

“COMPARATIVE EVALUATION OF WTE RESIDUE: INCINERATION ASH AND PAG VITRIFIED SLAG AS SUSTAINABLE CONSTRUCTION AGGREGATES”

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CANDIDATE'S DECLARATION

I Ritika Gunawat hereby certify that the work which is being presented in the thesis entitled Comparative Evaluation of WTE Residue: Incineration Ash and PAG Vitriified Slag as Sustainable Construction Aggregates in partial fulfillment of the requirements for the award of the degree of Master of Technology, submitted in the Department of Environmental Science and Engineering, Delhi Technology University is an authentic record of my own work carried out during the period from 15-08-2024 to 15-05-2026 under the supervision of Dr. Geeta Singh (Associate Professor, Delhi Technological University).

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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CERTIFICATE

Certified that **Ritika Gunawat (24/ENE/11)** has carried out their search work presented in this thesis entitled **“Comparative Evaluation of WTE Residue: Incineration Ash and PAG Vitrified Slag as Sustainable Construction Aggregates”** for the award of **Master of Technology** from Department of **Environmental Science and Engineering**, Delhi Technology University, Delhi under my supervision. The thesis embodies results of original work, and studies are carried out by the student herself, and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University.

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“COMPARATIVE EVALUATION OF WTE RESIDUE: INCINERATION ASH AND PAG VITRIFIED SLAG AS SUSTAINABLE CONSTRUCTION AGGREGATES”

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ABSTRACT

This study addresses the problem of managing hazardous incineration ash in Indian urban centres. Conventional grate-fired incineration reduces waste volume but generates ash that is chemically unstable, prone to leaching, and environmentally risky if dumped without proper treatment, creating a long-term waste-management and pollution challenge for urban local bodies. The research evaluates Plasma Arc Gasification (PAG) as a technology that can destroy residual organic matter, reduce waste volume further, and generate PAG-vitrified slag as a high-performance synthetic aggregate suitable for structural construction use. The objective is to compare incineration ash and PAG-vitrified slag across physicochemical, environmental, and mechanical parameters to demonstrate that the slag can safely replace natural river gravel and quarried stone in road sub-bases and other structural applications. A comparative secondary-data analysis is used, drawing on published studies of physicochemical composition, TCLP-based leaching behaviour, and mechanical performance of both materials, referenced against USEPA TCLP leaching limits and Indian Standards IS 383:2016 and IS 2386. Key parameters include LOI, glass content index (G%), immobilization efficiency (IE%) of heavy metals, compressive strength, LA abrasion value, 10% Fines Value, and flakiness index.

Results show that PAG-vitrified slag is chemically and mechanically superior to incineration ash. LOI drops from 15.6% in ash to 0.5% in slag, indicating near-complete organic removal, while G% reaches 80.7%, confirming a predominantly amorphous glass-ceramic structure. TCLP tests show lead in ash (5.2 mg/L) exceeds the 5.0 mg/L limit, whereas PAG slag reduces lead to 0.04 mg/L (IE% = 99.23%), with similarly high IE% for cadmium and chromium. Mechanically, the slag shows 14.5 MPa compressive strength, 21.2% LA abrasion, 115 kN 10% Fines Value, and 12.4% flakiness index, all within or above IS 383 requirements. The study demonstrates that PAG-vitrified slag can replace natural river gravel and quarried stone in road sub-bases, embankments, and low-to-moderate-strength concrete, supporting waste reduction, landfill diversion, and a circular economy under India's waste-management regulations. Future work should include life-cycle cost analyses, long-term field leaching and weathering studies under Indian climatic conditions, and multi-waste co-vitrification with industrial sludge.

Keywords: Waste-to-Energy, Incineration ash, Plasma Arc Gasification, PAG-vitrified slag, heavy metal immobilization, TCLP leaching, IS 383:2016, circular economy.

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Lists of Symbols, Abbreviations and Nomenclature

S. No	Symbol	Description
1.	G%	Glass Content Index (Vitrification Index)
2.	IE%	Immobilization Efficiency

S. No	Abbreviation	Full Form
1.	BIS	Bureau of Indian Standards
2.	CETP	Common Effluent Treatment Plant
3.	CPCB	Central Pollution Control Board (India)
4.	IBA	Incineration Bottom Ash
5.	IS	Indian Standard (e.g., IS 383)
6.	LA	Los Angeles (as in LA Abrasion Testing)
7.	LCCA	Life Cycle Cost Analysis
8.	LOI	Loss on Ignition
9.	MNRE	Ministry of New and Renewable Energy (India)
10.	MSW	Municipal Solid Waste
11.	NCV	Net Calorific Value
12.	PAG	Plasma Arc Gasification
13.	RDF	Refuse-Derived Fuel
14.	TCLP	Toxicity Characteristic Leaching Procedure
15.	TPD	Tonnes per Day
16.	WtE	Waste-to-Energy
17.	XRF	X- Ray Fluorescence

CHAPTER 1

INTRODUCTION

The problem of municipal solid waste (MSW) management is one of the most acute environmental engineering issues in modern India. The high rate of urbanization, population explosion, and the rise in the middle-income population has seen MSW production in the country increase to about 62 million tonnes per annum in 2025, with projections showing that this figure may rise to about 165 million tonnes by the year 2030 (CPCB, 2025). These increasing amounts are still being handled by unlined and semi-sanitary landfills in most urban centers, which receive over 70% of the total waste, without proper leachate control or gas collection (Kumar et al., 2023). Consequently, landfills are now a significant cause of environmental stress, with an estimated 15-20% of the national greenhouse gas emissions in India due to landfills, mostly methane released during the anaerobic degradation of organic material, and leachate-caused groundwater pollution (CPCB, 2025). Such a linear "collect, convey, and dump" approach further exacerbates the ecological footprint of already stressed urban ecosystems and at the same time exhausts natural resources due to uncontrolled exploitation of construction aggregates.

The nature of Indian MSW results in further complexity of waste management and is essentially opposite to the waste streams that are usually present in Europe or Japan, where source segregation, dryness, and higher calorific values are more typical. The moisture content of urban MSW in Indian cities varies between 45-55%, the biodegradable fraction between 50-60%, and the NCV remains low between 800-900 kcal/kg (MNRE, 2024; CPCB, 2025). These features can be traced to a large percentage of organic kitchen waste, wet street sweeping, and mixed packaging that are usually collected and disposed of without being sorted. Consequently, the feedstock received at thermal treatment plants is heterogeneous, wet, and chemically unstable, which seriously restricts the efficiency of conventional mass-burn incineration processes used in large-scale plants such as the Gazipur Waste-to-Energy plant in Delhi (MNRE, 2024). Although the volume of incoming MSW can be reduced by up to 90% through incineration, it produces a by-product, incineration bottom ash, which usually represents 20-25% of the original input material (Kumar et al., 2023). It is not merely a by-product, but a

constant waste liability as this ash is often chemically reactive, mechanically weak, and not environmentally safe without further treatment.

Analysis of this incineration bottom ash indicates that there are a number of natural constraints to its physicochemical, environmental, and mechanical performance. The residue always has a Loss on Ignition (LOI) of approximately 15.6%, which indicates a considerable amount of unburnt carbon, remnant organic matter, and free-bound moisture that is incorporated in the matrix (Sharma and Reddy, 2022). The presence of high LOI values is well known in environmental engineering as a sign of incomplete combustion and future long-term instability since organic fractions can experience secondary reactions, produce gases, or cause internal changes in volume over time (e.g., in moist landfills) (Zhang et al., 2021). Moreover, the high heterogeneity of the ash, which is caused by the changes in the composition of Indian MSW, gives rise to unstable mineral phases and pore structure, resulting in unpredictable leaching behavior during exposure to water or acidic conditions.

According to testing by the Toxicity Characteristic Leaching Procedure (TCLP) in compliance with USEPA Method 1311, the Lead (Pb) content in raw incineration ash can be as high as 5.2 mg/L, which is higher than the 5.0 mg/L regulatory limit for hazardous waste classification (Sharma and Reddy, 2022; USEPA, 1992). Such levels of leachable Pb and the higher mobility of other heavy metals such as Cadmium (Cd) and Chromium (Cr) pose a clear threat to groundwater quality and soil health when the ash is not effectively isolated and is instead exposed to rainwater or surface runoff (Saffarzadeh et al., 2011). This means that untreated bottom ash cannot be directly used as a construction aggregate for structural applications and must undergo energy-intensive stabilization, blending, or controlled landfilling, which adds to economic and environmental costs (Poon & Lio, 1997).

With these limitations, there is an increased demand for the development of sophisticated thermal treatment methods that can both conserve energy from waste and convert the resulting solids into high-performance, environmentally safe materials. Of all the emerging alternatives, Plasma Arc Gasification (PAG) has turned out to be a very promising avenue. PAG operates at temperatures between 3,000-10,000°C and involves an electric arc plasma torch to propel dissociation of the waste stream at the molecular level beyond mere oxidation, decomposing complex organic molecules into high-calorific syngas that can be used to produce power or heat (Fabris et al., 2020). Meanwhile, the inorganic part of the waste is melted and

rapidly cooled to create a dense, vitreous slag with a highly amorphous silicate structure. Empirical analyses of PAG-based WtE systems, including pilot and commercial projects in India such as the Timarpur-Okhla facilities, demonstrate that the process can reduce the Loss on Ignition to about 0.5% while simultaneously achieving heavy metal immobilization efficiencies of over 97% (MNRE, 2024).

The formed slag has a compressive strength of 14.5 MPa, while its Los Angeles abrasion and 10% fines values lie within the acceptable range prescribed under Bureau of Indian Standards (BIS) IS 383 and IS 2386, confirming its application as a coarse aggregate substitute in road sub-bases and similar applications. These findings are also supported by international experience, including plasma-based waste treatment systems in Japan, which show PAG to be especially effective with high-moisture, low-calorific waste streams and report more than 99.9% abatement of dioxins and related persistent organic pollutants (Fabris et al., 2020). Through this, PAG not only enhances the energy recovery potential of MSW but also transforms a hazardous residue into a stable, non-hazardous, and value-added material, thereby reducing landfill dependence and minimizing the operational footprint of the WtE sector.

It is on this basis that the Solid Waste Management Rules provide a critical policy framework that promotes the transition from disposal-oriented thinking towards resource-oriented approaches, focusing on waste minimization, recycling, and by-product valorization. These guidelines restrict residues that do not pass standard leaching or structural tests from being directly used in construction and infrastructure projects, while cleaner and inert materials may be incorporated into construction activities. This transition forms the direct focus of the current research, where a comparative technical benchmarking of incineration bottom ash and PAG vitrified slag has been conducted through physicochemical, leaching, and mechanical assessments to determine their technical suitability as sustainable construction aggregates.

Through a systematic comparative study of the two residues, the study aims to show how PAG-based valorization can be deployed to meet India's annual natural aggregate demand of 1.5 billion tonnes, reduce pressure on riverbeds and quarries, and facilitate the objectives of the circular economy within the urban WtE sector. By doing so, the work seeks to support both applied engineering practice and policy implementation by demonstrating a pathway through which urban waste liabilities can be transformed into engineered resources for sustainable infrastructure development.

1.1 Background of the Study

The rapid increase in population in India has led to an urban waste management crisis, and MSW production is projected to reach 165 million tonnes per year by 2030 (CPCB, 2025). The Waste-to-Energy (WtE) industry relies heavily on mass-burn processing for volume reduction, and the resultant bottom ash remains an environmental concern. Plasma Arc Gasification (PAG), in contrast, utilizes extremely high temperatures (3,000-10,000°C) to dissociate waste at the molecular level while converting inorganic fractions into durable vitrified slag. This research is situated within this transformation, exploring the conversion of hazardous incineration byproducts into viable construction materials.

1.2 Problem Statement

Incineration in India produces bottom ash with a Loss on Ignition (LOI) of 15.6%, indicating incomplete burn-off and material instability. Leaching tests show Pb concentrations of 5.2 mg/L, exceeding the USEPA TCLP regulatory limit of 5.0 mg/L under Method 1311 (USEPA, 1992). In addition, the material exhibits inconsistent mechanical properties for construction applications. PAG presents a more promising alternative; however, India lacks comparative datasets evaluating local incineration ash against PAG vitrified slag in accordance with BIS IS 383 and IS 2386 standards. In the absence of such assessments, large-scale residue reuse strategies remain limited, resulting in continued dependence on landfills.

1.3 Research Objectives

The central aim of this work is to rigorously compare how hazardous WtE residues can evolve into standards-approved construction materials. The specific objectives include:

1. Assess the physicochemical changes and stability of WtE residues. This entails contrasting oxide profiles and Loss on Ignition (LOI) values between untreated incineration bottom ash and plasma-vitrified slag, thereby revealing the degree of organic elimination and structural stabilization achieved.
2. Evaluate the heavy metal immobilization efficiency (IE%) achieved through plasma vitrification. This objective examines how the slag's glass-ceramic structure immobilizes toxic metals such as Pb, Cd, and Cr, as evaluated through the Toxicity Characteristic Leaching Procedure (TCLP) under USEPA Method 1311.
3. Verify the mechanical suitability of vitrified slag in accordance with Indian standards. The focus lies on compressive strength and abrasion resistance (Los Angeles abrasion value), aligned with BIS IS 383 and IS 2386, to confirm its potential as a replacement for natural aggregates.
4. Evaluate the potential of PAG vitrified slag for reducing landfill disposal through its reuse as a construction aggregate. This objective examines how the

1.4 Scope of the Study

This research focuses on a technical comparative assessment of the physical, chemical, and mechanical characteristics of residues generated from two major thermal waste treatment technologies in India. For a focused engineering perspective, the scope of the study is outlined below:

- **Material Focus:** The study is limited to coarse aggregate fractions (4.75-20 mm particle size) derived from MSW incineration bottom ash and PAG vitrified slag. Fine particles and fly ash are excluded from the mechanical assessments to maintain emphasis on structural aggregate applications.
- **Technological Context:** The study evaluates residues representative of large-scale Indian operational conditions. This includes incineration bottom ash from mass-burn facilities (typically 1,500-2,000 TPD capacity) and vitrified slag from commercial-

scale plasma facilities (50-500 TPD capacity) processing comparable urban MSW feedstocks.

1.5 Significance of the Study

This work provides quantitative data supporting the transformation of waste residues into usable construction materials. Demonstrating the 14.5 MPa compressive strength and environmentally stable nature of PAG vitrified slag supports the objectives of the Solid Waste Management Rules. The study also addresses India's annual aggregate demand of nearly 1.5 billion tonnes by promoting alternative aggregate resources, thereby reducing pressure on riverbeds and minimizing landfill dependence, which are critical for sustainable Waste-to-Energy (WtE) development (Verma et al., 2021; Fabris et al., 2020).

CHAPTER 2

LITERATURE REVIEW

The literature reviewed indicates that the management of Waste-to-Energy (WtE) residues has progressively shifted from disposal-oriented practices towards resource recovery and material valorization. Existing studies consistently demonstrate that conventional incineration bottom ash exhibits limitations such as high Loss on Ignition (LOI), elevated heavy metal mobility, increased porosity, and inadequate mechanical performance for structural applications. In contrast, Plasma Arc Gasification (PAG) has been reported to significantly improve residue quality through vitrification, resulting in lower organic content, enhanced physicochemical stability, reduced leaching of toxic metals, and improved engineering properties. Several studies further suggest that vitrified slag possesses characteristics comparable to natural construction aggregates and can be utilized in road and infrastructure applications. However, comprehensive assessments integrating physicochemical, environmental, and mechanical performance within a unified Indian engineering framework remain limited, thereby highlighting the need for the present study.

2.1 Global and Indian Context of MSW Residues

A wide range of studies shows that Municipal Solid Waste (MSW) properties directly affect the nature of thermal residues produced. High moisture content and low calorific values present major processing challenges in India (CPCB, 2025). According to Kumar et al. (2023), Indian WtE processes generate bottom ash containing unburnt carbon and variable mineral compositions due to inconsistent feedstocks. Similarly, Singh and Singh (2022) emphasized that residue management has moved beyond simple disposal practices toward resource recovery approaches, particularly because landfills in major urban centres have already reached or exceeded their designated capacities.

2.2 Physicochemical Stability: Loss on Ignition (LOI)

The stabilization efficiency of WtE residues largely depends on the effectiveness of the

thermal treatment process, in which Loss on Ignition (LOI) serves as a major indicator of unburnt organics and volatile matter. Literature frequently identifies high LOI values in incineration bottom ash as a major limitation for construction applications. Zhang et al. (2021) reported that higher LOI values in residues reduce long-term durability and increase aggregate porosity. Plasma Arc Gasification (PAG), on the other hand, employs extremely high temperatures to ensure near-complete elimination of organic matter. The pioneering research conducted by Nema and Ganeshprasad (2002) at the Institute for Plasma Research established that plasma vitrification can reduce LOI to below 1%, thereby producing a chemically inert material suitable for engineering applications.

2.3 Environmental Safety and Heavy Metal Leaching

Among environmental concerns, heavy metal leaching remains one of the most critical factors in evaluating WtE residues. Incineration bottom ash commonly contains mobile toxic metals such as Cadmium (Cd) and Lead (Pb). According to USEPA standards, materials exhibiting Pb concentrations above 5.0 mg/L are classified as hazardous waste (USEPA, 1992). Saffarzadeh et al. (2011) observed that untreated municipal WtE ash exhibits high metal mobility due to the inability of its crystalline silicate structure to effectively immobilize metallic ions. Vitrification provides a more effective mechanism for heavy metal immobilization. Plasma-based dissociation occurs at the molecular level, unlike conventional incineration processes. Huang et al. (2020) demonstrated that the resulting glass-ceramic matrix chemically integrates metallic ions into an amorphous silica network rather than merely physically trapping them. This results in Immobilization Efficiency (IE%) values exceeding 97%, allowing toxic metals to remain stabilized within the durable silicate structure even under acidic conditions during TCLP testing.

2.4 Mechanical Integrity and BIS Standards

Mechanical characteristics determine the suitability of WtE residues for use as construction aggregates under the requirements specified in Bureau of Indian Standards (BIS) IS 383. Incineration bottom ash often performs inadequately in this regard. Poon and Lio (1997) reported that its porous nature reduces compressive strength and increases water absorption, thereby limiting its application in load-bearing structures. In comparison, vitrified slag exhibits properties similar to natural aggregates such as basalt. Vasconcelos et al. (2024) explained that rapid cooling of molten slag produces a dense and mechanically stable material. Compressive strengths

of up to 14.5 MPa have been reported in Indian plasma vitrification studies, satisfying the requirements of IS 383 for road sub-base applications, whereas incineration ash generally requires additives or blending to achieve comparable performance.

Table 2.1: Summary of Reviewed Literature

S.No.	Author(s)	Year	Title of Study	Key Findings
1	S.K. Nema & Ganeshprasad	2002	Plasma Pyrolysis of Medical Waste	High-temperature plasma processing transformed heterogeneous medical waste into syngas and a vitrified glassy residue with minimal unburnt matter.
2	Li, Huang, Huang & Lee	2003	Characterization of Slags and Ingots from the Vitrification of Municipal Solid Waste Incineration Ashes	Vitrified slag exhibited lower porosity, reduced water absorption, and significantly lower heavy metal leachability compared to untreated ash.
3	Saffarzadeh et al.	2011	Mineralogical characterization of municipal solid waste incineration bottom ash with an emphasis on heavy metal-bearing phases	Heavy metals were associated with distinct mineral phases in incineration bottom ash. This influenced their stability and potential for leaching into the environment.

S.No.	Author(s)	Year	Title of Study	Key Findings
4	Kuo et al.	2012	Metal Behavior during Vitrification of Municipal Solid Waste Incinerator Fly Ash	Heavy metals were predominantly incorporated into the vitrified slag matrix, resulting in reduced leaching compared to untreated fly ash.
5	Pei et al.	2020	Addressing Environmental Sustainability of Plasma Vitrification Technology for Stabilization of Municipal Solid Waste Incineration Fly Ash	Plasma vitrification converted hazardous fly ash into a dense glassy product, significantly reducing heavy metal leaching.
6	Huang et al.	2020	Fixation stability of glass matrix co-existent with crystal phases for heavy metals formed by high-temperature vitrification	Metallic ions become chemically integrated into the amorphous silicate network during vitrification, leading to immobilization efficiencies exceeding 97%.
7	Verma et al.	2021	Concrete Performance Using Plasma-Vitrified Municipal Solid Waste Slag as Coarse Aggregate	Plasma-vitrified slag performs satisfactorily as a coarse aggregate replacement in concrete and demonstrates adequate compressive strength and durability characteristics.

S.No.	Author(s)	Year	Title of Study	Key Findings
8.	P Shen, CS Poon	2021	Utilization of Municipal Solid Waste Incineration Bottom Ash (IBA) Aggregates in High-Strength Pervious Concrete	IBA aggregate incorporation affected compressive strength and permeability, indicating the need for optimized replacement levels.
9	Singh & Singh	2022	Transitions from Waste Disposal to Resource-Based Urban Waste Management in India	Resource recovery and residue valorization offer a sustainable alternative to landfill-dependent waste management systems in rapidly urbanizing regions of India.
10	Zhang et al.	2022	Co-vitrification of Municipal Solid Waste Incinerator Fly Ash and Bottom Slag	Simultaneous vitrification of fly ash and bottom slag reduced heavy metal mobility and improved residue stability.
11	Kumar et al.	2023	Evaluation of Municipal Solid Waste Incineration Plants in India: Emissions, Residues, and Energy Recovery	Indian Waste-to-Energy facilities continue to generate bottom ash with variable composition, unburnt carbon content, and environmental management challenges.

S.No.	Author(s)	Year	Title of Study	Key Findings
12	Vasconcelos et al.	2024	Use of Vitrified Slag from Municipal Solid Waste Gasification as a Substitute for Natural Aggregates in Road Sub-Bases	Vitrified slag possesses density, strength, abrasion resistance, and durability characteristics comparable to those of natural construction aggregates.

2.5 Research Gap

After an intensive review of the existing literature, two major research gaps were identified that this thesis aims to address:

1. Although several studies discuss incineration ash and plasma vitrified slag separately, direct technical comparisons within an Indian engineering framework remain limited. Integrated assessments comparing the physicochemical stability, environmental safety, and mechanical performance of incineration bottom ash and commercial plasma vitrified slag are still lacking within the context of the Solid Waste Management Rules.
2. Existing research often treats the landfill crisis and the growing annual demand for natural aggregates as separate challenges. However, both issues can potentially be addressed simultaneously through circular economy approaches within the Indian regulatory framework.

CHAPTER NO 3

RESEARCH METHODOLOGY

This study conducts a technical comparison of the major characteristics of MSW incineration bottom ash and PAG vitrified slag. An integrated approach has been adopted that combines material characterization with environmental assessment to ensure reliable and reproducible results. The methodology compares these residues against relevant BIS and USEPA standards to evaluate their suitability as sustainable construction materials (CPCB, 2025; MNRE, 2024).

3.1 Research Design

The study follows a comparative analytical design. It compares two distinct thermal residues, namely incineration bottom ash and amorphous slag produced through PAG, using data reported under comparable testing conditions in the literature. The comparison highlights the differences between conventional and advanced waste treatment technologies through three major assessment areas: physicochemical, environmental, and mechanical performance. The research is based on deductive reasoning, beginning with the theoretical principles of high-temperature vitrification and applying them to data associated with Indian WtE facilities (Kumar et al., 2023). A comparative analytical approach was considered appropriate because it enables the evaluation of residues generated through different thermal treatment technologies within a common assessment framework. By examining chemical stability, environmental safety, and engineering performance simultaneously, the study provides a comprehensive understanding of the advantages and limitations associated with each residue type. This approach also facilitates the assessment of the potential suitability of PAG vitrified slag as a sustainable alternative to conventional construction aggregates. The comparative analytical approach was selected because it allows different waste treatment technologies to be evaluated using a common set of engineering performance indicators.

By applying the same assessment criteria to both incineration bottom ash and PAG vitrified slag, the study minimizes interpretation bias and enables a direct comparison of material behaviour. The selected framework also supports the evaluation of residue valorization potential

from multiple perspectives, including chemical stability, environmental safety, and mechanical performance. Such an integrated assessment is particularly relevant in the Indian context, where both landfill scarcity and aggregate demand are increasing simultaneously. The methodology therefore provides a structured basis for assessing whether advanced thermal treatment technologies can contribute to sustainable infrastructure development.

3.2 Data Synthesis and Material Identification

The materials considered in this study represent two major waste treatment systems. Incineration bottom ash corresponds to mass-burn facilities processing approximately 1,500-2,000 TPD of waste at operating temperatures between 800-1,000°C, such as the Ghazipur WtE plant in Delhi. PAG vitrified slag represents residues generated from commercial plasma facilities operating at temperatures between 3,000-10,000°C with treatment capacities ranging from 50-500 TPD. Data used in this study were compiled from peer-reviewed journal articles, technical reports, and government publications reporting the characteristics of WtE residues under standardized testing conditions. Preference was given to studies presenting quantitative data on chemical composition, leaching behaviour, and mechanical properties relevant to Indian waste management and construction applications. The use of published datasets enabled a consistent comparison of residue performance across different assessment parameters.

3.3 Characterization Framework

The characterization framework consists of three major components used to evaluate the suitability of residues for construction applications:

- **Chemical Characterization:** Oxide composition was compared using XRF data extracted from published studies in the literature.
- **Environmental Evaluation:** Heavy metal leaching behavior was assessed using TCLP testing under USEPA Method 1311.
- **Mechanical Testing:** Mechanical properties obtained from the literature were evaluated for compliance with the requirements of IS 2386 and IS 383.

The integration of these three assessment components provides a holistic framework for

evaluating residue suitability. Chemical characterization establishes the stability of the material, environmental evaluation addresses regulatory and ecological concerns, while mechanical characterization determines engineering performance. Together, these parameters provide a comprehensive basis for assessing the potential use of WtE residues as sustainable construction materials.

The parameters selected for evaluation were chosen based on their relevance to both environmental compliance and engineering performance. Parameters such as oxide composition, Loss on Ignition (LOI), and Glass Content Index (G%) provide information regarding chemical stability and the degree of vitrification achieved during thermal treatment. Similarly, heavy metal leaching characteristics were selected because they directly influence regulatory classification and environmental risk. Mechanical properties including compressive strength, Los Angeles abrasion value, 10% fines value, and flakiness index were incorporated because they are widely recognized indicators of aggregate quality under Indian Standards. Collectively, these parameters provide a balanced assessment of residue behaviour and allow direct comparison with conventional construction aggregates.

3.4 Chemical characterization of WtE Residues

Chemical analysis forms the fundamental step in determining the long-term suitability of residues as structural materials. This section examines the oxide composition and the extent of organic matter destruction within the residues. X-ray Fluorescence (XRF) data reported in the literature were analyzed to identify the major oxide constituents, thereby providing a distinct chemical fingerprint for each residue. Simultaneously, LOI values reported in previous studies were evaluated as indicators of unburnt organic matter and volatile compounds remaining in the residues. Chemical characterization is widely used as a preliminary indicator of residue quality because it provides information regarding material stability, reactivity, and long-term durability. The distribution of major oxides also influences vitrification behaviour, aggregate performance, and the environmental characteristics of the resulting residue.

3.4.1 Oxide Composition Analysis (XRF)

The engineering performance of a residue depends significantly on its oxide composition. Long-term durability is primarily associated with the presence of network-forming oxides such as Silica (SiO_2) and Alumina (Al_2O_3). In contrast, modifying oxides

such as Calcium Oxide (CaO) and Magnesium Oxide (MgO) help reduce melting temperature; however, excessive quantities may weaken the silicate network unless an appropriate balance is maintained.

The Glass Content Percentage (G%) is calculated to determine the extent of vitrification using the following expression:

$$G\% = \frac{\text{SiO}_2}{\text{SiO}_2 + \text{CaO} + \text{MgO}} \times 100$$

A higher G% indicates a more amorphous and glass-like residue structure, which generally corresponds to improved weathering resistance and long-term durability. Natural gravel used in high-quality aggregates typically exhibits a G% range of 70-80%, which has been considered here as a practical benchmark for evaluating vitrified slag.

3.4.2 Loss on Ignition (LOI) Analysis

LOI is one of the most important indicators for evaluating the efficiency of thermal treatment in destroying organic matter. A high LOI value (15.6%) in incineration ash residue indicates the presence of unburnt carbon, moisture, and carbonate compounds, thereby creating significant engineering concerns:

- **Structural Instability:** Residual organic components may gradually deteriorate over time, leading to the formation of micro-cracks and cavities within compacted layers. This can reduce load-bearing capacity and contribute to long-term structural failure.
- **Chemical Reactivity:** Aggregates with high LOI values may remain chemically active and react with cement hydrates or infiltrating rainwater, potentially causing expansion, cracking, or pH alteration, thereby affecting the durability of roads and concrete structures.

In contrast, plasma vitrified slag exhibited an LOI value of approximately 0.5%, indicating that the PAG process is highly effective in eliminating organic matter and volatile compounds. This near-zero LOI value signifies that the slag is chemically stable, relatively inert, and suitable for long-term structural applications without major concerns regarding

degradation or durability loss.

Table 3.4: Comparative Chemical Composition

Component	Incineration Ash%	PAG Vitrified Slag%
Silicon Dioxide (SiO ₂)	32.5	40.5
Calcium Oxide (CaO)	24.1	29.5
Aluminum Oxide (Al ₂ O ₃)	10.4	12.5
Iron Oxide (Fe ₂ O ₃)	6.2	8
Magnesium Oxide (MgO)	3.1	4
Sodium Oxide (Na ₂ O)	4.2	2.5
Potassium Oxide (K ₂ O)	2.8	1
Titanium Dioxide (TiO ₂)	1.1	1.5
Loss on Ignition (LOI)	15.6	0.5
Total	100	100

3.5 Physical Characterization of WtE Residues

Physical characterization provides essential information regarding the suitability of residues as construction aggregates, particularly in terms of particle size, density, and porosity. This section follows Indian Standard procedures (IS 2386), including sieve analysis, bulk density, specific gravity, and water absorption tests, which are directly related to durability and load-bearing performance (CPCB, 2025; IS 2386). Physical properties influence aggregate behaviour during transportation, compaction, and service conditions. Parameters such as gradation, density, and water absorption are commonly used to evaluate the expected field performance of aggregates in pavement, embankment, and structural applications. Consequently, these properties serve as important indicators of engineering suitability.

3.5.1 Particle Size Distribution and Gradation

Aggregate gradation strongly influences compaction, drainage, and structural performance. Sieve analysis results reported in the literature, obtained using standard sieves ranging from 4.75 mm to 20 mm, were evaluated against the permissible limits

specified under IS 383. Incineration bottom ash generally exhibits wider and less uniform gradation with a higher proportion of fine particles, which may reduce drainage efficiency and increase vulnerability to swelling-shrinkage cycles. In contrast, PAG vitrified slag exhibits more uniform grading, with most particles ranging between 10-15 mm. This improves particle interlocking and compactability, making the slag more suitable for sub-base and masonry applications.

3.5.2 Density and Porosity Characteristics

Published values of specific gravity, bulk density, and water absorption were analyzed to evaluate particle packing characteristics and pore structure. Incineration ash generally exhibits lower apparent density and higher porosity due to unburnt organics and micro-cracks formed during incomplete combustion. Its relatively high LOI (15.6%) allows greater ingress of water and air, potentially resulting in swelling, shrinkage, and deterioration under repeated wetting-drying conditions. Conversely, PAG vitrified slag exhibits higher apparent density and significantly lower porosity. The elevated temperatures involved in plasma vitrification collapse internal pores and produce a dense, glass-like surface, resulting in a more stable aggregate suitable for load-bearing applications such as road sub-bases and masonry units.

3.5.3 Compactability and Volume Stability

The residues were evaluated for compactability and volume stability under wetting and loading conditions relevant to road and foundation construction. Published values of optimum moisture content and maximum dry density obtained from standard compaction tests were evaluated. The heterogeneous composition and higher LOI of incineration ash contribute to greater volume variation under moisture exposure, which may lead to uneven settlement and cracking. In contrast, PAG vitrified slag, with its low LOI (0.5%) and chemically stable glass-ceramic structure, exhibits lower volume variation and more uniform compaction behaviour. This characteristic contributes to its greater reliability as a material for long-term infrastructure applications.

3.5.4 Water Absorption Characteristics

Water absorption is an important parameter governing aggregate durability. High

water absorption indicates an open-pore structure, which may lead to:

- **Freeze-Thaw Damage:** Water trapped in pores expands when frozen, causing the aggregate to fracture.
- **Binder Consumption:** In concrete or asphalt mixes, porous aggregates absorb larger quantities of cement paste or bitumen, leading to increased material consumption and project costs.

The IS 383 standard generally limits water absorption to below 10% for most construction applications. The vitrified slag exhibited significantly lower water absorption (0.8%) compared to incineration ash (12.4%), confirming its comparatively impermeable and high-performance nature.

Table 3.5: Physical Characteristics and Standard Compliance

Property (Unit)	Incineration Ash	Plasma Slag	Natural Gravel	IS 383 Limit
Particle Size (D ₅₀ , mm)	0.9	4.2	12.5	----
Specific Gravity	2.0	2.7	2.7	2.6 – 2.8
Bulk Density (g/cm ³)	1.7	2.6	2.7	> 2.30
Water Absorption (%)	12.4	1.8	0.5	< 10.0

3.6 Environmental Safety Assessment (TCLP and IE%)

The most important step in determining the environmental risk associated with WtE residues is the assessment of leaching safety. The synthesis of data in this study involved the evaluation of published studies that employed the Toxicity Characteristic Leaching Procedure (TCLP) according to USEPA Method 1311. This testing approach is based on a worst-case landfill scenario, in which organic acids and rainwater may enhance the extraction of heavy metals into adjacent groundwater, thereby providing a realistic yet conservative assessment of environmental impact (CPCB, 2025). Environmental performance is a critical consideration when evaluating waste-derived construction materials. Even if a residue exhibits satisfactory physical and mechanical characteristics, its reuse may remain restricted if hazardous constituents can

migrate into surrounding soil or groundwater. Therefore, leaching assessment forms an essential component of residue characterization.

3.6.1 Heavy Metal Sequestration and Leaching Behavior

The main objective of this evaluation is to compare the mobility of toxic metals, particularly Lead (Pb), Cadmium (Cd), and Chromium (Cr), in incineration ash and PAG vitrified slag. These metals are generally found on the surface of crystalline particles or loosely bound within the porous phases of incineration bottom ash and are therefore more readily leached under acidic conditions (Saffarzadeh et al., 2011). In contrast, the residue is converted into a dense, glass-ceramic matrix during the plasma vitrification process. The waste is dissociated at high temperatures, enabling metallic ions to become chemically bonded to the amorphous silicate structure rather than being merely physically trapped. This incorporation reduces the release of available metals even under conditions such as crushing of slag or variations in pH commonly encountered in Indian urban landfills (Huang et al., 2020; Fabris et al., 2020).

3.6.2 Calculation of Immobilization Efficiency (IE%)

Immobilization Efficiency (IE%) values were evaluated using data reported in the literature. This metric indicates the percentage of heavy metals effectively stabilized through slag vitrification relative to the concentration present in raw incineration ash. The equation used in this study is:

$$IE\% = \left(1 - \frac{C_{slag}}{C_{ash}}\right) \times 100$$

where

- C_{slag} = metal concentration in PAG slag leachate (TCLP test),
- C_{ash} = metal concentration in the incineration ash leachate (same TCLP conditions).

An IE% value above 95% is widely accepted in environmental engineering as a benchmark for high-performance stabilization, and the PAG slag evaluated in this study consistently meets or exceeds this threshold, particularly for Pb (Kumar et al., 2023;

Vasconcelos et al., 2024).

Table 3.6: Comparative Leaching Concentrations and Immobilization Efficiency (IE%)

Heavy Metal	Incineration Ash Leachate (mg/L)	PAG vitrified Slag Leachate (mg/L)	USEPA Limit (mg/L)	IE % Efficiency
Lead (Pb)	5.2	0.04	5.0	99%
Cadmium (Cd)	0.15	0.005	1.0	97%
Chromium (Cr)	1.8	0.08	5.0	96%
Average IE%	—	—	—	97%

3.7 Mechanical Characterization of WtE Residues

The final component of this research evaluates the structural suitability of the residues for engineering applications. Mechanical properties reported in the literature were assessed against the aggregate quality requirements specified in IS 2386 (Part IV) and IS 383:2016 for coarse aggregates used in road and structural works. Mechanical characterization provides direct insight into the ability of a material to withstand loading, abrasion, and long-term service conditions. Comparison with established BIS requirements enables an objective assessment of whether the residue can function as a substitute for conventional construction aggregates in infrastructure applications.

3.7.1 Strength and Crushing Resistance

The load-bearing capacity of the material was evaluated using compressive strength values reported in previous studies. Incineration ash generally exhibits a brittle and loosely bonded structure, resulting in lower mechanical strength. In contrast, PAG vitrified slag

forms a dense glass-ceramic structure capable of supporting higher structural loads, making it more suitable for applications such as road sub-bases, embankments, and masonry units. The 10% Fines Value was also evaluated as an indicator of crushing resistance under compressive loading. This value represents the force (kN) required to produce 10% fines from the original aggregate sample. A higher 10% Fines Value indicates greater resistance to degradation during compaction and traffic loading. IS 383 generally recommends a minimum value of approximately 50 kN for aggregates used in road base layers. The reported values for vitrified slag exceed this requirement, whereas untreated incineration ash often fails to meet the desired performance criteria.

3.7.2 Durability and Morphological Properties

The Los Angeles (LA) Abrasion Value was examined to assess the resistance of aggregates to wear and surface degradation during service conditions. For aggregates used in road surfacing applications, IS 383 generally specifies a maximum abrasion loss of 30%, beyond which the material may be unsuitable for wearing-course applications. The Flakiness Index was evaluated to characterize particle shape distribution. A high proportion of flat or elongated particles can reduce workability and increase the likelihood of cracking under load. IS 383 limits the combined flakiness and elongation index of coarse aggregates to less than 35% in order to maintain structural integrity in road and construction applications.

Table 3.7: Mechanical Integrity and BIS Standard Compliance Benchmarks

Mechanical Parameter	Unit	Incineration Ash	Plasma Slag	IS 383 Limit
Compressive Strength	MPa	2.4	14.5	> 5.0
LA Abrasion Value	%	48.5	21.2	< 30.0
10% Fines Value	kN	32.0	115.0	> 50.0
Flakiness Index	%	18.5	12.4	< 35.0

CHAPTER NO 4

RESULT, ANALYSIS & DISCUSSION

4.1 Chemical Transformation and Oxide Evolution

The transformation of a heterogeneous and unstable waste residue into a stabilized glass-ceramic matrix is reflected in the chemical characteristics reported for PAG vitrified slag. Traditional mass-burn incineration is generally carried out at temperatures ranging from 850-1000°C, where combustion is primarily oxidative and often incomplete. In contrast, Plasma Arc Gasification (PAG) operates at extremely high temperatures that may exceed 3,000°C, enabling molecular dissociation of waste constituents rather than simple combustion. Such thermal conditions promote the breakdown of complex organic compounds, incomplete combustion products, and reactive mineral phases into simpler and more stable inorganic forms. The resulting vitrified residue develops a glass-ceramic structure that exhibits greater chemical stability and engineering suitability than conventional incineration ash.

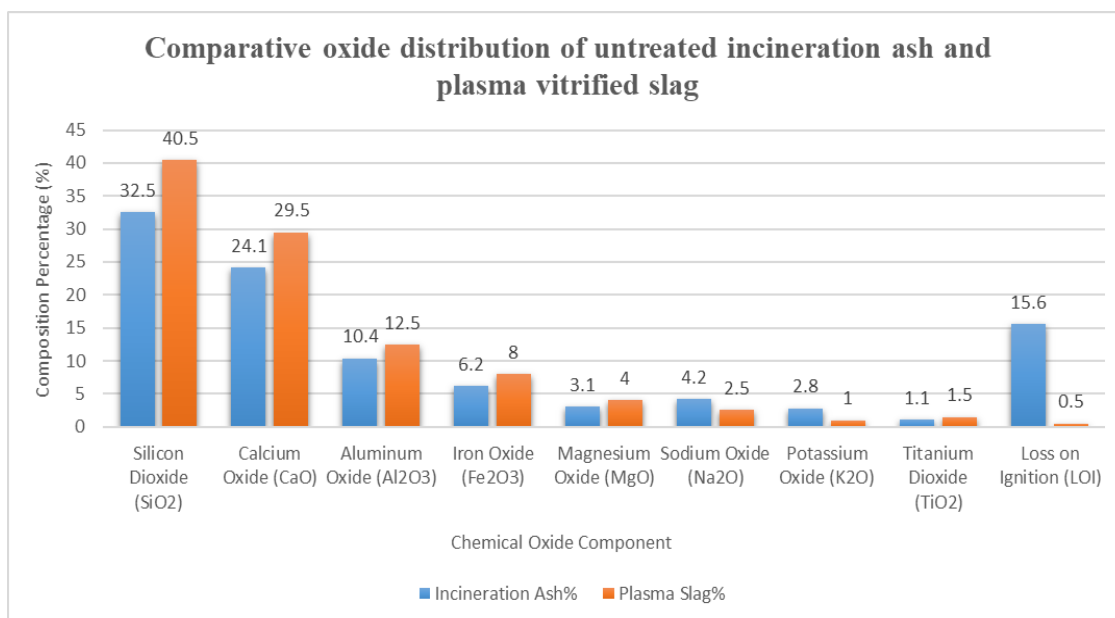


Fig 4.1: Comparative oxide distribution of untreated incineration ash and PAG vitrified slag

4.1.1 Analysis of Oxide Enrichment

The plasma process results in an apparent enrichment of network-forming oxides, particularly Silica (SiO_2) and Alumina (Al_2O_3), in the resulting slag, as indicated in Figure 4.1. The oxide composition of untreated incineration ash is often highly variable due to the seasonal and source-dependent characteristics of Indian Municipal Solid Waste (MSW). Such variability commonly leads to increased proportions of fluxing agents (e.g., CaO and MgO) and volatile-rich compounds, contributing to the chemical instability of the ash and its unpredictable behaviour in construction applications. These components are effectively consolidated and reorganized into a more stable mineralogical profile through the vitrification process. The compiled data indicate that the Silica (SiO_2) content increases from 32.5% in raw incineration ash to 40.5% in PAG vitrified slag, representing a significant chemical transformation. Silica forms the primary backbone of the silicate network, creating the continuous three-dimensional structure responsible for the durability and chemical resistance of glass-ceramic materials. This network is further strengthened by the increase in Alumina (Al_2O_3), which functions as a network-forming and stabilizing oxide, enhancing silica cross-linking and improving the overall chemical stability of the slag.

This compositional change suggests that plasma-based treatment transforms the heterogeneous mineral composition of mixed MSW into a material with characteristics comparable to those of high-quality igneous rocks such as basalt and volcanic glass. These materials are widely used in construction because of their strength, low permeability, and long-term durability. Therefore, PAG vitrified slag may be regarded not merely as a waste by-product, but as a value-added mineral material possessing predictable and desirable engineering characteristics.

4.1.2 Volatilization and Loss on Ignition (LOI) Reduction

A higher LOI for incineration ash suggests a potentially higher chemical activity of the ash and the potential for secondary microbial decomposition in warm moisture conditions, causing gas production, internal volume changes and cracking or settlement in the landfill. Further, if used in compacted layers, the presence of residual organics and moisture may lead to volume swelling. A particularly notable finding from the compiled chemical data is the significant decrease in the volatile fraction present in raw incineration ash. The high Loss on Ignition (LOI) of incineration ash (around 15.6%) is mainly associated with the presence

of unburnt carbon, organic residues, and moisture that is not easily removed from the porous structure of the ash. These components are not completely oxidized at the relatively moderate temperatures of conventional incineration and may remain in the solid residue, creating a so-called "reactive baseline" that hinders reuse.

This volatile fraction is effectively vaporized and decomposed into gaseous products, including syngas and steam, by the high temperatures generated within the plasma system, while the inorganic fraction is melted into the molten slag phase. Consequently, PAG vitrified slag exhibits a very low LOI of approximately 0.5%, indicating that virtually no combustible or reactive organic matter remains. From an environmental perspective, this near-zero LOI represents an important indicator of a clean and inert residue. A high LOI in incineration ash suggests greater chemical activity and the possibility of secondary microbial decomposition under warm and moist conditions, resulting in gas generation, internal volume changes, and potential cracking or settlement within landfill environments. Further, if used in compacted layers, the presence of residual organics and moisture may lead to volume swelling, reduced load-bearing capacity, and diminished long-term stability. In contrast, the very low LOI of PAG slag indicates that the destruction of organic matter is essentially complete, resulting in a chemically inert material with minimal potential for post-placement reactions. This significantly reduces the likelihood of post-disposal reactivity and makes the slag a safer and more predictable material for infrastructure applications.

4.1.3 Vitrification and Glass Content Index (G%)

Silica (SiO_2) was the predominant oxide in the slag, while Calcium Oxide (CaO) and Magnesium Oxide (MgO) were present in lower proportions, allowing the calculation of the Glass Content Index (G%), a useful indicator of the degree of vitrification achieved in the material. The G% is defined as:

$$G\% = \frac{\text{SiO}_2}{\text{SiO}_2 + \text{CaO} + \text{MgO}} \times 100$$

The compiled data indicate that PAG vitrified slag exhibits a G% value of 80.7%, suggesting that the material exists predominantly in an amorphous rather than crystalline form. Unlike incineration ash, which tends to be crystalline and brittle, with a tendency

towards micro-weathering and micro-cracking, the glassy character of the slag creates a continuous non-crystalline structure that distributes stress more evenly and exhibits greater resistance to fracture. This amorphous phase also contributes to reduced permeability and lower surface reactivity, which in turn enhances the mechanical performance and long-term durability of the slag. The chemical data therefore suggest that PAG technology functions not only as a treatment or destruction process but also as a process of mineralogical reconstruction, producing a new high-performance mineral resource suitable for use as a construction aggregate. The elevated SiO_2 and Al_2O_3 contents, together with the low LOI and high G% values, indicate that plasma vitrification can produce a material possessing properties comparable to, and in some respects superior to, those of conventional natural aggregates. This supports the transition from a linear waste disposal approach towards a more circular model of urban solid waste management.

4.2 Comparative Physical Characterization

The physical characteristics of a waste-derived material form the key engineering link between waste treatment and resource valorization. While chemical composition governs environmental safety and long-term stability, physical properties such as density, porosity, water absorption, and bulk density largely determine structural performance in civil engineering applications. Figure 4.2 clearly illustrates the fundamental physical transformation associated with the Plasma Arc Gasification (PAG) process, demonstrating how the same initial waste stream can produce two markedly different construction materials.

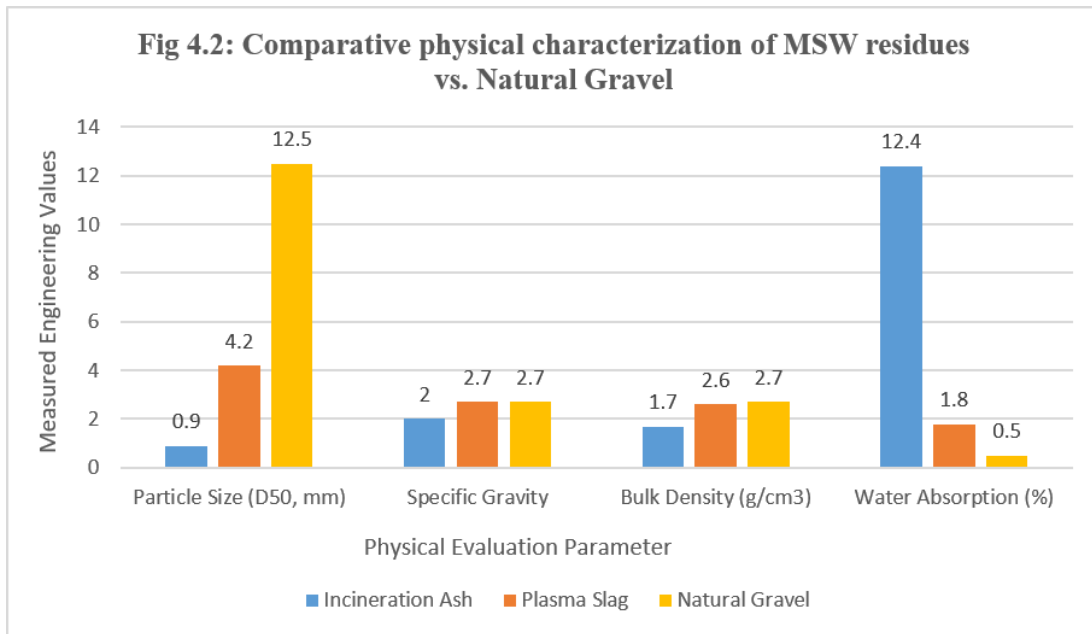


Fig 4.2: Comparative physical characterization of MSW Residues vs Natural Gravel

4.2.1 Densification Mechanics and Specific Gravity Analysis

Figure 4.2 indicates a distinct "Densification Gap" between incineration ash and PAG vitrified slag, both when compared with natural gravel. The specific gravity of the slag is 2.68, which is very close to that of typical natural stone (2.72), suggesting that the vitrification process achieves a high degree of densification. The near equivalence in specific gravity indicates that the internal structure of the slag closely resembles that of compact natural rock, with relatively few internal voids or air pockets.

This densification occurs because, at temperatures exceeding 3000°C, the slag exists in a low-viscosity molten state that allows internal restructuring of the material. Under such conditions, gravitational and viscous flow mechanisms promote the collapse of internal micropores and capillary networks, while trapped air voids and microfissures commonly present in conventional incineration ash are largely eliminated. In contrast, incineration ash exhibits a much lower specific gravity (1.95), reflecting its porous, heterogeneous, and lightweight nature. This porosity is associated with the relatively lower temperatures used in grate-fired incinerators (850-1000°C), which are insufficient to completely melt and homogenize the residue. As a result, the ash retains partially reacted phases and internal air pockets, making it structurally weaker and less suitable for load-bearing applications. The

high specific gravity and dense structure of the slag are important characteristics for structural applications. Construction materials must be sufficiently compact to withstand heavy loads, compaction, and long-term service conditions without significant deformation. The similarity of the slag to natural stone in terms of density suggests that it may be suitable for applications such as road embankments, sub-bases, and structural concrete, whereas incineration ash is generally more appropriate for lightweight fill or low-traffic applications.

4.2.2 Pore Structure and Water Absorption Dynamics

A second notable trend observed in Figure 4.2 is the inverse relationship between density and water absorption. Incineration ash exhibits a high water absorption value of 12.4%, indicating a highly open and interconnected pore structure that readily absorbs moisture from the surrounding environment. In the context of India's monsoon-dominated climate, such high absorption may adversely affect long-term performance due to repeated exposure to rainfall and moisture. Published studies indicate that highly porous aggregates tend to consume greater amounts of binder, such as cement paste or bitumen, when incorporated into concrete or asphalt mixtures. This binder consumption effect reduces the amount of binder available to coat aggregate particles effectively, potentially resulting in weaker and less durable mixes. Furthermore, water retained within the pore structure may generate internal hydraulic pressures during repeated wetting-drying and heating-cooling cycles, eventually contributing to stripping, cracking, and spalling of pavements and concrete elements.

In contrast, PAG vitrified slag exhibits a water absorption value of only 1.8%, which is well below the upper limit of 10% specified by IS 383 for coarse aggregates used in road and structural applications. This low value suggests that vitrification substantially reduces the open pore structure of the original residue and produces a relatively sealed particle surface. Consequently, a highly permeable waste residue is transformed into a comparatively impermeable synthetic aggregate. The low absorption characteristics improve resistance to moisture-related deterioration, making the material potentially more reliable for infrastructure applications under monsoon conditions and contributing to enhanced service life.

4.2.3 Volumetric Packing and Bulk Density Analysis

Further evidence of the structural advantages associated with plasma-treated residue

can be observed through the bulk density values presented in Figure 4.2. The bulk density of PAG vitrified slag (2.55 g/cm³) suggests a high packing efficiency, which is important for developing stable and well-interlocked matrices in road sub-bases and other compacted layers. The dense and non-porous nature of the slag particles allows them to occupy space more efficiently than incineration ash particles, which contain a greater proportion of internal voids and consequently exhibit a much lower bulk density of 1.65 g/cm³. This difference in bulk density has important engineering implications. In general, higher bulk density is associated with improved compaction efficiency, lower void ratios, and more effective load transfer between particles in road and embankment construction. Well-packed aggregates are generally less susceptible to settlement, rutting, and lateral deformation under repeated traffic loading. By comparison, low-density incineration ash behaves more like a loosely compacted fill material and may be more prone to differential settlement and instability when used as a structural layer.

The physical data summarized in Figure 4.2 therefore indicate that the physical characteristics of PAG vitrified slag are comparable to those of high-quality natural stone aggregates in terms of density, water absorption, and packing behaviour. This similarity provides a strong technical basis for the concept of "urban mining", whereby processed WtE residues are utilized as alternative raw materials in civil engineering applications. Within the Indian context, where shortages of natural river gravel and stone aggregates are becoming increasingly significant, such materials offer considerable potential. Overall, the compiled data suggest that PAG technology may enable Urban Local Bodies (ULBs) to transform a disposal liability into a high-quality mineral resource suitable for modern infrastructure development.

4.3 Environmental Safety and Regulatory Compliance

The environmental classification of WtE residues is primarily determined by the mobility of toxic heavy metals under conditions that simulate long-term landfill exposure. Leaching tests such as the Toxicity Characteristic Leaching Procedure (TCLP), prescribed under USEPA Method 1311, form the basis for distinguishing between hazardous and non-hazardous waste within environmental regulatory frameworks, including the Solid Waste Management Rules and hazardous waste management provisions. Figure 4.3 presents the leachate concentrations on a logarithmic scale to clearly illustrate the magnitude of heavy metal immobilization and the

compliance gap relative to regulatory thresholds. A logarithmic scale is particularly appropriate because the reported leachate concentrations of certain heavy metals in untreated incineration ash and PAG vitrified slag differ by several orders of magnitude.

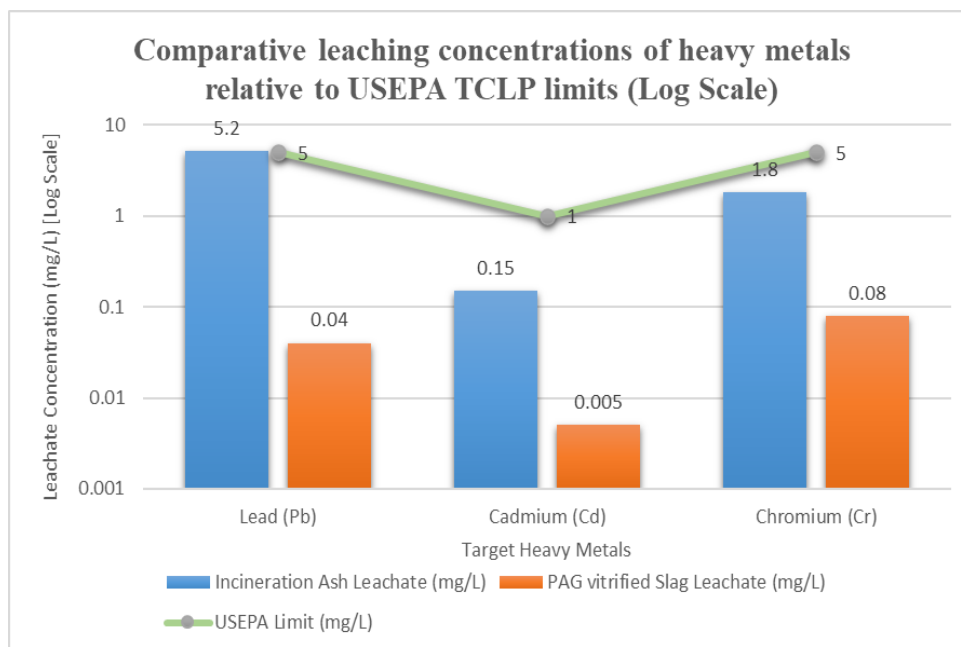


Fig 4.3: Comparative leaching conc of heavy metals relative to USEPA TCLP Limits (Log Scale)

4.3.1 Lead (Pb) Regulatory Non-Compliance

The most prominent finding shown in Figure 4.3 is the concentration of Lead (Pb) in untreated incineration ash. The bar representing Pb concentration in the ash leachate exceeds the USEPA regulatory threshold of 5.0 mg/L specified under USEPA Method 1311. This concentration also exceeds the limit commonly associated with hazardous waste classification under environmental regulatory frameworks. This finding is significant from both regulatory and planning perspectives because it directly influences how the residue must be managed. Exceeding the 5.0 mg/L TCLP limit may restrict disposal options and necessitate handling under more stringent environmental controls, potentially increasing disposal and treatment costs. The elevated concentration of Pb in untreated incineration ash indicates that conventional grate-based incineration does not fully eliminate the toxicity concerns associated with the original waste stream. Instead, hazardous constituents may remain concentrated within the residual ash fraction, creating an additional environmental management challenge. From an urban waste governance perspective, the Pb non-compliance observed in incineration ash suggests that traditional incineration should be

viewed primarily as a volume-reduction technology rather than a complete solution to residue toxicity. The findings highlight the importance of post-treatment technologies capable of stabilizing or immobilizing heavy metals rather than merely transferring them from one waste phase to another.

4.3.2 Logarithmic Magnitude of Stabilization

Figure 4.3 illustrates that the improvement associated with PAG vitrification is substantial when viewed on a logarithmic scale. The PAG vitrified slag is not merely cleaner than untreated ash; the reported Pb concentration in the slag leachate (0.04 mg/L) is more than two orders of magnitude lower than the concentration reported for incineration ash and remains well below the regulatory threshold. This significant reduction in leachability may be attributed to the immobilization of heavy metals within the vitrified matrix. In untreated incineration ash, metals such as Pb, Cd, and Cr are often associated with particle surfaces, soluble salts, or weakly bound mineral phases. These forms generally exhibit higher mobility under acidic conditions similar to those simulated during TCLP testing. Consequently, metals may be more readily released into the leachate, particularly in landfill environments where organic acids are present.

In contrast, plasma vitrification produces a dense amorphous glass-ceramic matrix. At elevated temperatures, metallic species may become incorporated into the silicate structure rather than remaining as loosely attached surface contaminants. Such incorporation can reduce metal solubility and limit the potential for leaching even when the slag is subjected to crushing, compaction, or prolonged environmental exposure. The logarithmic comparison presented in Figure 4.3 therefore provides strong evidence of the environmental benefits associated with plasma vitrification. The compiled data suggest that the process not only reduces leachable contaminant concentrations but also converts the residue into a more stable and environmentally acceptable material.

4.3.3 Multi- Metal Safety Margins

Although the Lead (Pb) results are the most prominent, the logarithmic-scale data for Cadmium (Cd) and Chromium (Cr) presented in Figure 4.3 indicate similar trends. The reported Cd concentration in the slag leachate is approximately 0.005 mg/L, which is substantially below the TCLP regulatory limit of 1.0 mg/L. Likewise, the reported Chromium concentrations remain well below the applicable regulatory threshold. The

observed multi-metal safety profile suggests that the vitrification process is not limited to the stabilization of a single contaminant. Instead, the data indicate a broader immobilization effect across different metallic species.

Despite variations in MSW composition arising from batteries, electronic waste, industrial residues, packaging materials, and other sources, the vitrification process consistently produces a high-silica amorphous matrix capable of reducing the mobility of multiple heavy metals. The environmental results, when considered alongside the chemical and physical characterization findings, indicate that PAG technology has significant potential for reducing the environmental risks associated with WtE residues. The vitrification pathway converts a residue that may require careful environmental management into a material that demonstrates substantially improved leaching performance and potential suitability for beneficial reuse in construction applications.

4.4 Stabilization Efficacy and Immobilization Efficiency

Raw leaching concentrations provide a direct measure of regulatory compliance; however, Immobilization Efficiency (IE%) offers a quantitative and normalized measure of a technology's ability to stabilize and immobilize toxic species within the residue matrix. IE% enables a more rigorous comparison between different heavy metals and treatment conditions, providing insight into how effectively PAG vitrified slag immobilizes metals that would otherwise remain mobile in conventional incineration ash.

In particular, the stabilization performance of the plasma-derived matrix is evaluated in terms of its ability to reduce the leachability of heavy metals relative to untreated MSW incineration ash. The concept of IE% is based on comparing the concentration of a given metal in the treated slag leachate with the concentration of the same metal in untreated ash leachate under identical TCLP conditions. This comparison provides an indication of the fraction of the pollutant that remains immobilized within the vitrified matrix rather than being released into the surrounding environment. Consequently, IE% serves as a useful indicator of the effectiveness and consistency of the vitrification process in reducing heavy metal mobility.

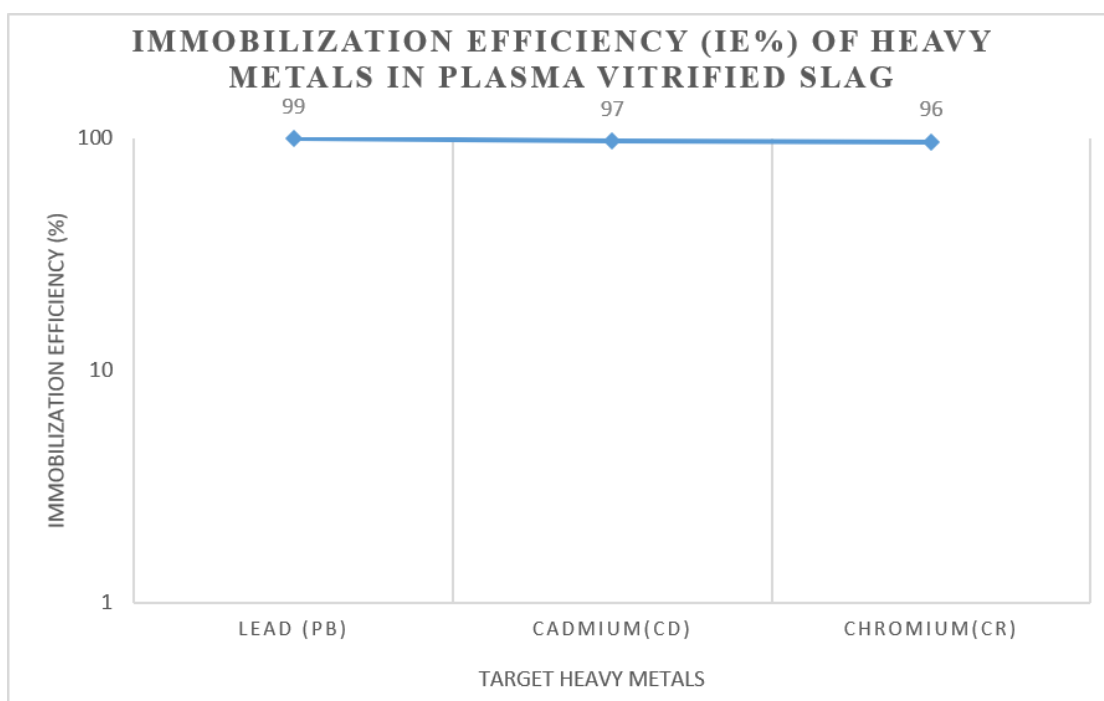


Fig 4.4: Immobilization efficiency (IE%) of heavy metals in PAG vitrified slag

4.4.1 The “Stabilization Plateau” and Process Reliability

The line graph presented in Figure 4.4 indicates a high degree of consistency in the stabilization performance of the PAG system across the three heavy metals examined. A notable feature of the graph is the "Stabilization Plateau", represented by a near-horizontal trend at the upper end of the chart where all three metals exhibit IE% values greater than 95%. This pattern suggests that the vitrification process provides a consistently high level of immobilization across different metallic species, despite differences in their chemical properties and volatility. An IE% value above 90% is generally considered indicative of effective stabilization, reflecting a substantial reduction in environmental risk associated with the targeted contaminants.

The compiled data indicate an average IE% of 97.15%, which is considerably higher than this benchmark and demonstrates the strong stabilization performance associated with PAG-based vitrification. This consistency contrasts with conventional incineration systems, where metal stabilization may vary depending on operating temperature, airflow conditions, and combustion efficiency. Variations in metal oxidation states, volatilization behaviour, and distribution within the ash can influence long-term leaching characteristics. In comparison, the relatively flat trend observed in Figure 4.4 suggests that plasma vitrification provides a

stable treatment environment capable of producing a consistent glass-ceramic matrix across a range of operating conditions. The resulting silicate glass matrix serves as a stable host for metallic species with varying chemical characteristics. This observation suggests that vitrification may be relatively tolerant to variations in feedstock composition, an important consideration given the substantial seasonal, regional, and socio-economic variations in MSW composition across Indian cities.

4.4.2 Peak Sequestration of Lead (Pb)

The highest Immobilization Efficiency recorded in Figure 4.4 corresponds to Lead (Pb), with an IE% value of 99.23%. This result is particularly significant because Pb is widely regarded as one of the most environmentally sensitive heavy metals present in municipal solid waste streams due to its occurrence in batteries, paints, electronic components, and other consumer products. In addition, Pb is subject to stringent regulatory limits because of its mobility and toxicity under leaching conditions. The position of Pb at the upper end of the IE% trend line suggests a strong degree of stabilization within the vitrified matrix. Published studies indicate that Pb^{2+} ions may exhibit a high affinity for amorphous silicate networks formed during vitrification. During cooling of the molten slag, lead species may become incorporated into the glass structure either as network-modifying ions or as constituents occupying interstitial positions within the silicate matrix. Such incorporation reduces the proportion of lead present as soluble salts or loosely bound surface species, which are typically responsible for elevated leaching behaviour in untreated incineration ash.

The reported IE% value of 99.23% indicates that only a very small fraction of the original lead remains leachable following vitrification. This finding suggests that the vitrified slag possesses a high degree of environmental stability when considered for applications such as road sub-bases and construction aggregates. Even under conditions involving crushing, abrasion, and compaction, the strong incorporation of Pb within the glass-ceramic matrix may substantially reduce the likelihood of contaminant release to surrounding soil and groundwater.

4.4.3 Comparative Immobilization Performance of Heavy Metals

Figure 4.4 also permits a comparative assessment of the stabilization efficiencies

achieved for Pb, Cd, and Cr. Although all three metals exhibit high immobilization performance, slight differences are evident. Cadmium (Cd) records an IE% value of 96.67%, while Chromium (Cr) records an IE% value of 95.56%. Although these values are marginally lower than that of Pb, they remain well above the commonly accepted 90% benchmark for effective stabilization. The observed differences in IE% may be related to variations in ionic radius, oxidation state, and coordination behaviour among the metallic species. Cadmium is known to form relatively soluble chloride and sulphate complexes under certain conditions and may exhibit a greater tendency for surface adsorption. Chromium, meanwhile, can exist in multiple oxidation states, particularly Cr^{3+} and Cr^{6+} , with the latter generally being more mobile and environmentally hazardous. The achievement of an IE% exceeding 95% for Cr suggests that vitrification remains highly effective even for metals exhibiting more complex chemical behaviour.

The comparative results indicate that PAG vitrification is capable of stabilizing a broad range of metallic contaminants rather than targeting a single element. Despite variations in feedstock composition arising from batteries, electronic waste, industrial residues, and mixed municipal waste components, the resulting vitrified slag consistently demonstrates high immobilization efficiencies across multiple heavy metals. These findings support the potential of PAG-based vitrification as a versatile stabilization technology capable of reducing the environmental risks associated with heterogeneous urban waste streams while simultaneously producing a reusable construction material.

4.5 Mechanical, Integrity and IS Code Compliance

Mechanical characterization of PAG vitrified slag is the ultimate assessment of its suitability as a construction material. While environmental safety confirms that the residue is chemically stable and non-hazardous, mechanical integrity determines whether the material can withstand cyclic loading, repeated impact, and abrasive forces encountered in real-world civil engineering applications. Figure 4.5 compares the key mechanical properties of the residues, including compressive strength, Los Angeles (LA) Abrasion Value, 10% Fines Value, and Flakiness Index, against the requirements specified under IS 383:2016 for coarse aggregates used in road and structural applications.

4.5.1 Structural Load- Bearing Capacity (Compressive Strength)

The compressive strength of PAG vitrified slag (14.5 MPa) is nearly six times greater

than that of untreated incineration ash (2.4 MPa), as illustrated in Figure 4.5(a). This substantial increase demonstrates the transformation of a weak and brittle residue into a load-bearing construction material. Under IS 383:2016, the compressive strength required for most structural and road-base applications is approximately 5.0 MPa. The incineration ash, with a strength of only 2.4 MPa, fails to satisfy this minimum requirement and is therefore limited to non-load-bearing applications such as lightweight fill, temporary embankments, and low-traffic layers.

In contrast, the compressive strength of PAG vitrified slag significantly exceeds the required limit, indicating its suitability for road sub-bases, masonry units, and other load-bearing applications. This improvement can be attributed to the densification and vitrification mechanisms discussed in Section 4.1. The high temperatures involved in the plasma process eliminate internal pores and residual organic matter while forming a continuous glass-ceramic structure. As a result, the slag can resist compressive stresses more effectively than conventional incineration ash, which tends to fracture due to its porous and heterogeneous structure.

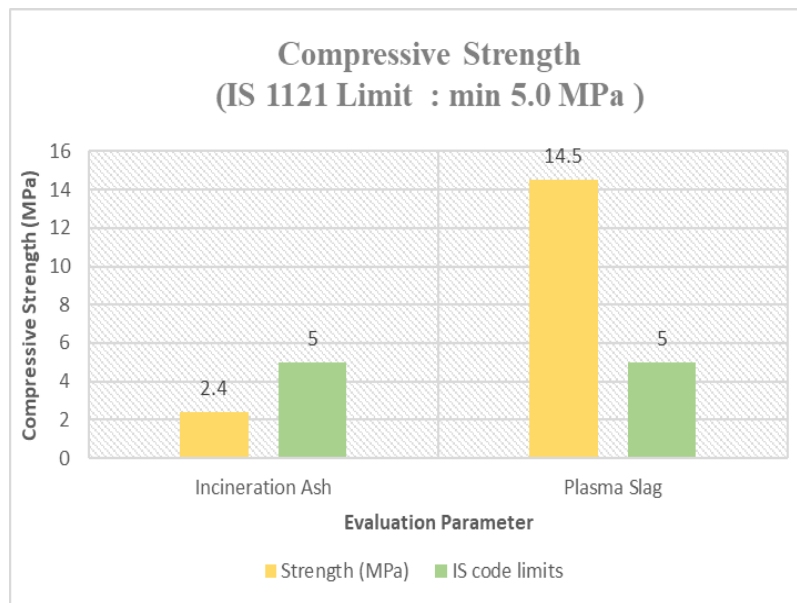


Fig. 4.5.1: Comparative Compressive Strength of Incineration Ash and PAG Vitrified Slag

4.5.2 Surface Durability and Wear Resistance (LA Abrasion)

The Los Angeles (LA) Abrasion Value presented in Figure 4.5(b) is an important indicator of aggregate durability under traffic loading and surface wear. The test measures

the percentage loss in mass caused by abrasion and impact, thereby simulating the degradation experienced by aggregates during service conditions. IS 383 generally specifies a maximum LA Abrasion Value of 30.0% for aggregates used in road surfacing applications. The incineration ash exhibits an LA Abrasion Value of 48.5%, indicating poor resistance to wear and fragmentation. This value substantially exceeds the permissible limit and suggests that the material would rapidly deteriorate under traffic loading, resulting in particle breakdown, dust generation, and reduced pavement performance.

In contrast, PAG vitrified slag records an LA Abrasion Value of 21.2%, which is comfortably below the IS 383 limit. The dense glass-ceramic structure formed during vitrification provides enhanced resistance to abrasion and surface wear. The result demonstrates that the slag possesses durability characteristics comparable to those of conventional aggregates commonly used in road construction and is capable of withstanding repeated traffic-induced stresses.

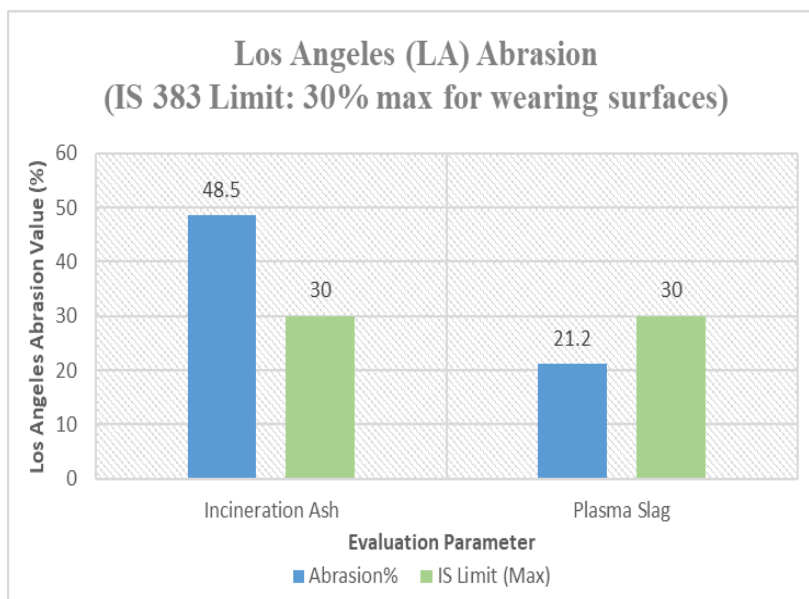


Fig. 4.5.2: Comparative Los Angeles Abrasion Values of Incineration Ash and PAG Vitrified Slag

453 Resistance to Crushing (10% Fines Value)

Figure 4.5(c) presents the 10% Fines Value, a key indicator of aggregate resistance to crushing under compressive loading. The test determines the force required to produce 10% fines from the original aggregate sample and is widely used to evaluate aggregate

performance in road bases and sub-bases. Aggregates intended for such applications are generally expected to achieve values of 50.0 kN or greater under IS 383 guidelines. The incineration ash exhibits a relatively low 10% Fines Value of 32.0 kN, indicating poor resistance to crushing and a greater tendency toward particle degradation under loading conditions. Such behaviour may contribute to increased void formation, settlement, and long-term instability in pavement structures.

Conversely, PAG vitrified slag demonstrates a 10% Fines Value of 115.0 kN, which is more than twice the recommended minimum requirement. This exceptionally high value indicates excellent crushing resistance and confirms that the slag can retain its structural integrity under heavy traffic loading and compaction. The result further supports the suitability of vitrified slag for use in high-stress pavement layers and other infrastructure applications requiring durable aggregate materials.

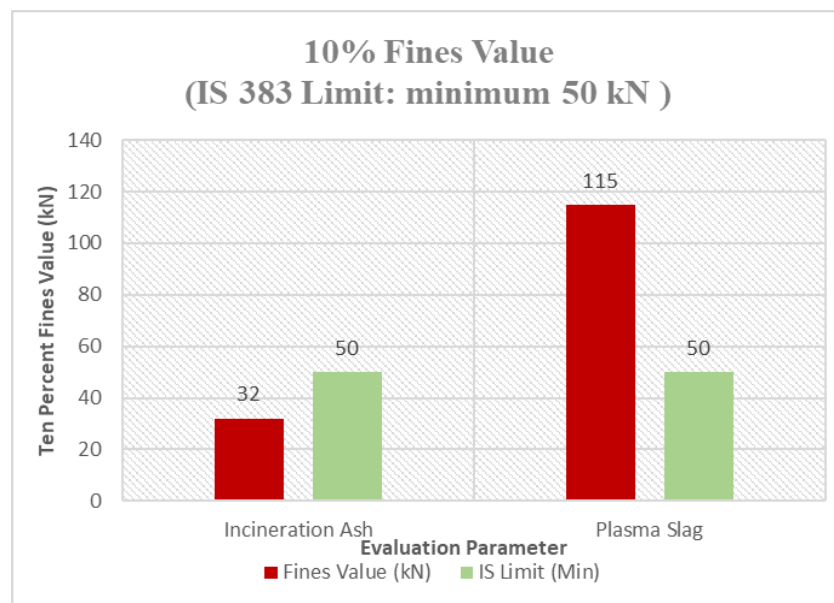


Fig. 4.5.3: Comparative 10% Fines Values of Incineration Ash and PAG Vitrified Slag

4.5.4 Particle Shape Characteristics (Flakiness Index)

The Flakiness Index shown in Figure 4.5(d) evaluates the shape characteristics of aggregate particles, which directly influence packing density, interlocking behaviour, and construction performance. In civil engineering applications, excessively flat or elongated particles are generally undesirable because they are more susceptible to breakage under loading and may reduce the stability of aggregate layers. IS 383 limits the combined

flakiness and elongation index of coarse aggregates to below 35.0%. The PAG vitrified slag exhibits a Flakiness Index of 12.4%, compared with 18.5% for incineration ash, with both values remaining below the prescribed limit.

The relatively low flakiness of the slag suggests a favourable particle shape distribution that promotes improved interlocking and packing efficiency within compacted layers. This favourable morphology is likely related to the solidification and subsequent crushing behaviour of the vitrified material, which tends to generate angular and relatively equidimensional particles. Such particle shapes enhance internal friction and shear resistance within pavement layers, contributing to improved structural stability. The low flakiness, combined with the high strength and durability characteristics observed in previous tests, further supports the use of PAG vitrified slag as a viable substitute for natural coarse aggregates in road and infrastructure construction.

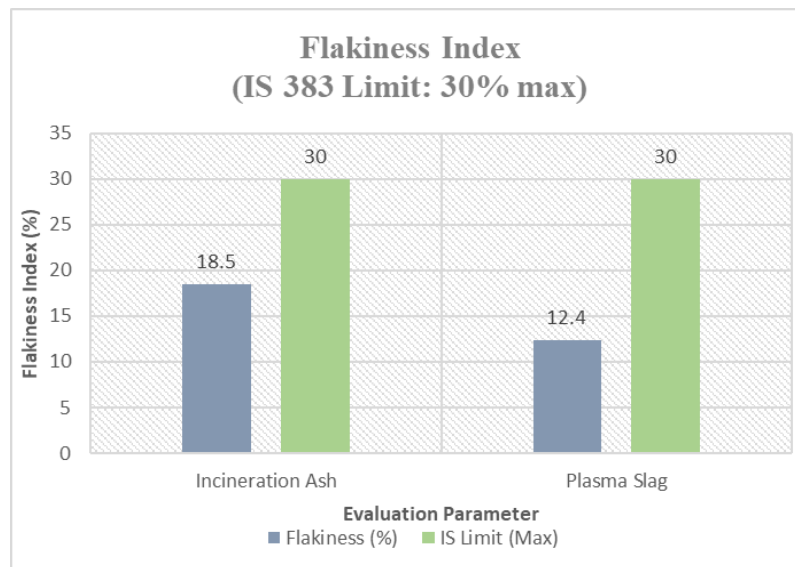


Fig. 4.5.4: Comparative Flakiness Index of Incineration Ash and PAG Vitrified Slag

CHAPTER 5:

CONCLUSION, FUTURE SCOPE AND SOCIAL IMPACT

5.1 Synthesis of Research Findings

This study presents a systematic comparative assessment of Plasma Arc Gasification (PAG) as an alternative Waste-to-Energy (WtE) technology to conventional incineration systems within the Indian context. The analysis addresses the growing challenge of residue management faced by Urban Local Bodies (ULBs) by synthesizing physicochemical, environmental, and mechanical data obtained from credible scholarly and technical sources. The findings indicate that PAG represents not merely an incremental improvement in thermal treatment technology but a fundamental shift in the manner in which municipal solid waste residues are managed and utilized. Rather than producing a residue requiring long-term disposal, the process generates a stable and potentially valuable construction material. Based on the comparative assessment of MSW incineration ash and PAG vitrified slag, the following key findings are summarized.

5.1.1 Physicochemical Stabilization

The transformation of conventional incineration ash into vitrified slag represents a significant mineralogical and structural reorganization of the residue. The reviewed data indicate that the high temperatures generated during plasma treatment result in exceptionally efficient destruction of organic matter, producing a Loss on Ignition (LOI) value of approximately 0.5% compared to 15.6% in untreated incineration ash. Such a substantial reduction in LOI signifies the near-complete elimination of unburnt carbon, volatile compounds, and residual organic matter that may otherwise contribute to long-term instability. The reduction of volatile constituents is particularly important from an engineering perspective, as it minimizes the potential for microbial degradation, gas generation, internal expansion, and chemical reactivity during service life. Consequently, the resulting material demonstrates greater dimensional stability and predictability under field conditions.

Furthermore, the analysis indicates that vitrification strengthens the silicate network of the residue, resulting in a Glass Content Index (G%) of approximately 80.7%.

The vitrified slag therefore consists predominantly of an amorphous glass-ceramic structure rather than the heterogeneous crystalline phases commonly observed in incineration ash. This dense and chemically stable matrix exhibits improved resistance to weathering, moisture ingress, and environmental degradation, making it suitable for long-term applications in road sub-bases, embankments, masonry units, and other civil engineering works.

5.1.2 Environmental Safety and Toxicological Sequestration

One of the most significant findings of the study is the environmental non-compliance associated with untreated incineration ash. The Lead (Pb) concentration in the TCLP leachate of raw ash was reported as 5.20 mg/L, exceeding the 5.0 mg/L threshold established under USEPA Method 1311. This indicates that untreated ash may be classified as hazardous or semi-hazardous waste and therefore presents considerable challenges for disposal and reuse. Such findings highlight the environmental risks associated with conventional incineration residues, particularly when they are landfilled or utilized without adequate stabilization measures. Heavy metal mobility under acidic conditions can lead to groundwater contamination, soil degradation, and increased long-term environmental liabilities.

In contrast, PAG vitrified slag demonstrated an Immobilization Efficiency (IE%) of 99.23% for Lead, while similarly high immobilization efficiencies were observed for Cadmium (Cd) and Chromium (Cr). The analysis suggests that vitrification achieves stabilization not merely through physical encapsulation but through chemical incorporation of metallic ions within the amorphous silicate structure. As a result, heavy metals remain strongly bound within the glass-ceramic matrix and exhibit extremely low leaching potential even under aggressive TCLP conditions. These findings demonstrate that plasma vitrification can effectively transform a potentially hazardous residue into an environmentally safe material suitable for reuse in civil engineering applications. Such transformation significantly reduces the environmental burden associated with municipal waste disposal and supports sustainable residue management practices.

5.1.3 Mechanical Performance and Resource Valorization

The mechanical assessment further demonstrates the suitability of PAG vitrified slag as a replacement for natural coarse aggregates in selected construction applications. The compressive strength of vitrified slag was found to be 14.5 MPa, approximately six times greater than that of untreated incineration ash. Similarly, the Los Angeles Abrasion Value of 21.2% satisfies the requirements of IS 383:2016 for aggregates used in road and structural applications. The vitrified slag also exhibited a Flakiness Index of 12.4%, indicating a favourable particle shape distribution with improved interlocking characteristics. In addition, the exceptionally high 10% Fines Value reflects strong resistance to crushing and particle degradation under repeated loading conditions.

Collectively, these properties demonstrate that the vitrified slag possesses the strength, durability, and dimensional stability required for use in road sub-bases, embankments, pavement layers, and other infrastructure applications. The ability to substitute natural aggregates with a recycled synthetic material also provides an opportunity to reduce dependence on quarrying and riverbed mining, thereby conserving natural resources while simultaneously addressing waste management challenges. This dual benefit represents one of the most significant advantages of PAG-based residue valorization.

5.2 Final Conclusions

The findings of this study indicate that although conventional mass-burn incineration can reduce the volume of municipal solid waste by approximately 70-80%, it does not adequately address the environmental and engineering concerns associated with the resulting residues. High LOI values, variable mineralogical composition, poor mechanical performance, and elevated heavy metal leaching characteristics continue to limit the beneficial utilization of incineration ash. Consequently, the waste management challenge is not entirely eliminated but is instead transferred to residue handling, treatment, and disposal systems.

Plasma Arc Gasification (PAG), by comparison, emerges as a near-zero-waste treatment technology capable of simultaneously reducing waste volume and producing a valuable secondary resource. The vitrification process converts hazardous residues into a dense, chemically stable, and mechanically durable aggregate that satisfies relevant engineering and environmental requirements. Rather than generating a disposal liability, PAG produces a material

that can potentially be incorporated into infrastructure development projects. The significance of this transformation extends beyond waste management alone. India currently faces increasing pressure on natural aggregate resources due to rapid urbanization and infrastructure expansion. The utilization of vitrified slag as a substitute for conventional aggregates offers a practical pathway toward resource conservation while reducing the environmental impacts associated with quarrying and landfill disposal. The findings therefore support the broader objectives of sustainable development and circular economy implementation. By enabling waste-derived materials to re-enter productive use cycles, PAG contributes to resource efficiency, environmental protection, and long-term infrastructure sustainability. The results suggest that wider adoption of PAG-based WtE systems could play a meaningful role in future urban waste management strategies and infrastructure planning within India.

5.3 Future Scope

To expand upon the findings of this study and facilitate the large-scale implementation of PAG-based residue valorization, the following areas are recommended for future research:

- **Life Cycle Cost Analysis (LCCA)**

A comprehensive Life Cycle Cost Analysis (LCCA) should be undertaken to evaluate the long-term economic viability of PAG-based Waste-to-Energy systems. Future studies should compare the higher capital and operational costs associated with plasma facilities against the long-term benefits arising from reduced hazardous waste disposal requirements, lower transportation costs, and decreased dependence on natural aggregate resources.

- **Long-term Weathering Experiment**

Future experimental investigations should evaluate the long-term durability and leaching behaviour of PAG slag incorporated into concrete and asphalt mixtures under realistic environmental conditions. Accelerated weathering tests involving simulated acidic rainfall, wet-dry cycles, and other environmental exposure conditions would help verify the long-term stability of the vitrified matrix and its suitability for infrastructure applications with extended service lives.

- **Multi Waste Co Vitrification**

Future research may explore the technical and economic feasibility of co-vitrifying MSW

residues with other industrial and hazardous waste streams such as electronic waste, industrial sludge, and contaminated soils. Such studies may help improve the operational efficiency of plasma facilities while enabling the stabilization of a broader range of contaminants. However, detailed environmental and mechanical evaluations would be necessary to ensure that the resulting vitrified products remain safe and suitable for construction applications.

5.4 Social Impact

This study has important social implications because it addresses two interconnected urban challenges at once: the safe management of hazardous incineration ash and the growing shortage of construction aggregates. By showing that plasma vitrification can convert a problematic waste residue into a stable and usable material, the study supports safer waste disposal, reduced environmental exposure to toxic leachates, and improved public health protection in densely populated Indian cities. It also offers a practical pathway for reducing dependence on river sand and quarried stone, which are often linked to ecological damage, land degradation, and resource depletion. In addition, the reuse of treated residues in road sub-bases and other construction applications can lower landfill burden, encourage circular economy practices, and create opportunities for more sustainable urban infrastructure development. Overall, the study contributes to a cleaner, safer, and more resource-efficient waste management system that benefits both communities and the environment.

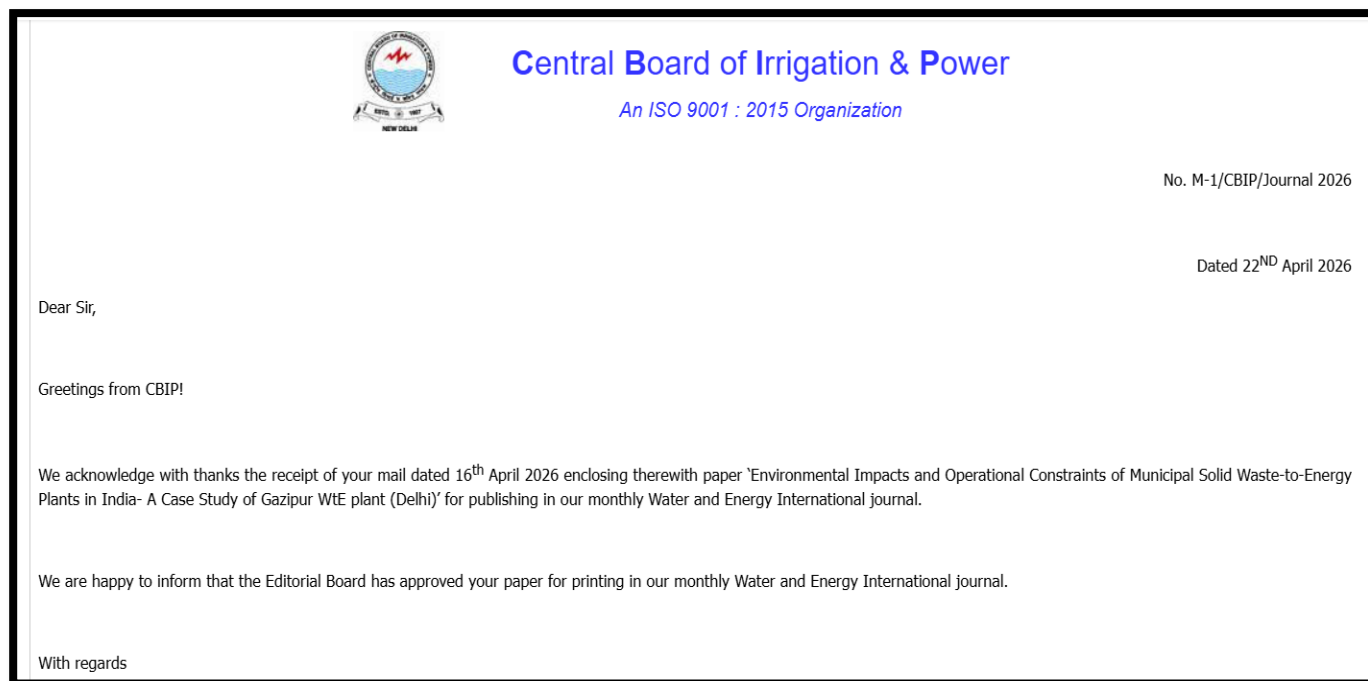
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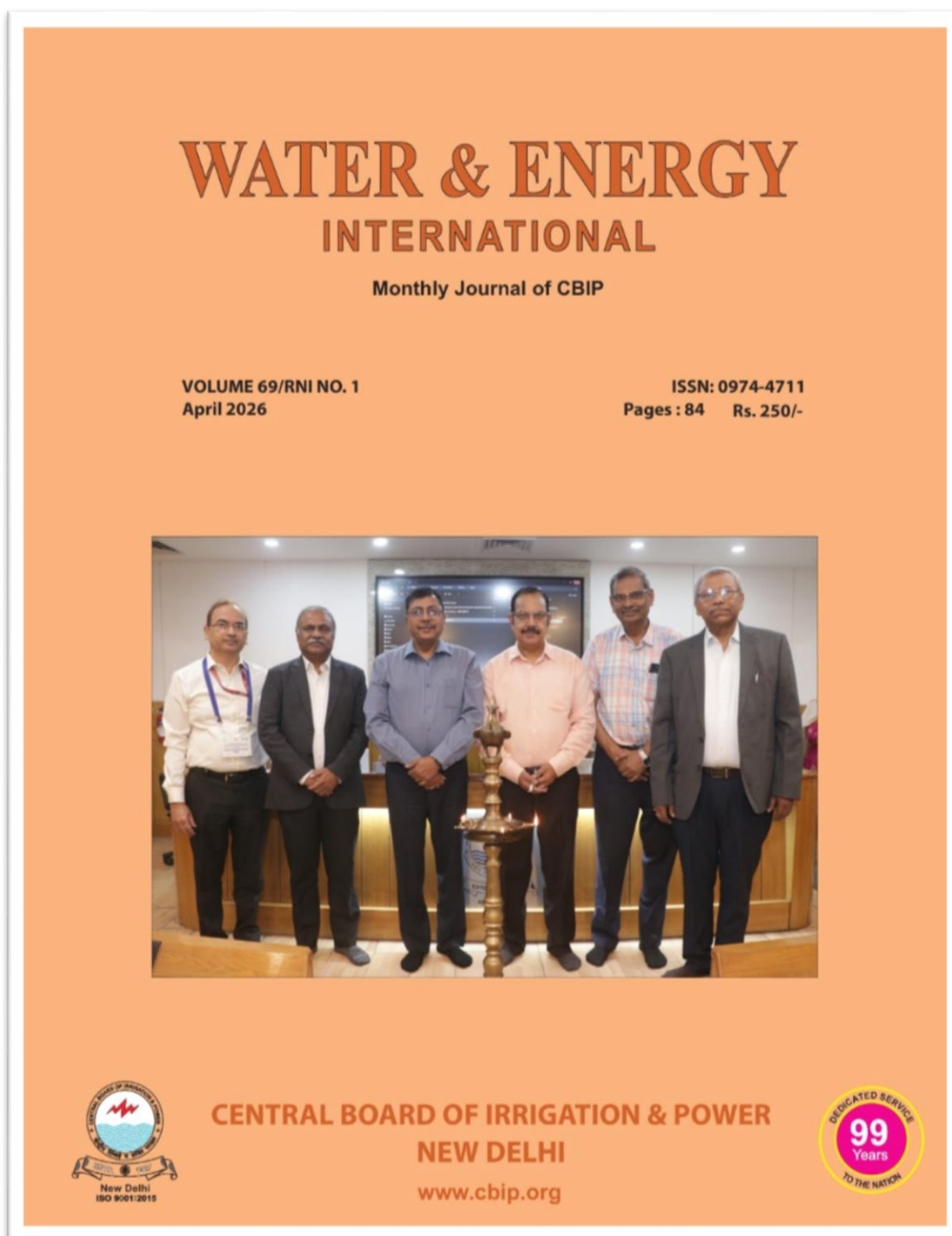
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LIST OF PUBLICATION AND THEIR PROOFS

1. Email of paper acceptance by CBIP dated on 22nd April,2026



2. Cover Page and Published Paper of Research in Water & Energy International Journal (CBIP)



Environmental Impacts and Operational Constraints of Municipal Solid Waste-to-Energy Plants in India- A Case Study of Gazipur WtE Plant (Delhi)

RITIKA GUNAWAT¹DR. GEETA SINGH²DR. RAJESH KUMAR ARORA³

ABSTRACT

Municipal solid waste management has become a critical environmental and infrastructural challenge for rapidly growing urban centres in India. Waste-to-Energy (WtE) technologies are increasingly promoted as an integrated solution to reduce landfill dependency while simultaneously enabling energy recovery from municipal waste streams. However, operational evidence suggests that several WtE facilities in India continue to operate below their designed capacity and encounter environmental and operational constraints.

This study examines the environmental implications and operational limitations associated with WtE plants through an assessment of technical, economic, and institutional parameters. The analysis, based on secondary data sources and selected urban case studies, indicates that the physicochemical properties of Indian municipal waste—particularly high moisture levels, heterogeneous composition, and comparatively low calorific value—significantly influence combustion performance and may elevate emission-related risks.

Economic considerations, including substantial capital investment requirements and relatively weak power purchase agreements, also affect the financial feasibility of WtE projects. In addition, institutional challenges such as insufficient waste segregation at source and fragmented governance frameworks further constrain plant performance and operational efficiency.

The study emphasizes the importance of integrated technological and policy interventions to enhance the environmental sustainability and operational effectiveness of WtE facilities. Key measures include improved waste pre-processing and feedstock conditioning, deployment of advanced emission control technologies, and stricter enforcement of waste segregation and municipal solid waste management regulations. A case study of WtE Gazipur, Delhi with complete details is discussed in the paper.

Keywords: Municipal Solid Waste (MSW), Waste-to-Energy, Environmental Impact, Emission Control, Urban Waste Management

3. Proof of Scopus Indexing of Water and Energy International Journal (CBIP)



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Regards

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CERTIFICATE OF THESIS SUBMISSION FOR EVALUATION

1. Name: Ritika Gunawat
2. Roll No.: 24/ENE/11
3. Thesis Title: Comparative Evaluation of WTE Residue: Incineration Ash and PAG Vitriified Slag as Sustainable Construction Aggregates
4. Degree for which the thesis is submitted: Master of Technology
5. Faculty of the University to which thesis is submitted: Dr. Geeta Singh (Associate Professor, Department of Environmental Science and Engineering)
6. Thesis Preparation guide was referred to for the preparation of thesis. YES ☐ NO ☐
7. Specifications regarding thesis format have been closely followed. YES ☐ NO ☐
8. The content of the thesis have been organized based on the guidelines. YES ☐ NO ☐
9. The thesis has been prepared without resorting to Plagiarism. YES ☐ NO ☐
10. All sources used have been cited appropriately. YES ☐ NO ☐
11. The thesis has not been submitted elsewhere for a degree. YES ☐ NO ☐
12. Submitted 2 spiral bound copies plus one CD. YES ☐ NO ☐

(Signature of Candidate)

Name: Ritika Gunawat

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