

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

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

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In Partial Fulfillment of the Requirements for the
Degree of**

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**Ritika Gunawat
(24/ENE/11)**

Under the Supervision of

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**To the
Department Of Environmental Science and Engineering**

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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 Vittrified 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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RITIKA GUNAWAT

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. This creates a long-term waste-management and pollution challenge for urban local bodies, especially as landfill space shrinks and waste generation rises. 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 of this study is to compare incineration ash and PAG-vitrified slag across physicochemical, environmental, and mechanical parameters in order 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 the physicochemical composition, TCLP-based leaching behaviour, and mechanical performance of both incineration ash and PAG-vitrified slag. The analysis is based on commonly used regulatory references such as USEPA TCLP for leaching limits and Indian Standard IS 383:2016 and IS 2386 for aggregates. Key parameters include Loss on Ignition (LOI), glass content index (G%), Immobilization Efficiency (IE%) of heavy metals, compressive strength, Los Angeles (LA) abrasion value, 10% Fines Value, and flakiness index.

The results show that PAG-vitrified slag is chemically and mechanically superior to incineration

ash. The plasma process reduces LOI from about 15.6% in the incineration ash to 0.5% in the slag, indicating near-complete removal of unburnt carbon and organic matter. The G% rises to 80.7%, confirming a predominantly amorphous, glass-ceramic structure, while the silica and alumina content increase to levels comparable with high-quality volcanic rock. TCLP tests reveal that lead in the incineration ash (5.2 mg/L) exceeds the 5.0 mg/L limit, whereas PAG-vitrified slag lowers lead to 0.04 mg/L, with an IE% of 99.23% and similarly high IE% for cadmium and chromium. Mechanically, the slag shows a compressive strength of 14.5 MPa, an LA abrasion value of 21.2%, a 10% Fines Value of 115 kN, and a flakiness index of 12.4%, all within or above the IS 383 requirements for aggregates.

The study demonstrates that PAG-vitrified slag can be used as a structural construction aggregate, replacing natural river gravel and quarried stone in road sub-bases, embankments, and low-to-moderate-strength concrete elements. By converting a hazardous waste stream into a stable, inert material, the technology supports waste reduction, landfill diversion, resource valorization, and a circular economy approach under India's waste-management regulations, while also reducing dependence on natural aggregates.

For future work, the research recommends ²⁵life cycle cost analyses (LCCA) to evaluate the economic feasibility of PAG-based WtE systems, long-term field-scale leaching and weathering studies of slag-based concrete and pavements under Indian climatic conditions, and studies on multi-waste co-vitrification that combine incineration ash with industrial sludge or similar waste streams. These directions would strengthen the case for integrating PAG-vitrified slag into mainstream urban infrastructure planning.

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Lists of Symbols and Abbreviations

S. No	Symbol	Description
1.	G%	Glass Content Index (Vitrification Index)
2.	IE%	Immobilization Efficiency
3.	x	Element or mass fraction component

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

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CHAPTER I

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 number of middle-class income earners 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 disposal of materials collect, convey, and dump further exacerbates the ecological footprint of an already stressed urban ecosystems and at the same time exhaust 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 segregation of sources, dryness, and increased calorific value are more typical. The moisture content of urban MSW in Indian cities varies between 45-55% , biodegradable fraction between 50-60% , and a low NCV 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 without being sorted. Consequently, the feedstock received at thermal treatment plants is heterogeneous, wet and chemically unstable and this seriously restricts the efficiency of conventional mass burn incineration processes used in large scale plants like the Gazipur Waste to Energy plant in Delhi (MNRE, 2024). Although the reduction in volume of incoming MSW can be reduced up to 90% with incineration, it produces a by-product, the incineration bottom ash, which usually represents 20-25% of the original input material (Kumar et al., 2023). It is not merely a byproduct, 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 an Ignition Loss (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, and results 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 of hazardous waste classification (Sharma and Reddy, 2022; USEPA, 1992). Such amount of leachable Pb and higher mobility of other heavy metals like Cadmium (Cd) and Chromium (Cr) are a clear danger to the quality of groundwater and soil health when the ash is not effectively isolated and instead exposed to rainwater or surface run off (Saffarzadeh et al., 2011). This means that un-treated bottom ash cannot be directly used as a construction aggregate in their structural enhancement and has to undergo energy consuming stabilization, blending or controlled landfilling which adds to economic and environmental expenses (Poon & Lio, 1997).

With these limitations, there is an increased demand in the development of sophisticated thermal treatment methods that can both conserve energy in waste and convert the resulting solids into high performance, safe materials to the environment. Of all the new alternatives, the Plasma Arc Gasification (PAG) has turned out to be a very promising avenue. PAG operating at high temperature in between 3,000-10,000°C, involves electric arc plasma torch to propel dissociation of the waste stream at the molecular level beyond mere oxidation to decompose the complex organic molecules into high calorific syngas, which can be used to produce power or heat (Fabris et al., 2020). Meanwhile, the inorganic part of the waste is melted and quickly cooled to create a dense, vitreous slag of highly amorphous structure made up of silicate. Empirical analyses of PAG based WtE systems, such as pilot and commercial projects in India,

like the Timarpur Okhla facilities demonstrate that the process is able to reduce the Loss on Ignition to about 0.5% and at the same time achieve heavy metal immobilization efficiencies of over 97% (MNRE, 2024).

The formed slag has a compressive strength of 14.5 MPa, a Los Angeles abrasion and 10% fines values lie within the acceptable range as per Bureau of Indian Standards (BIS) IS 383 and IS 2386, which confirm its application as a coarse aggregate substitute in sub bases of the road and suchlike. 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 caloric waste streams, and reports of more than 99.9% of dioxins and related persistent organic pollutants abatement (Fabris et al., 2020). Through this PAG does not only enhances the energy recovery potential of MSW but also transforms a hazardous residue into a stable, nonhazardous and value-added substance, thus reducing the use of landfills and minimizing the operational footprint of the WtE sector.

It is on this basis that Solid Waste Management Rules 2026 offer a critical policy framework that promotes the transition from disposal-oriented thinking towards the resource-oriented approaches, focusing on minimization of waste, recycling and valorization of the by-products. These guidelines restrain residues that do not pass the standard leaching or structural tests to be directly used in the construction and infrastructure projects; cleaner, inert materials may be incorporated as part of construction work. This conversion is the direct focus of the current research, where comparative technical benchmarking of incineration bottom ash and PAG vitrified slag has been conducted through physicochemical, leaching, and mechanical assessments to determine their technical capability to be used 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 the 1.5 billion tonnes yearly natural aggregate demand in India, reduce pressure on the riverbeds and quarries, and facilitate the objectives of the circular economy in the urban WtE space. By so doing, the work will not only serve the applied engineering practice but the implementation of national policy, a way through which the transformation of the liability of urban waste can be realized into engineered resources to develop its infrastructure sustainably.

1.1 Background of the Study

The rapid increase in population in India has led to an urban crisis of waste management, and MSW production is projected to reach 165 million tonnes per year by 2030 (CPCB, 2025). The WtE industry relies greatly on mass-burn processing to maintain volume, and the resultant bottom ash remains a form of environmental nuisance. Plasma Arc Gasification (PAG), in its turn, uses the high temperatures (3,000-10,000°C) to break down atoms, and in the process, gathers energy as it combines inorganics to form long-lasting slag. This research is placed in this transformation, exploring the refurbishment of risky byproducts of incineration into viable construction products.

1.2 Problem Statement

Incineration in India produces bottom ash with 15.6% LOI, which is an indication of poor burn-off and instability. Pb has a leaching test reading of 5.2 mg/L, which is in violation of USEPA TCLP of 5.0 mg/L (Method 1311), and construction is erratic with strength bars. PAG is a more promising way forward, but India does not have adjacent data that compares local ash to PAG vitrified slag as specified in BIS IS 383/IS 2386. Without such measurements, residue reuse plans will not be scaled up, and will continue to depend heavily 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. Specific objectives include:

1. Assess the physicochemical changes and stability in WtE residues. This entails contrasting oxide profiles and Loss on Ignition (LOI) between untreated incineration bottom ash and plasma-vitrified slag, revealing the degree of organic elimination and structural solidification achieved.
2. Measure the heavy metal immobilization efficiency (IE%) from plasma vitrification. It examines how the slag's glass-ceramic structure captures toxins like Pb, Cd, and Cr, tested via Toxicity Characteristic Leaching Procedure (TCLP) under USEPA Method 1311.
3. Verify mechanical suitability of vitrified slag per Indian norms. Focus lies on compressive strength and abrasion resistance (LA value), aligned with BIS IS 383 and IS 2386, to confirm potential as natural aggregate replacements.
4. Gauge landfill avoidance tied to policy goals. Analyze how shifting ash to PAG vitrified slag meets Solid Waste Management Rules 2026 requirements, bolstering circular economy practices in India's building industry.

1.4 Research Questions

This study tackles these core inquiries on transforming WtE residues:

- In what ways does Plasma Arc Gasification (PAG)'s thermal regime enhance chemical phase stability and organic content reduction in MSW residues versus mass-burn incineration?
- How effectively does vitrification alter leaching behavior and heavy metal entrapment within the waste structure?
- Does PAG slag reliably meet mechanical and endurance criteria under Indian Standards (IS 383) for eco-friendly construction aggregates?
- What role can vitrification play in driving a circular economy for city waste, in line with India's regulatory framework?

1.5 Scope of the Study

This research narrows in on a technical side-by-side assessment of physical, chemical, and mechanical traits in residues from two key thermal waste treatments in India. For a sharp engineering lens, the study's limits are outlined below:

- **Material Focus:** Targets only coarse aggregates (4.75–20 mm particles) from MSW incineration bottom ash and PAG vitrified slag. Fine particles and fly ash stay out of mechanical tests to hone in on structural substitutes.
- **Technological Context:** The study evaluates residues representative of large-scale Indian operational contexts. 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.

1.6 Significance of the Study

This work provides quantitative data to reframe waste burdens as buildable goods. Proving PAG slag's 14.5 MPa compressive strength and leach-proof profile strengthens SWM Rules 2026 aims. It aims to tackle India's 1.5 billion-tonne aggregate shortfall yearly, safeguarding riverbeds and easing dumpsite loads—key for WtE sustainability (Verma et al., 2021; Fabris et al., 2020).

CHAPTER 2

LITERATURE REVIEW

The treatment of the products of Waste-to-Energy (WtE) facilities is a major issue in the environmental engineering field, especially in the context of the encouragement of the principles of the circular economy. As the cities in India contend with the growing volumes of waste, it is not the mere reduction of waste, but the best way to valorize these products, which has been of interest. Recent research tends to divide residues into products from the conventional incineration bottom ash and more advanced thermal products, such as PAG vitrified slag. Their environmental safety, as well as their possible structural uses, have been assessed consistently with the help of standardized procedures, such as the Toxicity Characteristic Leaching Procedure (TCLP) from the USEPA (Method 1311).

I. 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 and low calorific values are certain processing problems faced in India (CPCB, 2025). According to Kumar et al. (2023), the Indian WtE processes yield unburnt carbon and mineral compositions in the bottom ash, that gets varied due to the inconsistent feedstocks. In the same vein, Singh and Singh (2022) emphasized that the residues management process has surpassed the disposal stage and entered the essential stage of resource recovery by now, especially because now landfills in big cities have already reached the designated capacity.

II. Physicochemical Stability: Loss on Ignition (LOI)

The ability of the thermal process to stabilize WtE residues depends on the efficacy of the thermal process in which Loss on Ignition (LOI) represents a central indicator of unburnt organics and volatiles. The literature often mentions that high LOI in incineration bottom ash is a major hindrance to its application in construction. Zhang et al. (2021) claim that the higher the LOI in the residue, the lower the long-term durability of the material and the higher the porosity in the aggregate. Plasma Arc Gasification (PAG) on the other hand employs very high temperatures to make sure that all the organic material is eliminated. The radical research undertaken by Nema and Ganeshprasad (2002) at the Institute of Plasma Research established

the basis that the slag can be plasma-vitrified to achieve an LOI of less than 1 percent, which created a material that is not only chemically inert but also can be utilized in the needs of engineering.

III. Environmental Safety and Heavy Metal Leaching

In the list of environmental factors, the most important factor will always be the heavy metal leaching in the determination of WtE residues. Cadmium (Cd), Lead (Pb) and other mobile toxins in incineration bottom ash are typically present. According to the standards by the USEPA (1992) materials that have Pb above 5.0 mg/L is a hazardous material. Saffarzadeh et al. (2011) have discovered that untreated ash of municipal WtE sites has a high mobility of metals which may be attributed to the fact that, the crystalline silicate structure of such ash cannot fix ions.

Vitrification is a better way of immobilizing such metals. Dissociation of plasma occurs in a specific manner at the molecular level, which is not found in the case of ordinary incineration. Huang et al. (2020) showed that the resulting glass-ceramic matrix contains the metallic ions, which are chemically integrated into an amorphous silica backbone, rather than physically trapped. This gives a high Immobilization Efficiency (IE%) of more than 97% and the toxins would be retained by the durable silicate network even during acidic conditions as it would happen during TCLP testing.

IV. Mechanical Integrity and BIS Standards

Mechanical properties determine the suitability of residues to be used as construction aggregate, under the strict Bureau of Indian Standards (BIS) through the IS 383. Ash incinerated is usually ineffective in this case. Poon and Lio (1997) found that its porosity character makes it less compressive and more water absorbing making it not suitable in load bearing.

In comparison, the vitrified slag resembles the natural materials, including basalt. Vasconcelos et al. (2024) explained that the solidification of molten slag occurs rapidly to create a solid product that is dense. The compressive strengths measured up to 14.5 MPa in Indian plasma installation tests and match the requirements of the IS 383 of road sub-bases, and incineration ash needs additives or mixes to produce similar results.

2.1 Research Gap

After an intensive review of present literature, three major research gaps were discovered that

this thesis aims to address-

1. Even though most of the work presents incineration ash or plasma slag detail separately, there is a dearth of work to present direct technical comparisons within a single Indian engineering framework; There is a consistent lack of integrated assessments of the physicochemical stability, environmental safety and mechanical performance, unique to large-scale incineration versus those of commercial plasma vitrified slag as per Solid Waste Management Rules 2026.
2. Research papers treat landfill crisis and heavy annual requirement of aggregates as two separate issues when on the contrary both the problems can be solved simultaneously with the concept of circular economy within Indian regulatory framework.

CHAPTER NO 3

RESEARCH METHODOLOGY

This paper will conduct an unambiguous technical comparison of the main characteristics of MSW incineration bottom ash and PAG vitrified slag. It adopts an integrated strategy that connects the testing of materials with the environmental tests to ensure the results are reliable and can be repeated. The method is used to compare these residues with standard BIS and USEPA rules, providing solid numbers to use them as green construction materials (CPCB, 2025; MNRE, 2024).

3.1 Research Design

The study has a comparative experimental design. This makes us compare two different thermal products i.e. bottom ash from incineration and amorphous slag from PAG, under identical test conditions. It demonstrates the difference between regular and advanced waste treatments by adhering to three key areas (physicochemical, environmental, and mechanical). The research is dedicated to deductive logic: we begin with concepts of high-heat vitrification and apply them to the information about real Indian WtE plants (Kumar et al., 2023).

3.2 Data Synthesis and Material Identification

There are two large types of waste processing sources of materials. Incineration bottom ash is on par with mass-burn plants which process 1,500-2,000 TPD, burning waste at temperature 800-1,000°C such as Ghazipur Plant in Delhi. PAG vitrified slag burns waste at temperature of 3,000-10,000°C in commercial plasma plants output ranges from 50- 500 TPD.

3.3 Characterization Framework

The method has three parts to check if residues work for construction:

- **Chemical Characterization:** XRF checks oxide composition; standard LOI testing at 1,000°C measures organic matter and chemical stability of the residue.
- **Environmental Evaluation:** TCLP (USEPA Method 1311) tests heavy metal leaching like in landfills, to calculate vitrification's IE%.
- **Mechanical Testing:** Tests compression strength and LA abrasion for coarse aggregates, following IS 2386 and IS 383.

3.4 CHEMICAL Properties Testing (XRF and LOI)

Chemical analysis is the fundamental step towards determining how well the residues can perform as structural material over time. This section of the work examines the composition of oxides and the extent to which the organic matter is burned off. X ray Fluorescence (XRF) spectroscopy was used to identify the main oxide components, giving a clear “chemical fingerprint” of each residue. Simultaneously, the Loss on Ignition (LOI) test was conducted, by heating samples to 1,000°C in a muffle furnace and calculating the mass loss that remained, which represents the amount of unburnt organic matter and volatiles.

3.4.1 Role of Oxide Constitution and Vitrification

The engineering strength of a residue depends heavily on its oxide balance. Long term durability in material is attained by the presence of network forming oxides such as Silica (SiO₂) and Alumina (Al₂O₃). Whereas modifiers such as oxides like Calcium Oxide (CaO) and Magnesium Oxide (MgO), are used to reduce the melting temperature; but in excess they can also weaken the silicate network unless a balance is achieved.

The Glass Content Percentage (G%) has been calculated here to identify the level of material vitrified using formula:

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

The higher the G%, the more the material turns out to be amorphous and glass- like as residue which further translates to better resistance to weathering and high durability. The natural gravel used in high quality aggregates is typically the one with a G% range of 70-80%, which is used here as a pragmatic standard of evaluating the vitrified slag.

3.4.2 Technical Significance of Loss on Ignition (LOI)

LOI is one of the most important indicators of analyzing how efficient the thermal process is in destroying organic matter. A high LOI (15.6%) in incineration ash residue is an evidence of presence of unburnt carbon, moisture, and carbonates; it poses real engineering hazards:

- **Structural instability:** The organic components will cause long term instability in structure as slowly those components will deteriorate with time and miniature cracks and cavities will be formed in the compacted layers, depleting the load bearing capacity and promoting long term failure.
- **Chemical reactivity:** High LOI aggregates may be inclined to be "active" material i.e. they can react with cement hydrates or rain water leading to potential expansion, cracking or pH alteration which consequently affect the durability of roads and concrete works.

On the other hand, the plasma vitrified slag contained an LOI of around 0.5% showing that the PAG process is useful in practically completely destroying organic material and other volatile matter. This near zero value signifies that the slag is not only chemical stable but also inert and can be utilized for permanent use as structural material in construction without grave concerns of long-term corrosion.

Table 3.1: 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	10

3.5 PHYSICAL Properties Testing (Grain Size, Density, and Porosity)

The physical characterization provides important data about the performance of residue as construction aggregates, particularly regarding particle size, density and porosity. This part of the work uses Indian Standard procedures (IS 2386) of coarse aggregates, such as sieve analysis (particle size distribution), bulk density, specific gravity and water absorption tests, which are inextricably connected with the durability and load-bearing behavior [CPCB, 2025; IS 2386].

3.5.1 Particle Size Distribution and Gradation

Aggregate grading has a strong influence on the compaction, drainage and structural response of an aggregate. The sieve analysis was performed with the help of standard sieves (4.75 mm- 20 mm) according to the size fraction chosen in this work. The findings were compared to the allowable limits in the IS 383 of coarse aggregates in sub bases of roads and in concrete.

The incineration bottom ash tends to exhibit wider and less uniform gradation, with more percentage of finer particle that may lead to reduced drainage in roads and increased vulnerability to swelling- shrinkage cycles under wetting. PAG vitrified slag tends to be more uniformly graded, and with most particles ranging around 10-15 mm. This gradation enhances particle interlock and compactability and makes the slag more appropriate to use in sub base and masonry layers.

3.5.2 Density and Porosity Behavior

Water displacement and volumetric fill methods were used to determine the apparent specific gravity, bulk density, and water absorption to evaluate how tightly the particles can pack and to assess the void space in material. The apparent density of incineration ash tends to be lower and the open porosity is higher partly because of unburnt organics and micro cracks formed from unburned combustion. The comparatively large LOI (15.6%) and void spaces enable entry of comparatively more water and air, and may result in swelling, shrinkage or recurrent wetting-drying damage under the Indian urban conditions.

Conversely, the PAG vitrified slag has greater apparent density and a considerably lower porosity. The high temperatures of plasma vitrification cause internal pores to

collapse, and result in a dense, glossy surface, which allows the formation of a less permeable, more stable aggregate that can be used in load bearing applications like road sub bases and masonry units.

3.5.3 Compactability and Volume Stability

Wetting and loading conditions of the residues were also tested to assess their compactability and volume stability during construction of roads and foundations. The procedures of estimating the optimum moisture content and maximum dry density involved standard compaction type tests, per the procedures of IS 2386.

The heterogeneous composition of the incineration ash, which has greater LOI, tends to have greater volume changes when exposed to moisture, in part due to reactive fines and remaining organics. This may result in uneven settlement and cracking during traffic or seasonal rainfall. The low LOI (0.5%) and chemically stable, glass ceramic structure of the PAG slag exhibits much less volume change and more homogeneous compaction. This characteristic contributes to its greater reliability as material to be used in long term infrastructure projects in Indian cities.

3.5.4 Water Absorption and Porosity

Water absorption is of critical importance for the durability of an aggregate. High water absorption indicates an open-pore structure, which can lead to:

- **Freeze-Thaw Damage:** Water trapped in pores expands when frozen, causing the aggregate to shatter.
- **Binder Consumption:** In concrete or asphalt mixes, porous aggregates "soak up" expensive cement paste or bitumen, leading to increased project costs.

The IS 383 standard generally limits water absorption to **below 10%** for most construction applications. As shown in the data, the vitrified slag (0.8%) far outperforms the incineration ash (12.4%), confirming its status as an impermeable, high-performance material.

Table 3.2: Physical Characteristics and Standard Compliance

Property (Unit)	Incineration Ash	Plasma Slag	Natural Gravel	IS 383 Limit
Particle Size (D_{50} , mm)	0.85	4.20	12.50	> 4.75
Specific Gravity	1.95	2.68	2.72	2.6 – 2.8
Bulk Density (g/cm^3)	1.65	2.55	2.65	> 2.30
Water Absorption (%)	12.40	1.80	0.50	< 10.0

3.6 LEACHING SAFETY TESTING (TCLP and IE%)

The most important action towards determining the environmental risk associated with WtE residues is to assess the leaching safety. The synthesis of data in this study involved existing work that used the Toxicity Characteristic Leaching Procedure (TCLP) according to USEPA Method 1311. This technique model is based on the worst-case scenario of landfill, in which organic acids and rainwater may enhance the extraction of heavy metals into the adjacent groundwater, which gives a realistic but conservative assessment of the environmental effect [CPCB, 2025].

3.6.1 Heavy Metal Sequestration and Leaching Behavior

The main goal of this part of the evaluation is to compare the mobility of toxic metals—in particular 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 held in the porous phases in incineration bottom ash and are thus relatively readily leached under acidic environments [Saffarzadeh et al., 2011].

On the contrary, the residue is converted into a dense, glass ceramic matrix in the plasma vitrification process. The waste is dissociated at a high temperature to enable metallic ions to be chemically bonded to the amorphous silicate structure, rather than being trapped physically. This incorporation lowers the release of available metals, despite crushing of slag or a changing pH condition as often seen in Indian urban landfills [Huang et al., 2020; Fabris et al., 2020].

3.6.2 Calculation of Immobilization Efficiency (IE%)

(IE%) was calculated. This metric indicates what **percentage of heavy metals** have been effectively stabilized by vitrification of slag relative to the initial concentration in raw incineration ash. The equation used in this study is:

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

where

- C_{slag} = metal concentration in the 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 in this study consistently meets or exceeds this threshold, particularly for Pb [Kumar et al., 2023; Vasconcelos et al., 2024].

Table 3.3: 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)	5.20	0.04	5.0	99.23%
Cadmium (Cd)	0.15	0.005	1.0	96.67%
Chromium (Cr)	1.80	0.08	5.0	95.56%
Average IE%	—	—	—	97.15%

3.7 MECHANICAL Properties Testing

The last pillar of this research analyzes the structural readiness of the residues to be used in engineering activities. Each and every test was conducted in line with the requirements laid down in IS 2386 (Part IV) such that the obtained tests were directly compared with the aggregate quality requirements of IS 383:2016 of coarse aggregates in road and structural works.

3.7.1 Strength and Crushing Resistance

The load bearing capacity of the material was measured using compressive strength test. The ash produced by incineration is usually brittle and loosely bonded, and the particles are not strongly joined together. Conversely, the PAG vitrified slag forms a dense glass ceramic structure that is more capable of supporting heavy structural loads, which is more applicable as a road sub base, embankment, and masonry units.

The 10% Fines Value test as well was conducted in order to measure crushing resistance under constant pressure. This value is the force (in kilo Newtons, kN) needed to generate 10% fines of the starting coarse portion. The 10% Fines Value is higher which means that it is more resistant to degradation during compaction and under traffic. The IS 383 standard normally requires a minimum of approximately 50 kN of aggregates in road base layers, and the vitrified slag in this case is well above this requirement, whereas untreated incineration ash usually does not meet expectations.

3.7.2 Durability and Morphological Properties

The Abrasion Value was taken in Los Angeles (LA) to identify the resistance of the material to wear and tear of the surface during traffic and maintenance operations. In the case of aggregates to be applied to the road wearing surfaces, the IS 383 usually places a maximum of 30% abrasion loss; anything exceeding this would be deemed inappropriate to be used in the surfacing layers.

Flakiness Index was determined to describe the distribution of shape of the particles. A large percentage of flat or elongated particles (i.e. flaky or elongated aggregates) decreases workability in concrete and causes more splitting or cracking under load. IS 383 restricts flakiness and elongation index of coarse aggregates (combined) to less

than 35 percent to facilitate structural integrity when used in road and structural construction.

Table 3.4: 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

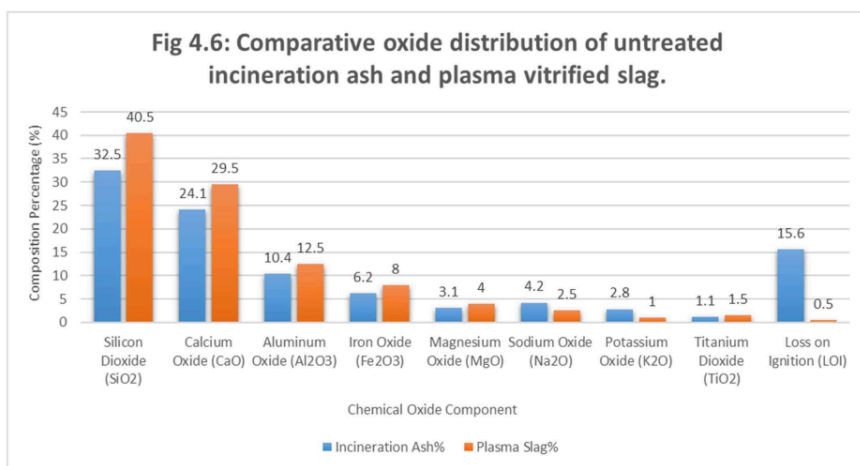
CHAPTER NO 4

RESULT & ANALYSIS

4.1 Chemical Transformation and Oxide Evolution

The transformation of a heterogeneous, unstable waste residue to a stabilized glass ceramic matrix is powered by the strong thermal gradients produced within the plasma reactor. Traditional mass burn incineration is usually carried out at a temperature range of 850-1000°C at which combustion is mainly oxidative with only partial combustion. Conversely, the plasma arc creates a local high temperature environment of ultra-high temperature to the extent of 3,000 °C, causing total molecular dissociation of the waste instead of mere burning. This high temperature allows the disintegration of complex organic compounds, incomplete combustion products, and reactive mineral phases into simpler, more stable inorganic compounds that can be re-constituted to a glass ceramic network.

Fig1: Comparative oxide distribution of untreated incineration ash and plasma vitrified slag



4.1.1 Analysis of Oxide Enrichment

The plasma process causes an apparent and uniform enrichment of network forming oxides, especially Silica (SiO_2) and Alumina (Al_2O_3) in the resulting slag as indicated in Figure 4.1. The oxide composition in untreated incineration ash is extremely unpredictable and irregular which is due to seasonal and source dependent characteristics of Indian Municipal Solid Waste (MSW). Such variability commonly leads to large amounts of fluxing agents (e.g. CaO , MgO), and volatile rich compounds, which are the cause of the chemical instability of the ash and its unpredictable behavior in the construction industry.

These components are however effectively consolidated and reorganized into a stable mineralogical profile by the vitrification process. The analytical data demonstrates that the Silica (SiO_2) content increases from a 32.5% value in raw incineration ash to a 40.5% value in PAG vitrified slag; that is a change both chemically and technically important. Materials silica is the main backbone of the silicate network, making up the continuous, three-dimensional structure that provides glass ceramic materials with durability and resistance to chemical attack. This network is further enhanced by the co-increase in the Alumina (Al_2O_3) which functions as a network forming or network stabilizing agent and increases the degree to which the silica tetrahedra cross link or the overall stability of the slag in a chemical sense.

This rearrangement implies that the plasma-based treatment has been successful in turning the chemical composition of mixed MSW into a material with composition akin to that of high-quality igneous rocks like basalt or volcanic glasses. These types of materials find application in the construction industry due to their strengths, low permeability, and long-term stability which means that the PAG slag is not just a byproduct but an intentionally created mineral phase with predictable and desirable characteristics.

4.1.2 Volatilization and Loss on Ignition (LOI) Reduction

A particularly notable finding from the chemical analysis is the significant decrease in the volatile fraction that is typically not detected or underestimated in raw incineration ash. The high Loss on Ignition (LOI) of incineration ash (around 15.6%) is mainly associated with the presence of unburned carbon, organic residues, and moisture that is

not easily removable 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, steam, and other gaseous products, by the high temperature of the plasma arc, whereas the inorganic part is melted into the molten slag phase. Therefore the PAG vitrified slag has a very low LOI – around 0.5%, which means that virtually no combustible and reactive organic matter is present. Environmentally, this near zero LOI is an important sign of a “clean” and inert residue, from an engineering perspective.

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, load bearing capacity and long term stability. However, the very low LOI of the PAG slag indicates that destruction of any organics is essentially complete and that the material is therefore like a chemically inert solid with no significant post placement reactions. This removes the possibility of post disposal reactivity, and makes the slag much safer and more predictable for use in infrastructure projects.

4.1.3 Vitrification and Glass Content Index (G%)

The concentration of Silica (SiO_2) was the predominant oxide in the slag, and the concentration of Calcium Oxide (CaO) and Magnesium Oxide (MgO) were clustered around it which allowed the calculation of Glass Content Index (G%), a useful parameter to indicate a degree of vitrification of the slag. The G% is defined as:

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

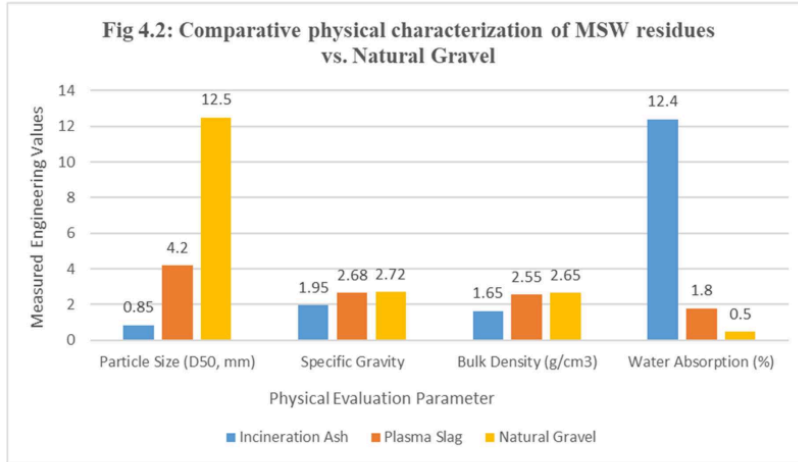
The results have revealed that the PAG vitrified slag has a G% value of 80.7% which means that it is mostly in the amorphous form and not a crystalline conglomerate.

Unlike incineration ash, which is crystalline and brittle, with a tendency to micro wet and micro crack, and to weather preferentially along planes, the "glassy" character of the slag ensures a continuous, non-crystalline structure that distributes stress more even and will be resistant to fracture. This amorphous phase is also responsible for the low permeability and low surface reactivity, which is why the slag has a superior mechanical performance and long term durability.

The chemical data thus provide evidence that PAG technology is not just a treatment or destruction process, but actually a reconstruction process of the mineralogical character of the residue, producing a new high performance mineral resource, suitable for reliable use as a construction aggregate. The SiO_2 content, the Al_2O_3 content, the low value of LOI and the high value of G% clearly indicate that plasma vitrification can produce a material that has a properties similar to, and in many aspects, superior to that of the natural aggregates obtained from conventional methods, thus promoting a shift from linear waste disposal to a circular one in the management of urban solid waste.

4.2 Comparative Physical Characterization

The physical characteristics of a waste residue material form the key engineering link between the process of "waste treatment" and "resource valorization". Although chemical composition dictates the safety and long-term stability of the material, physical properties like density, porosity, water absorption, and bulk density dictate the structural performance of the material in civil construction applications. Figure 4.2 shows clearly that there was a fundamental physical change in the residue due to the Plasma Arc Gasification (PAG) process which shows how the same initial waste can be transformed into two quite different construction materials.

Fig 2: Comparative physical characterization of MSW Residues vs Natural Gravel

4.2.1 Densification Mechanics and Specific Gravity Realism

Figure 4.2 indicates that there is a distinct “Densification Gap” between the incineration ash and the PAG vitrified slag, both when compared to Natural Gravel. The Specific Gravity of the slag is 2.68, very close to that of typical natural stone (2.72) which means that the vitrification process has virtually reached 100% densification of the residue. The near equality in specific gravity intimates that the internal structure of the slag is very similar to compact and natural occurring rock, and that there is little internal voids or air pocket.

This densification is obtained because at temperatures higher than 3000°C, the slag is in a low viscosity molten state, and in this state, the internal forces can work on the melt. In this way, gravitational and viscous flow mechanism cause the internal micro pores and capillary networks to collapse and most of the trapped air voids and micro fissures that were “frozen” in conventional incineration ash are removed. However, the incineration ash has a much lower Specific Gravity (1.95) which directly reflects the porous, fluffy and heterogeneous nature of the incineration ash. This porosity is the result of the relatively low temperatures used for processing the residues in grate fired incinerators (850-1000°C), which is not high enough to completely melt and homogenize the residue. This ash retains unreacted organic and inorganic phases

which are partially vitrified, and in which the air pockets are still present; making it structurally weaker and not suitable for load bearing applications.

The high specific gravity and dense structure of the slag are practical and almost a non-negotiable requirement for structural applications for practicing civil engineer. The material should be compact enough to not be deformed by heavy load, compaction and long-term loading. The behavior of the slag to that of natural stone density indicates that it is a suitable for heavy load bearing material like road embankments, sub bases and structural concrete, while the incineration ash is more suited for activities like light weight fill or low traffic application.

4.2.2 Pore Structure and Water Absorption Dynamics

A second general trend that can be seen in Figure 4.2 is that there is a negative correlation between density and water absorption. The incineration ash has a high water absorption of 12.4%, which means that the aggregate has a very open and interconnected pore structure, like a “sponge”, and will tend to absorb water from the environment. The other drawback of this high absorption, in the context of India's monsoon dominated climate, is that the construction material requires frequent and intensive exposure to rain, causing a large structural and economic loss.

It has been found that when the aggregates are porous like incineration ash, they consume a considerable amount of binder (bituminous mixes or cement paste) when used in the production of bituminous mixes or concrete. This “binder consumption” effect causes less binder to coat the particles and to create a good, continuous matrix and gives rise to under bonded, weak and brittle mixes. Further, the internal hydraulic pressure of the water entrained in the pores can form during the thermal cycles, which are repeated wetting and drying and heating and cooling, and eventually lead to surface stripping, cracking and spalling of pavements and concrete elements.

On the other hand, the PAG vitrified slag has only 1.8% water absorption which is below the upper limit of 10% for coarse aggregates in road and structural applications as laid down by IS 383. The low value verifies that the vitrification process was completed successfully and that the original open pore structure of the waste residue is collapsed and the surface of the particles is fully sealed, a highly permeable and water sensitive waste residue is converted into an impermeable, high performance synthetic aggregate. The compact structure of low absorption is able to

better resist damage caused by moisture affecting conditions, resulting in a more reliable use of infrastructure with the slag under monsoon affected conditions and increasing the service life.

4.2.3 Volumetric Packing and Bulk Density Analysis

As an added justification for the structural superiority of the plasma treated residue Bulk Density values are also included in Figure 4.2. The bulk density of the slag (2.55 g/cm³) suggests that the particles will be able to pack together with a high packing efficiency, which is important in the development of a stable and well interlocked matrix in road sub bases and other compacted layers. However, the slag particles are dense, non porous and compact, therefore they occupy space better than the lighter particles with air filling inside of the incineration ash, which reveals much lower bulk density of 1.65g/cm³.

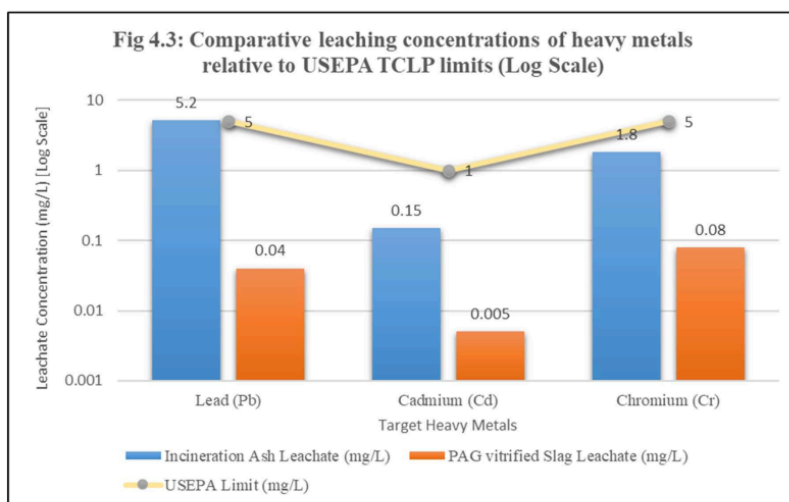
This difference in bulk density leads to obvious engineering consequences. In general, the greater bulk density, the more efficient compaction, the lower void ratio, and the better load transfer between particles; for construction of road and embankment. Well-packed, dense aggregates will not settle, rut or spread laterally as much as poorly packed aggregates under repeated traffic loads. The low bulk density incineration ash, on the other hand, acts more like a loosely compacted fill, and is more likely to cause differential settlements and instability of any structure in which it is placed as a structural layer.

The physical data given in the summary in Figure 4.2 therefore shows that the physical characteristics of the plasma converted residue are very similar to high quality natural stone aggregates in terms of density, absorption and packability. This physical equivalence provides a sound technical argument for “urban mining”, namely the use of processed WtE residues as a substitute raw material in civil engineering, especially in the Indian context where there is a severe shortage of natural river gravel and stone aggregates. Overall, the results indicate that PAG technology can help urban local bodies to transform a liability for disposal into a mineral resource of a high quality, suitable in volume and performance to modern infrastructure.

4.3 Environmental Safety and Regulatory Compliance

The environmental classification of WtE residues is essentially based on the mobility of toxic heavy metals under conditions that mimic long exposure under landfill conditions. Leaching tests like the Toxicity Characteristic Leaching Procedure (TCLP) which is prescribed in the USEPA Method 1311 are the basis for the distinction between non-hazardous and hazardous waste in regulatory frameworks (Solid Waste Management Rules, hazardous waste provisions, etc.). A logarithmic scale has been used in Figure 4.3 to clearly show the magnitude of the immobilization, and to show the compliance gap with the environmental boundaries, as the leachate concentrations of some heavy metals in untreated incineration ash and plasma vitrified slag can vary by several orders of magnitude.

Fig 3: Comparative leaching conc of heavy metals relative to USEPA TCLP Limits (Log Scale)



4.3.1 The “Regulatory Crisis”: Lead (Pb) Non- Compliance

The most prominent finding shown in figure 4.3 is the concentration of Lead (Pb) in untreated incineration ash. The bar showing the concentration of Pb in the ash leachate clearly is above the USEPA limit line at 5.0 mg/L that indicates the regulatory limit as stated in the USEPA 1311 - Toxicity Characteristic test. This value is also in line with

the hazardous waste classification criteria laid ¹² under the Solid Waste Management Rules, 2016 and amended in 2026, wherein the wastes which are greater than this are classified as hazardous or semi hazardous waste.

This is a very important single data point from a regulatory and planning point of view since this data point directly drives the regulation and planning of how the residue is to be managed. The 5.0 mg/L limit on the TCLP leachate means that if the Pb level is exceeded in that leachate, the material cannot be disposed of in a municipal landfill, and must be shipped to Treatment, Storage and Disposal Facilities (TSDFs) that must comply with more stringent environmental controls, and induce higher disposal costs. The higher concentration of hazardous elements in the incineration ash (not meeting the limit of leaching concentration of Pb) shows that the incineration process using grate is not the solution to the toxicity issue; on the contrary, it puts the hazardous elements into a secondary waste which might become a liability for financial and environmental burden.

Thus, the Pb non compliance of incineration ash can be seen as evidence, from the urban waste governance perspective, that traditional incineration cannot be considered as a final waste management solution but a technology which shifts the problem from the raw MSW stream to a more concentrated and dangerous residue stream. It indicates a "regulatory crisis" calling for new thermal treatment processes to stabilize or immobilize these metals and not move them from one phase to another.

4.3.2 Logarithmic Magnitude of Stabilization

Figure 4.3 shows that the logarithmic scale reveals the improvement associated with PAG vitrification is not incremental but exponential. The PAG vitrified slag is not simply "cleaner" than the raw ash, it is approximately two orders of magnitude safer from the perspective of results in terms of leaching of Pb. The concentration of Pb in the TCLP leachate for the incineration ash lies very close to or above the 5.0 mg/L failure line, while for the PAG slag the leachate concentration of Pb is around 0.04 mg/L or more than 100 times lower.

The vitrification process has given rise to such huge reduction in levels of leaching that it reflects the sequestration of the heavy metals down to the molecular level. Heavy metals like Pb, Cd and Cr are most commonly attached to the surface of ash

particles as cations, as soluble salts in which they are encapsulated, and/or loosely bound to the crystalline mineral phases of Ash. These forms have relatively high bioavailability and are soluble under acidic or oxidizing conditions, just what the TCLP test emulates. Consequently, metals may be readily leached into the leachate, particularly if organic acids are present as is often the case in landfill environments.

²⁴ At temperatures higher than 3000°C, however, the ions of the metallic compounds in a PAG slag are thermally dissociated and become chemically bound to the silicate glass network, thus forming a dense, amorphous silicate glass ceramic matrix. Heavy metal ions are not necessarily physically trapped but also may be incorporated into the structure of the silicate lattice, in interstitial positions, or in stable coordination complexes with surrounding oxygen. Such chemical bonding effectively “locks” the toxins inside the glass backbone, significantly lowers their solubility, and makes them much less likely to be leached into the environment, even when the slag is compacted or crushed and when it is subjected to sub-surface infiltration or landfill leachate, which repeatedly weakens the acidity or oxidation.

The logarithmic comparison in Fig. 4.3 is a good visual proof then of the technological superiority of plasma vitrification from an environmental safety point of view. It demonstrates that the process not only removes polluting chemicals but also transforms them to a non-hazardous substance by embedding the pollutants in a stable, inert matrix which transforms the waste to a nonhazardous resource.

4.3.3 Multi- Metal Safety Margins

While the Lead (Pb) test results are the most dramatic, the log scale bars of Cadmium (Cd) and Chromium (Cr) on Figure 4.3 show a similar pattern of large margins of safety for several heavy metals. Cadmium is presented at a concentration of approximately 0.005 mg/L in the slag leachate is very low, and is close to the baseline of the log scale, and well below TCLP specified regulatory limit of 1.0 mg/L. Thus, the concentrations of Chromium in the slag leachate are also well below the hazardous waste level, and the benefits of vitrification extend beyond just one element.

The multi metal safety profile here agrees that the PAG system does not stabilize selectively but that it has a “universal sequestration effect.” It is important to note that the chemical composition of the matrix of the vitrified slag produced is stable and inert

despite the nature of the MSW feedstock (batteries, the electronic waste components, industrial sludge, mixed packaging with traces of metals, etc.). There also seems to be a consistent production of high silicate, amorphous phase in the plasma processing steps, which seem to uniformly trap and freeze a wide range of metallic species, a necessary precondition for long term acceptance of the slag in various environmental and regulatory contexts.

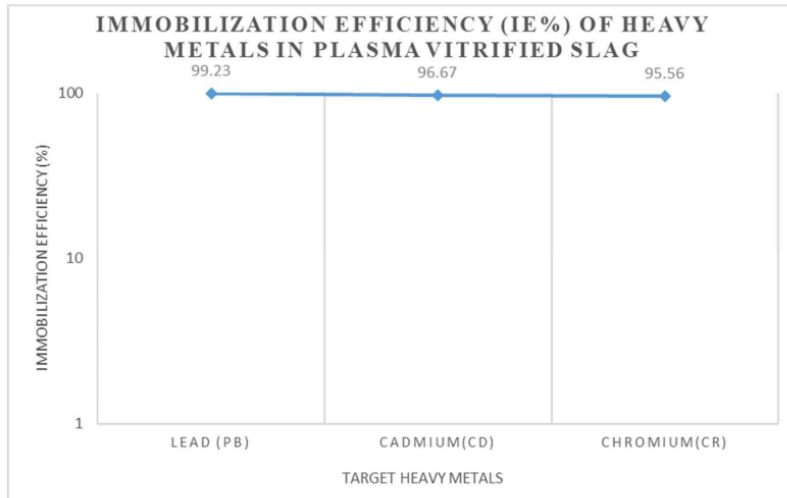
The data in this section, combined with the chemical and physical results, demonstrate that PAG technology can truly “declassify” the hazardous waste to make it into a non hazardous, useful construction product. The technologically advanced vitrification pathway enables municipalities to solve the toxicological liabilities of urban waste permanently, by turning it into safe, high performance aggregates which can be used for infrastructure development; instead of being considered as a toxic by-product which has to be carefully separated.

4.4 Stabilization Efficacy and Immobilization Efficiency

Raw leaching concentrations represent a direct measure of regulatory compliance but Immobilization Efficiency (IE%) can be used to provide a quantitative and normalized measure of a technology's intrinsic ability to neutralize and immobilize toxic species in the residue matrix. IE% provides a more stringent comparison between different heavy metals and treatment conditions, giving insight as to how well the PAG vitrified slag “cages” the heavy metals that would otherwise be very mobile in the conventional incineration ash.

In particular, the stabilization performance of the plasma matrix is examined with regard to the reduction of the leachability of these substances as compared with the untreated MSW incineration ash in terms of thoroughness and consistency. The concept of IE% is that the concentration of a given metal in the treated slag leachate is divided by the concentration of the same metal in the untreated ash leachate at the same TCLP conditions, thus providing an indication of the fraction of the pollutant not released; that is, the fraction of the pollutant that is effectively immobilized rather than simply diluted.

Fig 4: Immobilization efficiency (IE%) of heavy metals in PAG vitrified slag



4.4.1 The “Stabilization Plateau” and Process Reliability

The line graph in Fig. 4.4 shows that there is an amazing stability and consistency in the PAG system's performance with respect to the three heavy metals concerned. What is striking about this graph is the “Stabilization Plateau”—a band of near-horizontal, or horizontal, stability, near the top of the chart, where all three metals have an IE% of > 95%. This trend suggests that the vitrification process is very strong and repeatable, and that it can provide this degree of immobilization for any kind of metal, irrespective of its chemical nature and volatility.

It is accepted that an IE% of 90% or higher is a high performance indicator, meaning that the treatment method can significantly mitigate environmental risk associated with the targeted pollutant(s) in practice. According to the present data the mean of the IE% was 97.15% which is far above this value indicating that PAG based vitrification process is approaching to near absolute stabilization of the heavy metals tested.

This reliability is in contrast to the conventional incineration technique where the extent of the metal stabilization is highly variable depending on the temperature of operation, airflow and combustion efficiency. In such systems, the oxidation state of

the metal, the extent of volatilization, and the distribution of the metal in the ash can vary as a function of the process conditions, which will subsequently influence the long term leaching behavior. However the flat, high efficiency line in Figure 4.4 shows that the plasma Arc stabilises the “Process Equilibrium” within the reactor, even in the face of the extreme thermal gradients and dynamics in the melt.

The final matrix: silicate glass, is invariably a stable host for the metal species, whatever the boiling point, volatility, or ionic behavior of the specific metal is. This indicates that the process of vitrification is tolerant of variations in the feedstock—a very important quality considering the variations in the composition of MSWs in different cities of India owing to various factors such as seasons, locations, socio-economic conditions etc.

4.4.2 Peak Sequestration of Lead (Pb)

The most technically relevant results of the stabilization analysis are the highest IE% value obtained in the line graph, which is for Lead (Pb) at IE%=99.23%. As mentioned above, Lead is the most important “problem element” in MSW residues in India primarily because of its presence in relatively large quantity in the waste stream (from batteries, paints, etc), its mobility under the leaching conditions and its stringency under the hazardous waste regulations like USEPA 1311.

The pattern of the IE% trend line is such that the topmost position belongs to Pb, implying a very high chemical affinity of Pb^{2+} ions to an amorphous silicate network created during the vitrification process. During the cooling of the plasma melt, the Pb ions seem to be able to enter the glass not only as “passive” fillers or as “trapped” impurities but also as a substitute component of the glass, as modifier ions, which are capable of interacting with the glass lattice consisting of silicate ions. Being a relatively large, low field strength cation, lead can function as a network modifier in silicate glasses and either replace a smaller network forming cation or it can be present as interstitial within the glass matrix. This integration prevents Pb ions as surface bound and soluble salts, which are the primary forms having high leaching ability in the incineration ash.

The concentration of immobilized lead in the final product is 99.23% which means that the slag is environmentally stable during its use as a road sub base or structural aggregate, even under mechanical stress and surface degradation during the use time.

Road and construction uses often involve crushing, abrasion and subsequent compaction; these activities may uncover new internal surfaces that may not otherwise have oozed out trapped contaminants. Nevertheless, the extent of chemical incorporation of Pb in the glass backbone is high and the leachable fraction of Pb is negligible even after such physical disintegration, which offers a secure and durable protection against contamination of the groundwater and/or enrichment of the surface soil by leaching.

4.4.3 Comparative Stabilization Analysis

Figure 4.4 also allows the detailed comparison of stabilization efficiency of the three studied heavy metals Pb, Cd, and Cr and demonstrates an Efficiency Gap between them, despite them all being in the range of high performance. The values of IE% indicate that Cadmium (Cd) has a total immobilization rate of 96.67 percent whereas Chromium (Cr) has 95.56 percent. Such values are a little lower than that of Pb, yet they are quite high, exceeding the 90% mark, which means that the PAG system is also very effective in these elements.

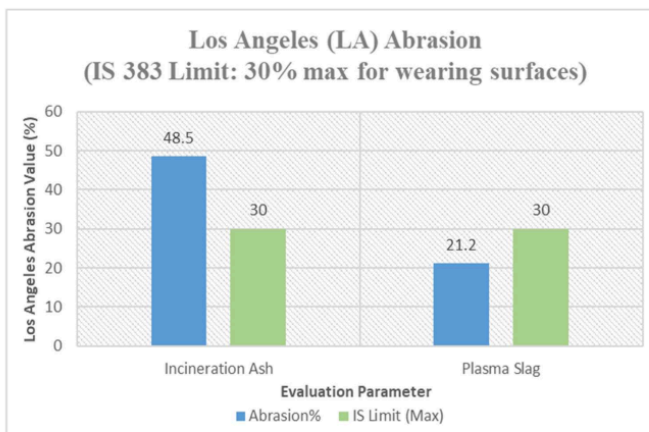
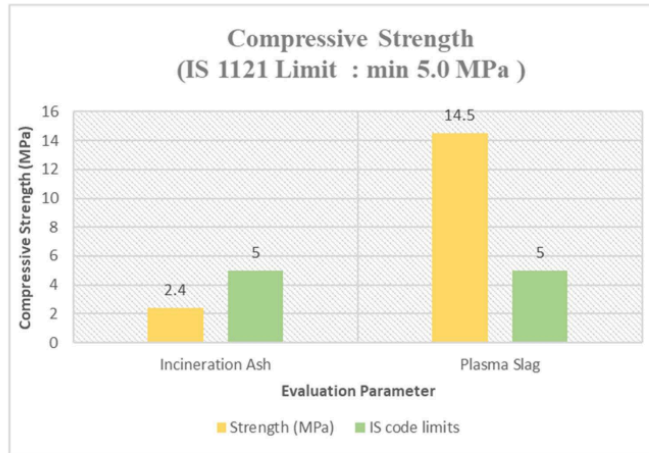
The measured difference in the percentage of the IE could probably be explained by the difference in the ionic radii, oxidation states, and the coordination preference of the metallic species. Take the example of Cadmium; under some conditions it is known to form fairly soluble complexes of chloride or sulfate and has a high propensity to adsorb itself on the surfaces of particles. Conversely, Chromium may exist in various oxidation states - especially trivalent (Cr^{3+}) and hexavalent (Cr^{6+}) with the latter being more mobile and toxic than the former. The fact that the percentage of IE of over 95% of Cr is still attained by the PAG process even with its complicated redox characteristics indicates that the reducing or mixed atmosphere inside the plasma furnace is conducive to the formation of less soluble Cr $3+$ species that can be integrated in the silicate structure.

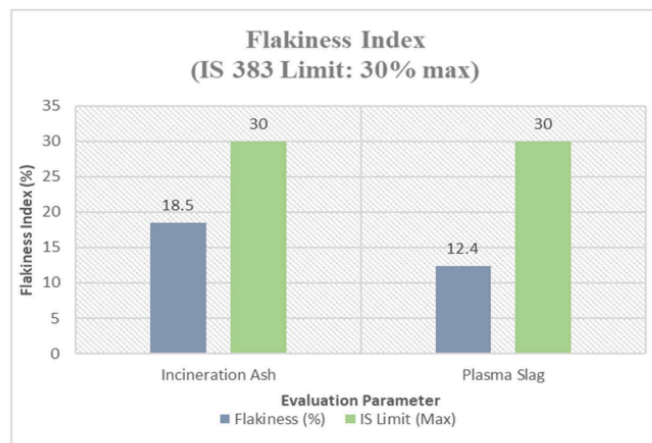
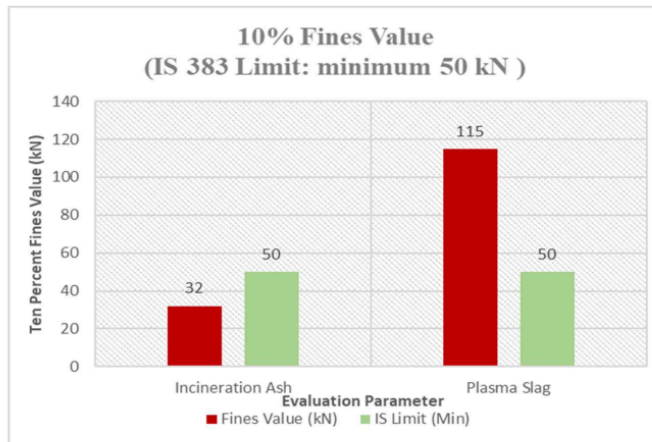
This comparative analysis shows that the PAG system provides a “Universal Sequestration effect but not process selective or element selective treatment. Irrespective of the chemical complexity and variability of the urban MSW feedstock, be it batteries, electronic waste fragments, industrial sludge, or mixed consumer product, the resulting vitrified slag always effectively captures a wide range of heavy metals. The quantitative defensible case of using PAG based vitrification as a universal

stabilization technology of the complex and heterogeneous urban waste, which can significantly reduce the environmental risk of MSW residues, and at the same time produce a safe, reusable construction material is the mathematical accuracy of the IE% trend line in Figure

4.5 Mechanical, Integrity, and IS Code Compliance.

Mechanical characterization of PAG vitrified slag is the ultimate test of its structural preparedness to be used as a construction material. Although environmental safety means that the residue is non-hazardous and chemically stable, it is mechanical integrity which ultimately defines whether the material can sustain the cyclic loading, repeated impact and abrasive forces experienced in the real-world civil engineering. In this respect, Figure 4.5 compares the main mechanical properties of the residues such as compressive strength, Los Angeles (LA) abrasion, 10 percent Fines Value, and Flakiness Index with the benchmarks identified by the Bureau of Indian Standards (BIS) in the road bases, sub bases, and other road infrastructure using coarse aggregates as identified under IS 383:2016.

Fig 5: Mechanical performance and IS Code compliance**(a) Strength Test (b) Abrasion Test (c) 10% Fines (d) Flakiness**



4.5.1 Structural Load- Bearing Capacity (Compressive Strength)

The compressive strength of the plasma vitrified slag (14.5 MPa) is nearly six times greater than the one of the untreated incineration ash (2.4 MPa) as illustrated in Figure 4.5(a). This sharp contrast shows a definite change to a weak, brittle residue to a high strength, load bearing aggregate.

Under the context of the IS 383:2016, the compressive strength value of most structural uses even in the lower grade of the construction layers is approximately 5.0 MPa. The incineration ash has a low strength of just 2.4 Mpa, which is not sufficient to satisfy even this simplest structural requirement, and in practice it is limited to non load bearing applications, like lightweight fill, low traffic embankments, or temporary leveling layers. The plasma slag however, is much higher than the 5.0 MPa standard, and it means that it can be used in a load bearing application, e.g. road sub bases, lightly loaded concrete and masonry units.

This Strength Leap is a straightforward extension of the mineralogical and microstructural densification, which is described in Section 4.1, in which the high temperatures of the plasma collapse internal pores, eliminate organic matter, and give rise to continuous, interlocking silicate framework. The vitrified slag can withstand compressive loads without fracturing or disintegrating much, like the porous, friable structure of incineration ash, which fractures internally under moderate stress, resulting in a much more stable and dependable aggregate to use in infrastructure projects.

4.5.2 Surface Durability and Wear Resistance (LA Abrasion)

One of the most important parameters of assessing the suitability of an aggregate in road wearing courses and high traffic surfaces is the Los Angeles (LA) Abrasion Value, which is shown in Figure 4.5(b). The LA Abrasion test is a test of the percentage of loss of mass to abrasion and impact in a rotating drum using steel balls, and represents the wear that occurred during traffic and maintenance activities. In the case of aggregates employed in the application of layers of flexible pavements, the IS 383 standard generally gives a maximum LA Abrasion Value at 30.0, above which the aggregate is deemed too weak and likely to be subject to surface degradation that occurs quickly.

The incineration ash has a very high LA Abrasion Value of 48.5% meaning that it is very prone to wear on its surface, dust generation and breakage under traffic loading. This is so high that the ash cannot be used in the Indian highways and in the urban streets or any high traffic road surface since it would easily break down resulting in rutting, dust emission and poor riding quality.

Conversely, the PAG vitrified slag has an LA Abrasion Value of 21.2% which is significantly lower than the 30.0% mark and is similar to high quality natural aggregates like limestone and basalt. The dense, glass ceramic microstructure and high resistance to surface abrasion of the slag is manifested in the signature of Hardness indicating that the glassy character of the material does not mean the material is fragile. Rather, the slag has surface toughness which enables it to resist the continuous friction and grinding of heavy-duty vehicle tires and thus can be a viable substitute to the conventional aggregates used in road wearing layers.

4.5.3 Resistance to Crushing (10% Fines Value)

Figure 4.5(c) shows 10 percent Fines Value, which is one of the main indicators of resistance to crushing of an aggregate when subjected to frequent loading and compaction. The test identifies the force (in kilonewtons, kN) needed to generate 10 percent fines (particles less than a given size) of the starting coarse fraction. This measure is particularly critical in road bases and sub bases where the material should be able to withstand crushing and particle degradation with time, especially with high traffic and compaction. Aggregates of road base layers are usually anticipated to have 10 percent Fines Value of 50.0 kN or higher in the IS 383 standard.

The measurements indicate that the incineration ash collapses with a relatively low force of 32.0 kN which is far below the 50.0 kN standard, indicating its low resistance to crushing and high rate of fragmentation. It implies that it is likely to lose its strength and become easily broken in the presence of moderate compaction that results in decreased density, increased ratios of voids, and possible rutting of the pavement.

Conversely, the vitrified slag produced by the PAG has a crushing resistance of 115.0 kN, triple that of the minimum. This high 10% Fines Value means that the slag is hard and tough and durable and will be able to sustain its particle size distribution when subjected to heavy traffic conditions. Resistance to crushing will make the slag

workable in high stress layers of the flexible and rigid pavements of the Indian subcontinent and offer a stable, long-lasting foundation of road networks.

4.5.5 Morphological Suitability (Flakiness Index)

The Flakiness Index, measured in Figure 4.5(d) determines the shape and angularity of the aggregate particles, which directly influences the packing density, internal friction and workability in construction mixes. In civil engineering, flaky (thin, flat) and elongated particles are typically not desirable as they are more likely to crack under pressure, lessen the internal stability and decrease the workability of the concrete and asphalt mixtures. A combination of flakiness and elongation index of less than 35.0% is usually a limitation of the IS 383 standard on the use of coarse aggregates in structural and road base applications.

The PAG vitrified slag has a low Flakiness Index of 12.4% compared to the 18.5% of incineration ash and well below the 35.0% limit. This positive form distribution can be attributed to the fact that, the molten slag when cooled or crushed (after solidification) will naturally tend to break up in angular cubical shapes, as opposed to fine, thin, and flat shapes. Such angular and cubical forms give the pavement matrix better interlocking, which increases internal friction, shear strength, and stability of the road structure.

The fact that the slag is morphologically superior further supports the fact that it can be used as an alternative to natural coarse aggregates in the construction of roads and other infrastructural projects. The low flakiness coupled with high density and great interlocking properties ensure that the PAG vitrified slag is a sound material structurally and also helps in long term performance and durability of pavements and embankments constructed using the material.

CHAPTER 5:

CONCLUSION, FUTURE SCOPE AND SOCIAL IMPACT

5.1 Synthesis of Research Findings

The paper has conducted a systematic comparative secondary research study aimed at analyzing the effectiveness of Plasma Arc Gasification (PAG) as an alternative waste to energy method to conventional methods used in the Indian scenario. The research directly tackles the pressing issue of the so-called crisis of residue that the Urban Local Bodies (ULBs) of the country face today by synthesizing and interpreting chemical, physical, and mechanical datasets based on credible scholarly and technical sources. It is seen that PAG is not merely a slight improvement in thermal treatment but a qualitative change in the approach to the management and appreciation of urban waste residues. Based on the combined assessment of MSW incineration ash and PAG vitrified slag, the following conclusions are made:

5.1.1 Physicochemical Stabilization

The change of traditional incineration ash to vitrified slag implies a mineralogical and structural reorganization of the residue in its entirety. The study demonstrates that the plasma temperature of about 3,000°C attained has an extraordinarily high organic destruction efficiency with a near zero Loss on Ignition of 0.5 percent in the slag, as opposed to 15.6 percent in the incineration ash. This radical decrease of LOI is an effective way of removing the existence of unburnt carbon and volatiles leftover and so eradicating the danger of long-term microbial degradation, interior gas creation and chemical off-gassing of the compacted material.

Moreover, the data attests to the fact that the silicate network, dominated by Silica (SiO_2) is fortified and strengthened during vitrification resulting in a high Glass Content (G%) of 80.7%. This implies that the PAG system transforms a heterogeneous, chemically active ash, composed of mixed crystalline and porous phases, to a homogeneous, amorphous, glass ceramic matrix. The resulting structure is much less reactive and more resistant to attack by the environment and is therefore appropriate in long term exposure in infrastructure applications like road sub base, embankment and

masonry units.

5.1.2 Environmental Safety and Toxicological Sequestration

Among the most important discoveries of our research is the regulatory noncompliance of untreated incineration ash to the standard environmental leaching requirements. The Lead (Pb) content in the TCLP leachate of the raw ash (5.20 mg/L) is determined to be more than the 5.0 mg/L limit of USEPA Method 1311 that under modern environmental regulations qualifies the material as either a hazardous or semi hazardous waste. This finding emphasizes the toxicity hazard of the conventional incineration residues particularly in cases where they are kept in a land fill or utilized without proper stabilization.

Conversely, the PAG vitrification process had an Immobilization Efficiency (IE%) of 99.23% with Lead and very high IE% values with all other heavy metals tested, such as Cadmium (Cd) and Chromium (Cr). The discussion reveals that vitrification is not simply a physical barrier, but it enables encapsulation of toxic species at the molecular level in the amorphous silicate lattice. The metal ions are not loosely adsorbed onto the surfaces of the particles but are in this configuration chemically incorporated into the glass ceramic structure. Consequently, the leach line levels of these metals in the slag are far below the regulatory limits even in acidic environments as in TCLP testing. This substantiates that the process of vitrification transforms a hazardous waste stream into a non-hazardous, environmentally safe aggregate that can be used again in civil engineering activities for Structural Substitution and Mechanical Valorization.

Mechanical testing and engineering analysis indicate that PAG vitrified slag can be used in most of the construction works as a substitute to natural coarse aggregates. Slag compressive strength is 14.5 MPa and Los Angeles (LA) Abrasion Value is 21.2% which are comfortably below and above the minimum requirements in the IS 383:2016 of aggregates in structural and road base layers. Compressive strength is approximately six times greater than that of the incineration ash indicating the dense and well bonded structure of the vitrified material.

Also, the Flakiness Index of the slag stands at 12.4% and is lower than incineration ash. This implies that there are more cubical and angular particles with good interlocking potential. The high crushing resistance, low wear, and desirable particle shape make the slag especially appropriate to be used in the road subbases, base

courses, and elements with minimal loads. These findings indicate that the PAG vitrified slag could be incorporated in pavement systems and urban infrastructure developments without affecting the engineering functionality or the service life of the system, and thus, the reliance on quarried and river-based aggregates could be minimized.

5.2 Final Conclusions

The study finds that although conventional mass burn incineration has achieved considerable success in the reduction of the quantity of municipal solid waste by 70-80%, it has not been effective in addressing the qualitative and environmental risks of the residues generated. This high LOI, variable mineralogy, and heavy metals leaching in incineration bottom ash is also a shifted liability, i.e., the waste issue is not solved but is transferred to the hazardous waste storage and treatment plants. The remaining ash will cause long term management expenses, the risk of contamination, and restrictions on reuse in civil infrastructure.

Plasma Arc Gasification (PAG) in comparison becomes a better near zero waste treatment technology which not only reduces the volume (near 99%) but also produces a valuable byproduct in vitrified slag. Turning toxic ash into a stable, synthetic aggregate according to Indian construction standards, PAG helps contribute to the objectives of a Circular Economy where waste is discussed as an asset, not a liability. With this technology, urban waste will be redirected out of landfills, turned into useful construction products, and reintroduced into the national infrastructure network.

In the fast-paced urbanization of cities in India, this shift is of paramount concern, as it not only removes the strain on the natural aggregate resources, lessens the environmental impact of garbage collection, and promotes the policy aims of the Solid Waste Management Rules 2026. The results of this paper thus reveal that PAG based WtE systems implementation can become a major facilitator to sustainable urban development and resource efficient infrastructure planning in the Indian scenario.

5.3 Recommendations for Policy and Industry

It is proposed ²⁶based on the results of this analysis that the following policy and industry level recommendations be put in place to enable safe and large scale use of PAG vitrified slag:

- **Unification of Slag Utilization**

¹²The Indian Roads Congress (IRC) and the Bureau of Indian Standards (BIS) need to come up with certain technical guidelines and specifications to be used in the utilization of vitrified MSW slag in public works, such as road building, embankments, and other civil engineering works. Acceptable limits to the performance of LOI, leaching behavior, compressive strength, abrasion resistance, and particle shape should be stipulated to provide a clear direction on grading, placement, and compaction to produce uniform performance on projects. Clear standards would assist in creating trust amongst the engineers, contractors, and ULBs to increase the use of slag based materials.

- **Extended Producer Responsibility (EPR) Construction Materials.**

Extended Producer Responsibility (EPR) type mechanisms which involve offering financial incentives and regulatory assistance to construction companies that use recycled synthetic aggregates (e.g. PAG vitrified slag) in place of natural river gravel and stone should be included in the policy frameworks. Such incentives may be special bidding requirements on public tenders, lower environmental charges, or tax rebates on projects satisfying some minimum slag content requirements. With economic gains and environmental performance on the same plane, EPR style policies would then motivate the construction industry to use slag-based materials as a new norm, which would then speed up the urban sector shift to a circular economy.

5.4 Suggestions for Further Research

To expand the results of this paper and facilitate the scale-up of the PAG based residue valorization to the operational level, the following recommendations can be given to the future research:

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

Life Cycle Cost Analysis (LCCA) needs to be done in details to determine the economic feasibility of PAG based WtE systems throughout their operations. This should be done

by a study to compare higher capital and energy costs of plasma facilities with the long term savings that can be achieved through avoided hazardous waste landfilling fees, lower transportation costs and lower procurement costs of natural aggregates.

- **Long-term Weathering Experiment**

The long-term durability and leaching characteristic of PAG slag based concrete and asphalt mixtures in the real world environment should be studied in future experimental studies. Accelerated weathering tests such as exposure to simulated acidic rain and repeated wet-dry and freeze-thaw cycles would be used to confirm that the vitrified matrix retains its integrity and low leachability during a service life of 30-50 years. These studies would be particularly important for designing high performance pavement and structure designs that can sustain heavy traffic loads and severe climatic conditions in Indian cities.

- **Multi Waste Co Vitrification**

Further studies may examine the technical and economic opportunities of co vitrifying MSW residues with other hazardous or industrial waste streams, e.g., E waste, industrial sludge, or some types of contaminated soils. With an appropriate combination of these materials in a controlled ratio, perhaps one can maximize the throughput and economic performance of plasma facilities and stabilize a broader range of pollutants in a single process. But these co vitrification tests need to be well planned and observed so that the resulting slag can be safe to use in construction, in terms of environmental and mechanical quality,

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