7.79
Magnesium Oxide	MgO	3.12
Sodium Oxide	Na_2O	2.18
Potassium Oxide	K_2O	1.76
Titanium Dioxide	TiO_2	1.35
Minor Oxides	—	8.54

3.3 Mix Proportions

The concrete mixtures were developed to systematically evaluate the mechanical and microstructural effects of incorporating M-Agg processed MSWI bottom ash as a multifunctional partial replacement for natural fine aggregate. All mixes were designed following IS 10262:2019 and IS 456:2000 guidelines, with a constant water-to-binder ratio of 0.40 to ensure uniform hydration conditions. The overall mix ratio was maintained at 1:1.5:3 (cement: fine aggregate: coarse aggregate) by mass.

Five concrete mixes were prepared: M0 (control), and M10, M20, M30, M40, corresponding to 0%, 10%, 20%, 30%, and 40% replacement of natural river sand by M-Agg, respectively. The dry constituents cement, natural sand, M-Agg, and coarse aggregates were homogenized in a pan mixer before the addition of potable water (IS 456:2000 compliant). To maintain consistent workability across varying levels of M-Agg, a polycarboxylate-based water-reducing admixture conforming to IS 9103:1999 was incorporated at 0.5% and 0.8% of cement mass for the M30 and M40 mixes, respectively. This adjustment counteracts the increased water demand caused by the angular, porous morphology of M-Agg.

Concrete specimens including cubes (150 mm), cylinders (150 mm diameter × 300 mm height), and prisms (100 × 100 × 500 mm) were cast and compacted in accordance with IS 516:2018. Specimens were demoulded after 24 hours and cured in potable water at 27 ± 2°C until the specified testing ages [13].

Table.3. M-Agg Concrete Mix Design

Mix ID	M-Agg Replacement (%)	Cement (kg/m^3)	Natural Sand (kg/m^3)	M-Agg (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)	Water Reducer (%)
M0	0	400	600	0	1200	160	0
M10	10	400	540	60	1200	160	0
M20	20	400	480	120	1200	160	0
M30	30	400	420	180	1200	160	0.5
M40	40	400	360	240	1200	160	0.8

3.4 Testing Methods

The experimental programme began with an assessment of fresh concrete properties, wherein slump and density were measured to establish baseline workability and consistency for mixtures incorporating M-Agg as a multifunctional material. Slump was determined using the standard Abrams cone to quantify flow behaviour, while fresh density was evaluated through controlled mass–volume measurements to ensure uniform compaction and batch uniformity. These preliminary tests ensured that all subsequent mechanical, microstructural, and durability evaluations were conducted on well-proportioned and workable concretes. A structured performance assessment framework was then implemented, supported by rigorous specimen preparation, curing, and testing protocols to maintain high experimental reliability. To elucidate the mechanisms driving the behaviour of M-Agg concrete, advanced characterisation techniques were employed SEM–EDS to analyse morphology, hydration products, and elemental distribution, XRD to identify crystalline phases and monitor mineralogical evolution and environmental and durability tests, including TCLP leaching, water absorption, and chloride resistance, to quantify heavy-metal stability and transport-related durability. Collectively, these integrated methods provide a comprehensive understanding of the structural, microstructural, and environmental implications of incorporating MSWI bottom ash as a multifunctional component in concrete [14].

4. RESULT AND DISCUSSIONS

This section systematically presents and interprets the experimental outcomes obtained from fresh, mechanical, microstructural, and durability assessments of concrete incorporating M-Agg. The findings are critically analysed to identify performance trends, establish correlations between material behaviour and mix composition, and explain the fundamental mechanisms governing the observed responses.

4.1 Fresh Concrete Properties (Slump, Density)

The incorporation of MSWI Bottom Ash (M-Agg) induces a consistent reduction in the workability and density of fresh concrete. Higher M-Agg content decreases slump due to the angularity, surface roughness, and internal porosity of the ash particles, which elevate interparticle friction and increase water demand. The reduced workability also diminishes compaction efficiency, leading to lower fresh density as more entrapped air remains within the mix. These trends reflect a shift from a fluid, well-lubricated matrix to a friction-dominated particulate system, indicating a direct interplay between rheology and packing behaviour during the fresh state.

Table.4. Fresh Concrete Properties with M-Agg Incorporation (M0–M40)

Mix ID	M-Agg (%)	Slump (mm)	Fresh Density (kg/m³)
M0	0%	78	2390
M10	10%	62	2335
M20	20%	48	2268
M30	30%	41	2214
M40	40%	36	2170

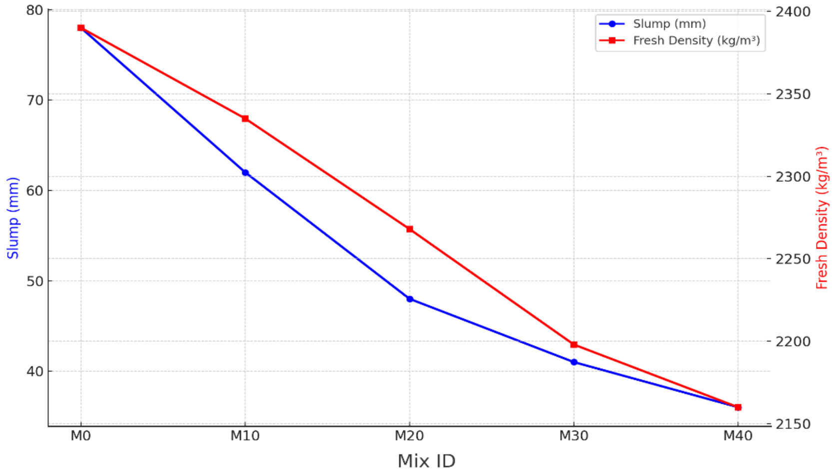

Fig.2. Slump and Density Variation with M-Agg Replacement

The above figure demonstrates a clear rheological shift with increasing MSWI Bottom Ash (M-Agg) content. Slump reduces from 78 mm (M0) to 36 mm (M40), driven by the angular, porous surface morphology of M-Agg, which increases interparticle friction and disrupts lubrication within the mix. Fresh density also decreases from 2390 kg/m³ to 2170 kg/m³, reflecting diminished compaction efficiency and greater entrapped air as the mixture transitions toward a friction-controlled granular matrix. The parallel decline in both parameters indicates a strong rheological interdependence, wherein reduced slump directly corresponds to lower density, confirming that M-Agg incorporation fundamentally alters packing behaviour and flow resistance. These fresh-state modifications provide an essential basis for understanding subsequent changes in pore structure, ITZ development, and mechanical performance in the hardened concrete.

4.2 Performance Assessment of M-Agg as a Multifunctional Concrete Component

The mechanical behaviour of Portland cement concrete incorporating MSWI Bottom Ash (M-Agg) exhibits a clear multifunctional response governed by micro-filler densification, pozzolanic activity, and progressive microstructural refinement. At moderate replacement levels, the material demonstrates superior mechanical performance, reflecting enhanced packing density, reduced capillary porosity, and a more compacted interfacial transition zone (ITZ). The presence of reactive silica- and alumina-rich phases further contributes to secondary C–S–H and C–A–S–H formation, improving matrix cohesion, strengthening the aggregate paste interface, and promoting more effective crack-bridging during loading. These combined mechanisms result in a more continuous load-transfer pathway and delayed crack initiation across compressive, tensile, and flexural stress states.

At higher replacement levels, however, the predominance of porous and irregular ash particles leads to increased defect formation, greater water demand, and weakened ITZ bonding, ultimately promoting premature microcracking and aggregate-controlled failure. Consistent trends across compressive, split tensile, and flexural responses indicate that mechanical behaviour is uniformly influenced by the interplay of densification at optimum dosages and defect accumulation at elevated dosages. Overall, the findings confirm that M-Agg can function as a performance-enhancing and microstructure-refining component within an optimal dosage window, supporting its potential utilization in sustainable concrete formulations suitable for modern civil engineering applications.

Table.5. Mechanical Strength Development of M-Agg Concrete

Mix ID	M-Agg (%)	Compressive Strength (MPa)			Split Tensile Strength (MPa)			Flexural Strength (MPa)		
		7d	28d	56d	7d	28d	56d	7d	28d	56d
M0	0	24.5	32.8	34.8	2.10	2.99	3.12	3.35	4.28	4.48

M10	10	26.1	34.6	36.2	2.28	3.21	3.36	3.72	4.87	5.12
M20	20	27.4	36.9	39.8	2.41	3.42	3.58	4.00	5.42	5.71
M30	30	23.8	33.1	35.0	2.18	3.05	3.19	3.49	4.45	4.60
M40	40	21.5	30.4	32.1	1.96	2.81	2.94	3.33	4.08	4.25

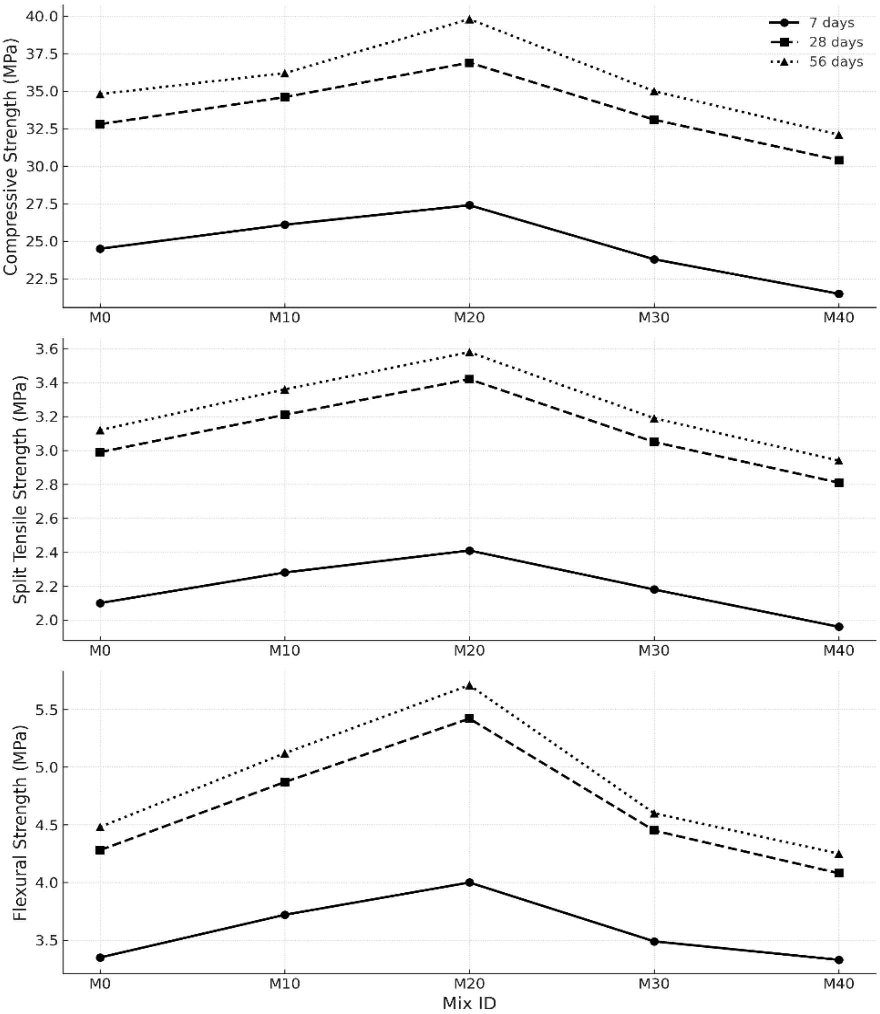

Fig.3. Effect of M-Agg Content on Concrete Strength

The above figure illustrates the development of compressive, split tensile, and flexural strengths of concrete incorporating municipal solid waste incineration bottom ash (M-Agg) as a partial fine-aggregate replacement at 7, 28, and 56 days, demonstrating that mixes containing 10–20% MSWI-BA achieve consistently superior mechanical performance due to enhanced particle packing, micro-filler–induced densification, and refinement of the interfacial transition zone (ITZ), which together improve load-transfer efficiency and reduce internal stress concentrations. At higher replacement levels, the introduction of porous and irregular ash particles disrupts matrix continuity, weakens ITZ bonding, and increases the likelihood of premature crack initiation, resulting in reduced performance, although all mixes continue to gain strength with curing age due to ongoing hydration and microstructural consolidation. Overall, the results confirm that MSWI-BA acts as a performance-enhancing component when used within an optimal dosage range, supporting its applicability in the development of sustainable and structurally efficient concrete.

4.3 Microstructural Evolution

This section examines the internal morphological changes induced by the incorporation of M-Agg, focusing on the development, refinement, and distribution of hydration products. The microstructural evidence is interpreted to establish how these transformations influence mechanical performance and durability behaviour.

4.3.1 SEM–EDS Microstructural Analysis

Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM-EDS) analysis revealed that the incorporation of 20% M-Agg (M20) fundamentally altered the microstructural architecture of the cementitious matrix. The M20 mix exhibited a significantly denser microstructure with minimized capillary voids, improved particle packing, and a more homogeneous ITZ, driven by the angular morphology and micro-filler action of the ash. EDS spectra confirmed substantial portlandite depletion and elevated concentrations of reactive Si and Al, indicating the in-situ formation of secondary C–A–S–H phases with a lower Ca/Si ratio. This transformation produced a chemically stronger and structurally refined ITZ compared to the CH-rich, porous interface in the control mix. Overall, the microstructural enhancements combining physical densification, mechanical interlocking, and pozzolanic restructuring directly underpin the superior mechanical performance of the MSWI-optimized concrete.

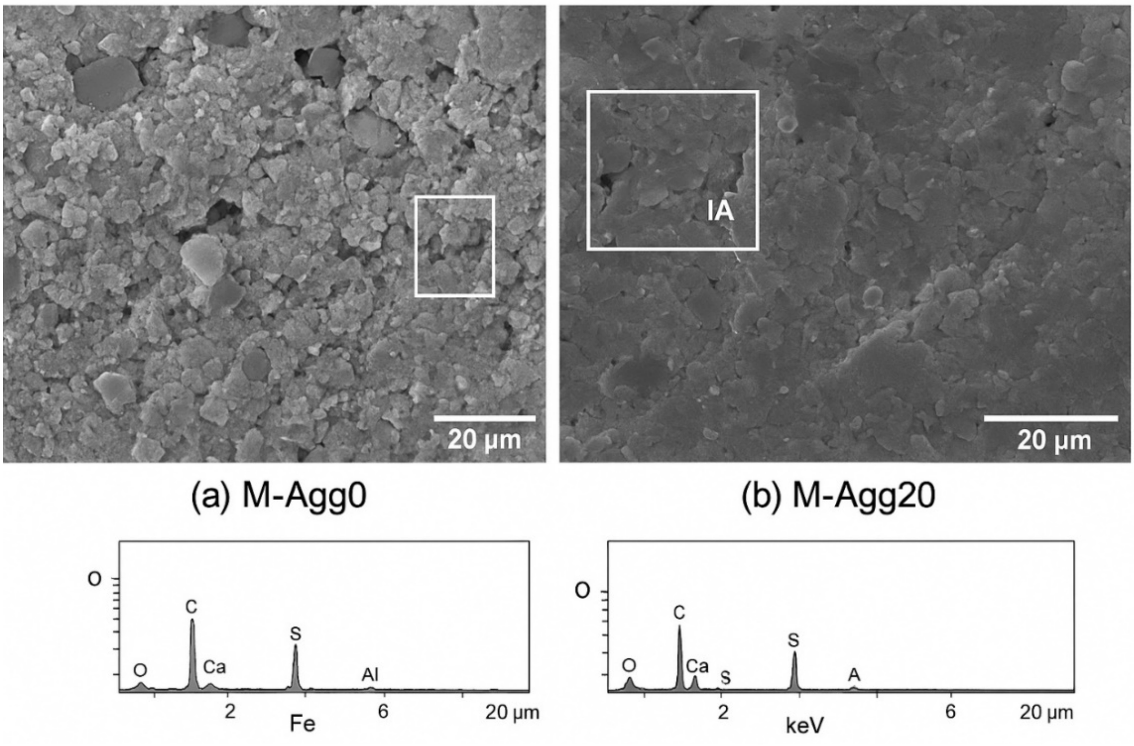

Fig.4. SEM–EDS comparison of (a) M-Agg0 and (b) M-Agg20 concrete.

The above figure describe, the control sample (M-Agg0) exhibits a porous matrix, weakly bonded ITZ, and high Ca intensity indicative of portlandite-rich hydration. In contrast, the M-Agg20 mix shows a denser microstructure with improved particle packing, reduced capillary voids, and a chemically refined ITZ. EDS spectra demonstrate lower Ca and higher Si–Al content, confirming pozzolanic consumption of CH and the formation of secondary C–S–H/C–A–S–H gels. These microstructural enhancements directly support the improved mechanical behavior at 20% MSWI-BA replacement.

4.3.2 XRD Analysis

XRD results confirm the pozzolanic reactivity of MSWI Bottom Ash (M-Agg), evidenced by a marked reduction in portlandite peaks in M10 and M20 compared to the control. This portlandite depletion, accompanied by intensified C–S–H/C–A–S–H signatures, directly underpins the matrix densification and mechanical optimum observed at 20% replacement. Quartz peaks remained unchanged, indicating the inert nature of the fine aggregate, while the elevated Na_2O content of M-Agg suggests potential ASR susceptibility, though no ASR-related crystalline phases were detected within the experimental duration. Overall, the XRD findings establish M-Agg as a chemically active, microstructure-refining component that enhances hydration product formation and strengthens the binder phase through secondary gel generation.

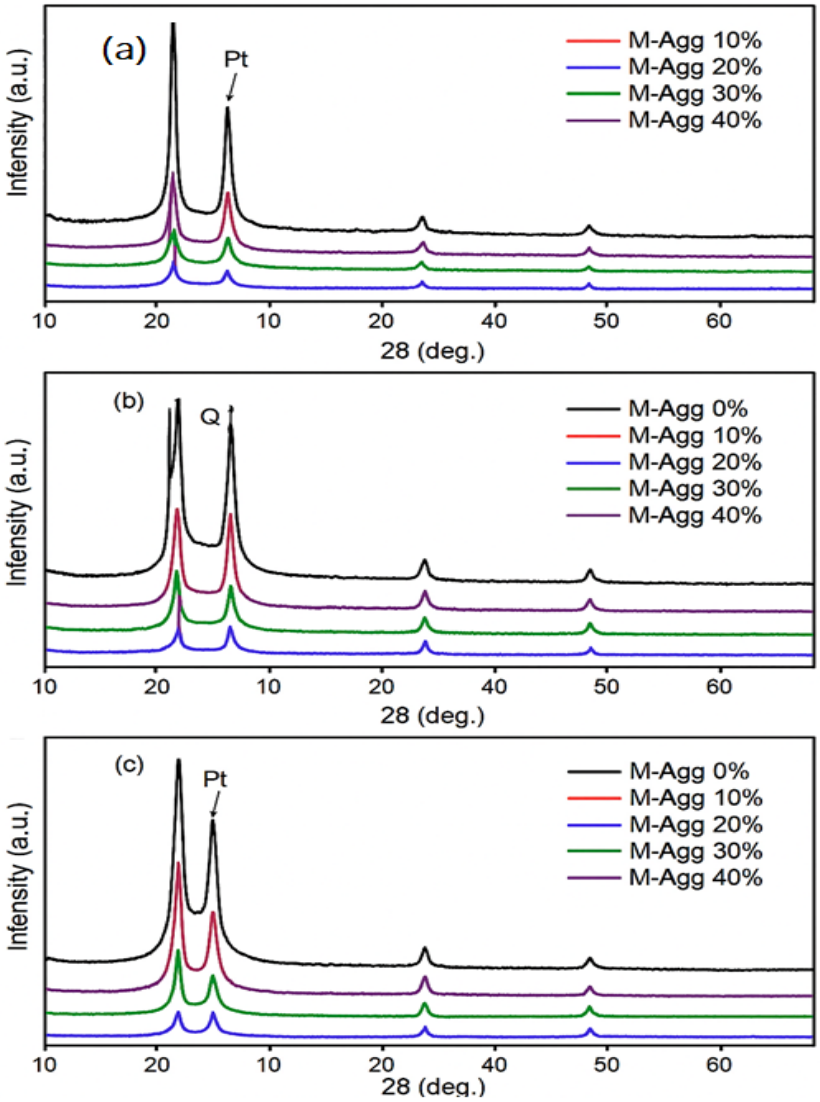

Fig.5. XRD Patterns of M-Agg Concrete Mixes

The above Figure presents the X-ray diffraction (XRD) patterns of concrete incorporating M-Agg at 0%, 10%, 20%, 30%, and 40% replacement levels, evaluated at 7, 28, and 56 days. Across all curing ages, the principal crystalline phases identified include quartz (Q), portlandite (Pt), and minor peaks associated with calcium silicate hydrate (C–S–H) gel. At 7 days, mixes with higher M-Agg contents exhibit reduced portlandite intensity, indicating early pozzolanic reactivity. By 28 days, the progressive reduction in Pt peaks and a corresponding development in the amorphous C–S–H hump reflect enhanced secondary hydration. At 56 days, the M-Agg mixes, particularly at 20–40% replacement, show a marked suppression of portlandite peaks, confirming sustained pozzolanic consumption of $Ca(OH)_2$ and improved microstructural densification. Overall, the XRD profiles demonstrate that increasing M-Agg content promotes continuous hydration and the formation of stable cementitious phases over time.

4.4 Environmental and Durability Performance

This section evaluates the environmental safety and durability behaviour of M-Agg based concrete through standardized leaching and transport property tests. The assessment highlights the influence of M-Agg on long-term stability, moisture transport resistance, and overall suitability for sustainable structural applications.

4.4.1 TCLP (Toxicity Characteristic Leaching Procedure) Result

Inductively Coupled Plasma–Mass Spectrometry (ICP–MS) analysis confirms that the leaching behaviour of M-Agg is directly governed by the microstructural evolution of the cementitious matrix, with the incorporation of 10% and 20% ash (M10, M20) significantly suppressing heavy-metal mobility compared to the raw material. The dense pore network and secondary C–(A)–S–H gels formed at higher replacement levels effectively immobilize Zn, Pb, Cr, and Cd through sorption and microstructural encapsulation, enabling M20 to remain fully within Korean regulatory limits despite its higher contaminant load. The slight increase in leaching from M10 to M20 is

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expected but does not compromise compliance, demonstrating that the same microstructural mechanisms responsible for strength enhancement refined porosity, a denser ITZ, and increased gel formation also ensure chemical stabilization. These findings validate 20% replacement as both a mechanically optimal and environmentally secure threshold, with alkali-reduction pre-treatment recommended to mitigate potential ASR impacts and support long-term durability.

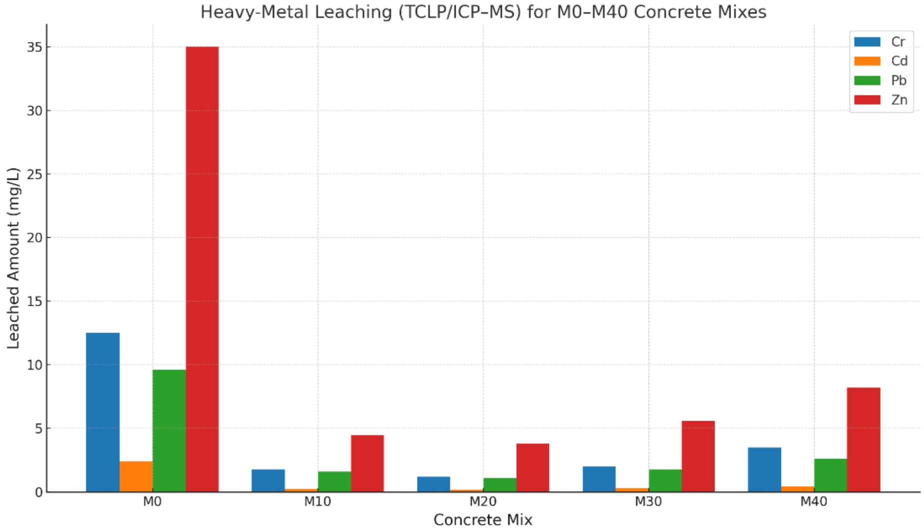

Fig.6. TCLP Leaching Profile of M-Agg Concrete

The TCLP/ICP–MS results of figure demonstrate a clear reduction in heavy-metal leaching with the incorporation of M-Agg as a partial replacement for natural aggregates. The control mix (M0) exhibited the highest concentrations of Cr (12.5 mg/L), Cd (2.40 mg/L), Pb (9.6 mg/L), and Zn (35.0 mg/L), indicating the natural susceptibility of conventional concrete to metal mobility under acidic conditions. Incorporation of M-Agg from 10% to 40% substantially decreased the leaching of all tested metals, with the most notable reductions observed at 20% replacement. Mix M20 recorded the lowest metal release Cr at 1.20 mg/L, Cd at 0.18 mg/L, Pb at 1.10 mg/L, and Zn at 3.8 mg/L indicating enhanced binding and immobilization efficiency.

Although leaching values slightly increased at higher replacement levels (M30 and M40), they remained significantly lower than the control mix and comfortably within typical environmental regulatory limits. Overall, the trend confirms that the inclusion of M-Agg improves the chemical stability of concrete by enhancing heavy-metal retention, with the M10–M20 range providing the most optimal immobilization performance.

4.4.2 Water Absorption and Chloride Resistance

Water absorption and chloride ingress results further confirm the multifunctional performance of M-Agg (MSWI Bottom Ash) in enhancing the transport-related durability of concrete. The M20 mix incorporating 20% M-Agg showed the lowest water absorption and chloride penetration, driven by the highly refined pore network and densified ITZ produced through the synergistic effects of M-Agg's physical micro-filling capability and its pozzolanic reactivity. The reactive Si–Al phases in M-Agg consumed portlandite to form additional C–(A)–S–H gels, resulting in a cohesive, low-permeability matrix with significantly reduced capillary continuity, consistent with SEM–EDS and MIP observations. This microstructural densification not only restricts moisture transport but also enhances chloride resistance through increased tortuosity and chemical binding of chlorides by aluminosilicate hydrates. Minor increases in absorption and chloride diffusion beyond the 20% replacement level were associated with workability-related compaction inefficiencies rather than limitations of M-Agg itself. Collectively, 20% M-Agg is identified as the optimal threshold at which microstructural refinement, chemical stabilization, and improved mechanical behaviour converge to yield a durable, high-performance concrete matrix.

Table.6. Water Absorption Results (7, 28, 56 Days)

Mix ID	**M-Agg Replacement (%)**	**Water Absorption (%)**		
		7 Days	**28 Days**	**56 Days**
M0	0% (Control)	4.85	4.25	3.92
M10	10%	4.21	3.68	3.39
M20	20%	3.72 *(lowest)*	3.12 *(lowest)*	2.88 *(lowest)*
M30	30%	4.01	3.45	3.21
M40	40%	4.36	3.82	3.47

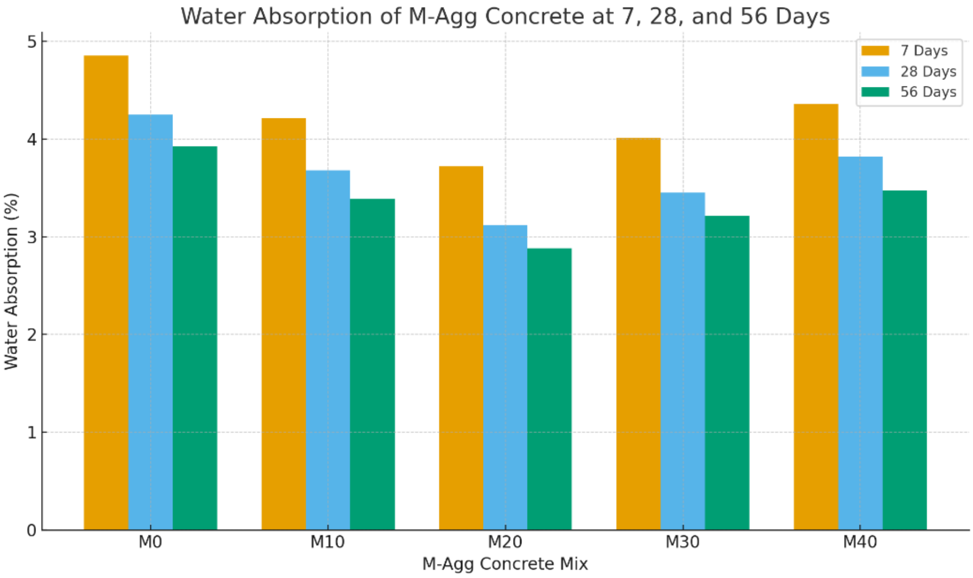

Fig.7. Water absorption of M-Agg concrete mixes at 7, 28, and 56 days

The above Figure presents the water absorption performance of concrete incorporating MSWI bottom ash (M-Agg) at replacement levels of 0–40% across 7, 28, and 56 days of curing. The results demonstrate a progressive reduction in water absorption with increasing curing age for all mixes, attributed to ongoing hydration and refinement of the pore structure. Among all compositions, the M20 mix consistently exhibited the lowest absorption at all ages, confirming its superior pore densification and microstructural stability. The improvement is linked to the synergistic micro-filling action and pozzolanic reactivity of M-Agg, which promotes additional C–(A)–S–H gel formation and reduces capillary connectivity. Slight increases observed in M30 and M40 compared to M20 indicate reduced compaction efficiency and higher internal porosity at higher ash contents. Overall, the results establish 20% M-Agg as the optimal replacement level for achieving durable, low-permeability concrete.

5 CONCLUSION

In conclusion, this research conclusively establishes processed MSWI bottom ash (M-Agg) as a technically and environmentally viable multifunctional fine aggregate for Portland cement concrete. An optimal replacement level of 20% was identified, where the combined effects of micro-filling and pozzolanic reactivity produced the most refined pore structure, densified ITZ, and enhanced formation of secondary C–(A)–S–H gels. These microstructural improvements translated directly into increased mechanical strength and reduced transport-related durability parameters. Environmental assessment further confirmed that all mixes remained within regulatory leaching limits, demonstrating the safe utilization of MSWI-BA in concrete. Although higher replacement levels showed marginal performance reductions associated with increased porosity and reduced workability, the M20 mix consistently delivered the best balance between performance enhancement and sustainability. Overall, the findings validate MSWI bottom ash not merely as a recycled filler, but as an engineered, performance-enhancing, and circular-economy-driven material suitable for large-scale civil infrastructure.

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