

Detoxification of Incinerator Ashes in Thermal Plasma Reactor: A Review

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ABSTRACT

Incineration of both industrial and municipal solid waste has been widely used due to its ability to reduce the volume of waste by about 90% and detoxify the waste. However, a great challenge associated with waste incineration is production of toxic fly and bottom ashes. These ashes contain heavy metals which enters water bodies through percolation and absorption, and their consequences on human and animals is enormous. Various researches were conducted on the application of thermal plasma arc technology to safely detoxify incinerator ashes. The final product from plasma treatment is a melt or vitreous slag within which toxic heavy metals are cemented. This paper reviewed the different studies conducted on the treatment of incinerator fly and bottom ashes in thermal plasma arc reactor. The review looked at the characteristics of the ashes, the thermal plasma reactor specifications, the operating conditions and the product characteristics. It also focused on effectiveness of the treatment processes in terms of volume reduction, detoxification, crystalline structure of the product and their usability. It is generally observed that thermal plasma arc reactors detoxify both fly and bottom incinerator ashes, reduce the volume of waste by about 90% and convert the ash to a vitreous slag where heavy metals are immobilized. Low basicity in parent ash favours conversion of ash into glassy vitreous slag.

Keywords:

Incinerator ashes, Thermal plasma,
Basicity, Vitreous slag, Leachability

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1. Introduction

There is an increase, globally, in the generation of solid waste due to urbanisation coupled with industrialisation. Incineration has been widely used in Europe and Asian countries to curtail the fast growth of municipal solid waste dumps in cities and villages [1]. Incineration detoxify solid waste and provides a means of reducing the volume of the waste by about 90% and also generates electricity by recovery of thermal energy [2-4]. However, incineration is associated with generation of byproducts; fly and bottom ashes. The fly and bottom ashes generated from incineration of waste contain significant amount of heavy metals and dioxins and therefore required a proper and safe means of disposal [2]. The advantages of thermal plasma melting include Steady state uniform flow of high temperature gas, rapid heating and reactor setup, versatility in treating different form of wastes and achieving higher volume compare to other treatment technologies. It is also a compact

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system with high throughput rates and thermal efficiency. The processing environment of thermal plasma is control with a lower off gas flow rate that leads to lower gas cleaning cost. There is the high possibility of always producing reusable/valuable materials such as slag. The disadvantage of this technology is the possible high consumption of electricity as a source of energy which reflects negatively on the economic efficiency of the system

Thermal plasma is being adopted at various levels as a means of melting and vitrification of ashes obtain from incinerators [2, 5, 6]. It produces a vitreous slag that is capable of safely immobilizing heavy metals in a stable form. At the same time persistent organic pollutants such as dioxins and furans are completely destroyed by the high temperature regime in the thermal plasma arc [6]. Heavy metals with low boiling point and vapour pressure such as zinc (Zn), lead (Pb) and Cadmium (Cd) are easily emitted during melting process. The energy source of plasma systems is electricity which is independent of the waste being destroyed; furthermore, the system can be small but possessing high temperature and energy densities that encourage chemical reactions within short residence time. [1,7] reported that the plasma technology has been utilized in the treatment of various hazardous wastes with satisfactory results.

Quite a number of studies have been devoted to the characterisation and applications of products obtained from vitrification processes [1-4, 7-13]. In most of the studies a significant decreased in volume of waste with a corresponding increase in density was observed. This paper reviewed the different studies conducted on the detoxification/treatment of incinerator fly and bottom ashes in thermal plasma arc reactor. The review focused on the specifications of thermal plasma reactors used for detoxifying incinerator ashes, the characteristics of the ash, and the products as well as factors responsible for product crystalline structure.

2. Thermal plasma generation

Thermal plasma arc is generated using plasma torch; a device that utilize electrical energy, using negative electrode (cathode) and positive electrode (anode). According to [14] thermal plasma arc can be generated using direct current (DC), alternating current (AC), microwave discharge (MW) or radio frequency (RF) induction. Thermal plasma arc is categorised into transferred arc and non-transferred arc. The transferred arc is generated by a torch assembly where one of the two electrodes is within the torch while the other electrode, usually the anode, is outside and separated from the torch. This arrangement allows the plasma to be generated outside the water-cooled body of the torch thereby generating a plasma arc with heating efficiency of over 90% [15]. The external electrode is usually a flat cylinder of a high thermal conductivity metal like copper or silver. The flat shape is to enhance a better distribution of the plasma [16]. The internal electrode is made either with a consumable material (like graphite), that is frequently substituted, or with a water-cooled metal. The outside electrode is usually the working piece, for conducting material, or a conductor holding the working piece, for non-conducting material.

In non-transferred arc plasma torch the two electrodes are located within the torch, and are water-cooled. High density and high temperature arc is generated in the space between the electrodes when electric current passes through them, the pressure of the flowing gas stream pushes the plasma beyond the anode through a nozzle creating a plasma jet. DC non-transferred plasma torches have lower power consumption and lower electrode degradation, they produce less noise and less vibration resulting into more stable operation; they have low heating efficiency, between 50 and 90% [15]. Table 1 shows the specifications of various thermal plasma arc reactors used for melting of incinerator ashes.

Table 1

Specification of thermal arc plasma reactors used for melting of incinerator ashes

Reactor scale	Input power	Reactor type	Reference
Pilot scale	135 kW	Transferred arc melting furnace	[17]
Pilot scale	367 kWh	Transferred arc melting furnace	[18]
Pilot scale	NA	Transferred arc melting furnace	[2]
Lab scale	100 kW	Non-transferred arc furnace	[19]
Lab scale	NA	A high frequency induction furnace	[9]
Lab scale	100 kW	Non-transferred arc	[10]
Lab scale	100 kW	Non-transferred arc	[1]
Pilot scale	1200 kW		
Lab scale	23.4 kW 22.75 kW	Inductively Coupled Plasma Torches	[4]
Industrial	1710 kW	DC plasma furnace	[3]
Lab scale	300 kW	Non-transferred arc	[20]
Lab scale	2-3 kW & 5-6 kW	Double arc plasma torch	[7]
Lab scale	100 kW	Transferred arc furnace	[13]
Industrial	NA	Transferred arc melting furnace	[21]
Lab scale	20 kW	Transferred arc	[22]
Lab scale	10 kW	Non-transferred arc	[23]
Pilot scale	20–30 kW 50–60 kW	Non-transferred double arc	[5]

NA = Not available

As shown in Table 1, with the exception of very few, most of the investigations were at laboratory scale employing either transferred or non-transferred DC arc torch. High temperature regime was generated mostly in the reactors alongside ultra-violet radiations. The inert gas and high temperature atmosphere employed in the processes suppress the generation of NO_x, SO_x and HCl [14, 17].

3. Characteristics of incinerator ashes

Treatment of incinerator ashes using thermal arc plasma were done mostly in the Asian countries (China, Japan and Taiwan) [3, 10, 21, 24, 25]. These ashes are by-products of incineration of a wide variety of waste ranging from municipal solid waste (MSW), medical waste (MW) and Laboratory waste (LW). Their characteristics takes cognisance of the waste-types and the sources within the incinerator; whether fly ash or bottom ash. All the studies under review, except for [20, 21], used ashes from municipal solid waste incinerator or medical waste incinerator. The exceptional two studies were on the treatment of laboratory waste incinerator ash. Medical waste incinerator (MWI) Ash has higher organic components as compared to municipal solid waste incinerator (MSWI) ash thus concentration of PCDD/Fs were higher in the MWI ash as against MSWI ash [12]. Table 2 shows the elemental composition of the raw ashes before subjecting to the plasma treatment. Whereas oxides like quick lime (CaO), Potassium Oxide (K₂O), alumina (Al₂O₃), ferric oxide (Fe₂O₃), sodium oxide (Na₂O), Magnesia (MgO), as well as silica (SiO₂) were found in all the ashes under review, oxides like zinc oxide (ZnO), copper oxide (CuO), titanium oxide (TiO₂), lead monoxide (PbO), Manganese Oxide (MnO) and diphosphorus pentoxide (P₂O₅) were not present in fly ashes used by some researchers [5, 7, 9, 11, 19]. Calcium oxide (quicklime), silica and alumina were the dominant compounds in the ashes. In comparing the composition of fly ash to bottom ash, [24] observed that fly ash had a higher CaO content as compared to bottom ash. In contrast, the SiO₂ content was higher in the bottom ash than in the fly ash.

4. Vitrification of ashes

Thermal plasma vitrification of incinerator ashes have been reported in literature [1-4, 7-13]. The high temperature plasma convert organics into gaseous products comprising mainly of synthetic gases and light hydrocarbons while the inorganics are melted into vitreous slag. Volume reduction of waste is in the range of 60 to 90% as shown in Table 3.

Table 3
Reduction ratio as a function of treatment temperature and treatment time

Operating conditions			Percentage reduction		References
Feed rate	Melting Temperature	Treatment period	Volume	Mass	[17]
50 kg/h	1,600 °C	4½ hours	64	17	[18]
100 kg/h	1,500 °C	NA	90.9	27	[2]
80 kg/h	1,300 °C	NA	NA	NA	[19]
2.4 kg/batch	1,350 °C	2 hours	64	17	[9]
3.5 kg/batch	1400 °C	20 min	NA	NA	[10]
	1,400 °C	1 hours	NA	NA	[1]
0.3 kg/batch	1500 °C	1 hours	NA	NA	[1]
0.43kg/h	NA	20 min	NA	NA	[11]
NA	1600 °C	2 hours	NA	NA	[3]
30 – 60 g/batch	NA	15 min	60- 73	NA	[7]
30 – 60 g/batch	NA	15 min	60-73	NA	[12]
100 kg/h	1900 °C	NA	80.2	36	[21]
125 kg/h	1500 °C	NA	NA	NA	[22]
25 g	NA	10 – 15 min	NA	NA	[26]

NA = Not available

4.1. Effect of basicity and additives on vitrification of ashes

The effectiveness of the vitrification process in converting incinerator ashes into vitreous slag depends on the ratio of quicklime (calcium oxide) to silica in the parent ash [24, 25, 27, 28]. This ratio, CaO/SiO_2 , commonly referred to as the basicity of the ash, affect the structural formation of the vitreous slag [29, 30]. Quicklime or calcium oxide (CaO) is a stabilizing agent while silica (SiO_2) is a vitrifying agent. The two compounds shift the product towards either crystallization phase or glassy phase. Fly ash is obtained mostly from the cyclone of Air Pollution Cleaning (APC) device and/or bag filters (bag house) of kilns [12, 17]. Due to low silica content (high basicity), fly ash will not form glassy product without the addition of glass formers [11, 18]. Thus some additives like silica, lime, alumina, liquid ceramic, glass cullet and scraps of fluorescent lamps were used to improve the silica content [7, 11, 31-35].

Table 2
Elemental composition of raw ashes

Compound	Composition (wt. %)												
	[17]	[18]	[2]	[19]	[9]	[1]	[1]	[11]	[3]	[7]	[13]	[22]	[5]
Ash Type	Fly ash	Fly ash	Fly ash	NI	Fly ash	Scrubber	Fly ash	Fly ash	Bottom ash	Fly ash	Fly ash	Fly ash	Fly ash
CaO	209,400	26.6	26.8418	32.96	19.7	42.57	28.04	15.3	13.1	22.95	26.8418	0.20	10.32
SiO₂	102, 100	18.1	16.0115	12.41	19.4	2.05	21.63	56.7	39.8	7.50	16.0115	NI	48.87
Cl⁻	111, 680	8.5	14.5447	NI	NI	31.5	9.8	NI	0.47	11.96	14.5447	NI	NI
S	NI	3.9	NI	NI	NI	NI	NI	NI	0.17	3.58	NI	NI	NI
SO₃	NI	NI	13.7206	NI	NI	3.79	8.31	6.18	NI	NI	13.7206	NI	0.70
K₂O	11,517	3.8	9.7911	2.41	8.1	4.64	4.43	1.8	0.38	2.79	9.7911	NI	1.77
Al₂O₃	60,900	13.3	4.3900	8.06	10.1	0.45	8.60	7.5	10.3	3.59	4.3900	NI	17.84
Fe₂O₃	2,862	3.0	3.4887	2.35	1.8	0.27	2.45	1.6	18.9	2.15	3.4887	NI	5.86
Na₂O	11,866	10.5	3.4451	5.15	8.9	4.83	4.55	1.5	1.12	2.26	3.4451	NI	1.88
P₂O₅	NI	3.1	2.0601	1.92	NI	0.37	3.07	NI	NI	1.12	2.0601	0.21	1.54
MgO	3,490	2.0	1.7615	2.23	2.8	0.98	2.87	1.5	2.21	2.61	1.7615	0.05	1.44
ZnO	4,363	4.0	1.3061	NI	NI	1.47	1.26	0.3	NI	NI	1.3061	68.95	NI
TiO₂	1, 710	NI	1.2495	2.18	1.9	0.09	2.00	0.8	NI	NI	1.2495	NI	0.88
PbO	2,094	NI	0.4562	NI	NI	0.47	0.22	NI	NI	NI	0.4562	1.57	NI
MnO	NI	3.0	0.1836	NI	NI	0.02	0.19	NI	NI	NI	0.1836	NI	NI
CuO	332	NI	0.1518	NI	NI	0.13	0.10	NI	0.29	NI	0.1518	15.34	NI
SnO₂	NI	NI	0.1501	NI	NI	0.15	0.26	NI	NI	NI	0.1501	0.26	NI
Br⁻	NI	NI	0.1161	NI	NI	NI	NI	NI	NI	NI	NI	NI	NI
BaO	NI	NI	0.0991	NI	NI	NI	NI	NI	NI	NI	0.0991	NI	NI
SrO	NI	NI	0.0977	NI	NI	NI	NI	NI	NI	NI	0.0977	NI	NI
Cr₂O₃	NI	0.2	0.0784	NI	NI	0.01	0.13	NI	NI	NI	0.0784	NI	NI
ZrO₂	NI	NI	0.0425	NI	NI	<0.01	<0.01	NI	NI	NI	0.0425	NI	NI
NiO	NI	NI	0.0138	NI	NI	<0.01	0.02	NI	NI	NI	NI	2.95	NI
Loss on ignition	NI	8.8%	NI	NI	NI	NI	NI	NI	NI	7.17%	NI	NI	NI

NI = No information, SA = Scrubber ash, FA = Fly ash

Although [7] are of the opinion that high chlorine content alongside low basicity in raw ash retard solidification of heavy metals, [36] observed an increased in solidification efficiency of Cr as basicity decreased from 0.8 to 0.4. However, for Cu, Zn, Pb and Ni, the efficiency of solidification increases slightly before decreasing with basicity from 0.8 to 0.4. lime (CaO or NaOH) were employed by some researchers as additives to enable development of crystal structure at lower temperatures [11]. [24] believed that the higher the quantity of bottom ash or cullet added to fly ash, the lower is the basicity of the mixture and the more tendency is the formation of amorphous glassy product. The researchers [24] obtained amorphous glassy slags when the ash basicity was within the range of 0.24-1.24. Similarly, [29] observed an increase in silica content with a corresponding decrease in basicity when glass cullet was added to fly ash. The researchers [29] obtained a dark brown vitrified products of amorphous glassy structure when the basicity of the parent ash was decreased from 2.94 to 0.28. Also [37] used cullet and fly ash at a basicity of 0.921 to vitrify ash in an electric heating furnace.

The use of other types of additives to fly ash prior to vitrification and the quantity of such additives needed are dependent upon the target product. Colouring agent, for example, were added to produce coloured glass material [10, 38, 39] while silica and liquid ceramic were added to improve the immobilization of heavy metal within the vitrified glass matrix [7, 18, 26]. Equally scraps fluorescent lamp and glass cullet were added to enhance vitrification of the ash [4, 29, 40]. Types of ashes subjected to thermal plasma treatment, the parent waste ash, and the additive used in the melting treatment are shown in Table 4.

Table 4

Incinerator ash types and the additives used in the thermal plasma arc melting

Type of Incinerator	Fly/Bottom ash	Additive	Reference
MSWI	Fly ash	Silica & Alumina	[17]
MSWI	Fly ash	Pulp & paper boiler ash	[18]
MSWI	Fly ash	No additive	[2]
MSWI	Not indicated	No additive	[19]
MSWI	Fly ash	No additive	[9]
MSWI	Bottom & Fly ashes	Colouring agents	[10]
MSWI	Scrubber ash & Fly ash	No additive	[1]
MSWI	Bottom & Fly ashes	Scraps of fluorescent lamps	[4]
MSWI	Fly ash	With and without Lime	[11]
MSWI	Wet Bottom ash	No additive	[3]
LWI	Bottom & Fly ashes	Sludge, activated carbon & cullet	[37]
MSWI & MWI	Fly ash	Silica & liquid ceramic	[7]
MWI	Fly ash	No additive	[12]
MSWI	Fly ash	No additive	[13]
LWI	Fly ash	wastewater sludge & glass cullet	[21]
MSWI	Fly ash	Chromium-rich sewage sludge	[22]
Not available	Fly ash	Wastewater sludge	[23]
MSWI	Fly ash	No additive	[5]

4.2. Effect of cooling method on product slag

Vitreous slag and ingot are the two products derived from vitrification of incineration ashes. Slag is the inorganic components of the ash that is vitrified and transformed to a melt [37, 41, 42] while the ingot is the molten form of high boiling-point-metals with large specific weight [43, 44]. Ingot is obtained where there is large percentage of the high-boiling-point-metals with large specific weight in the ash, the metals are not completely gasified but rather collected, as the heaviest product, at the bottom of the vitreous slag [44]. However, most fly ashes contained little or insignificant amount

of high-boiling-point-metals and therefore, vitrification of such ashes result to one-phase-vitreous-slag embedding the non-gasified-heavy-metals presence [37]. The resulting molten slag from vitrification is either rapidly quenched in water [45, 46] or slowly cooled in ambient air [13]. Quenching of the slag leads to a more amorphous product while air cooling results to a more crystallized structure [1, 13, 20, 25].

A number of studies compared the effect of the two cooling methods (quenching in water and gradual cooling in air) on the structural formation of the vitreous slag [47]. According to [18] quick cooling results to an amorphous structure where the silicate molecule matrix lock-in the contaminants heavy metals and prevent their leaching to the environment. Similarly, [23] observed that water-cooled slag shows better elution proof when compared to air-cooled slag. On the other hand, slow cooling results to a product with crystalline structure. Similar results were reported in literature [28, 30, 47-50]. However, a different view was presented by [13] where they argue that water-quenched slag manifests less physical hardness and more porosity as compared to air-cooled or composite-cooled slag which also have better vitreous appearance. Deviating from the common practice, [51] used compressed air to quenched the vitreous slag obtained from vitrification of municipal solid waste incinerator bottom ash.

4.3. Crystalline structure of vitreous slag

The crystalline phases of the microstructural materials (glass ceramics) obtained from thermal plasma melting of incinerator ashes as shown in Table 5 are gehlenite ($\text{Ca}_2\text{Al}_2\text{SiO}_7$), akermanite ($\text{Ca}_2\text{MgSi}_2\text{O}_7$), wollastonite (CaSiO_3), mayenite ($\text{Ca}_{12}\text{Al}_{14}\text{O}_{33}$) and anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$).

Table 5
Slag crystalline phases in relation to cooling method

Slag Cooling method	Major crystalline phase	Reference
Gradual cooling at a rate of $10^\circ\text{C}/\text{min}$.	Gehlenite ($\text{Ca}_2\text{Al}_2\text{SiO}_7$) & Akermanite ($\text{Ca}_2\text{MgSi}_2\text{O}_7$)	[19]
Rapid quenching in water	Gehlenite ($\text{Ca}_2\text{Al}_2\text{SiO}_7$)	[9]
Rapid quenching in water	Gehlenite ($\text{Ca}_2\text{Al}_2\text{SiO}_7$) & Wollastonite (CaSiO_3)	[10]
Lab-scale slag was air cooled	Mayenite ($\text{Ca}_{12}\text{Al}_{14}\text{O}_{33}$) & Gehlenite ($\text{Ca}_2\text{Al}_2\text{SiO}_7$)	[1]
Pilot-scale was water-quenched	Gehlenite & Diopside ($\text{Ca}(\text{Mg},\text{Al})(\text{Si},\text{Al})_2\text{O}_6$)	[1]
Cooling in ambient atmosphere	Wollastonite (CaSiO_3) Anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$)	[11]
NI	Akermanite ($\text{Ca}_2\text{MgSi}_2\text{O}_7$) Anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$), Rondorfite, Wadalite	[7]
Water quenched, air cooled & composite cooling	Gehlenite ($\text{Ca}_2\text{Al}_2\text{SiO}_7$) and Akermanite ($\text{Ca}_2\text{MgSi}_2\text{O}_7$)	[13]
NI	CrO_3 reduced to Cr_2O_3	[21]

NI = No information

The nature of the amorphous product is a function of Ash-silica ratio [7, 17] or cooling method adopted [1]. Rapid quenching of slag resulted to a gehlenite crystal structure [9] or a dual structure of gehlenite and wollasonite [10]. Wollastonite and anorthite were the main crystalline phases found in the air-cooled product observed by [11]. However, addition of lime to fly ash brings forth to gehlenite as a third phase to develop. Similarly, [19] obtained, through slow cooling, crystalline products of gehlenite and akermanite, while [1] obtained a combination of gehlenite, mayenite and calcium magnesium chloride silicate ($\text{Ca}_8\text{Mg}(\text{SiO}_4)_4\text{Cl}_2$). The success reported by [10] shows the

transformational effects of additives on slag which not only manifest in appearance but impacted on mechanical and chemical properties as well. Table 6 is showing properties of crystalline structure from previous researches.

Table 6

Properties of crystalline structure of vitreous slag from previous researches.

Reference	[1]	[7]	[9]	[10]	[11]	[19]
Density (g cm ⁻³)	NA	1.89-3.11	1.4-1.7	2.0-2.4	2.75-2.9	2.93-2.99
Porosity (%)	NA	NA	47.2	25.3-31.2	NA	0.86-2.68
Water absorption (%)	NA	NA	33.4	10.6-18.1	NA	0.28-0.91
Compressive strength (MPa)	314.7	NA	36.1	13.9-98.1	NA	NA
bending strength (MPa)	110.0	NA	15.9	13.9-24.7	NA	NA
Vickers hardness (GPa)	7.9	NA	NA	1.0-2.2	7.0	NA
Knoop hardness (<i>Hv</i>) (GPa)	2.9	NA	NA	NA	NA	4.57-4.84
Mohs hardness	NA	NA	NA	NA	NA	6.5-7.0
Thermal expansion coefficient (10 ⁻⁶ mm C; 25–450°C)	NA	NA	NA	NA	NA	8.21-9.85

4.4. Leachability of heavy metals

Stability of slags obtained from thermal plasma melting of incinerator ash were measured by the various research groups using toxicity characteristics leaching procedure (TLCP) as shown in Table 6. Result from the various studies shows that concentrations of metals in leachate were below the maximum limit prescribed by regulatory bodies. All the slags, irrespective of cooling methods, shows a great resistance to leaching. However, quenching of slag in water was shown to produce the most elution-proof slag as against slow cooling in ambient air [1, 13]. [1, 13] observed a higher concentrations of heavy metals from TLCP of air-cooled slag, though below the maximum regulatory limit, as against TLCP result of water-quenched and composite-cooled slag. A concern is the non-regulated metals and substances which, according to [20], may require further treatment/stabilization.

Most of the research works under review shows a heavy metal concentration reduction in leachate from vitreous slag to a level 15 times less than that from the parent ash [4, 12]. There is a general drastic reduction or complete elimination of PCDD/Fs from the vitreous slag. [12] reported a complete elimination whereas [3] observed traces of the PCDD/Fs only in bag house. Though the impact of additives on slag is far reaching, [10] reported that coloured glass-ceramics retarded the leachability characteristics for heaviest metals as even detected metals are at level lower than regulatory limits.

Table 7

Result of Toxicity Characteristics Leaching Procedure of Slags according to researchers

Elements (mg/L)	Zn	Cd	Pb	Cu	Ni	Hg	Cr	As	Se	Reference
Slag-I	<0.1	<0.1	0.4	<0.1	NA	NA	NA	NA	NA	[19]
Slag-II	<0.1	<0.1	0.3	<0.1	NA	NA	NA	NA	NA	
Quenched Slag	ND	ND	0.3	<0.1	NA	NA	NA	NA	NA	
TCLP Limit (Taiwan)	25	1.0	5.0	15.0	NA	0.2	2.5	5	1	
Slag	NA	<0.005	<0.05	<0.03	<0.05	3×10^{-5}	<0.05	2.48×10^{-3}	NA	[2]
TCLP Limit (China)	100	1	5	100	5	0.1	5	5	NA	
Slag 1	5.94	0.0865	0.0243	1.533	0.0504	NA	BDL	NA	NA	[10]
Slag 2	0.084	BDL	BDL	0.2972	0.308	NA	BDL	NA	NA	
Slag 3	0.054	0.0559	0.4946	0.0544	0.0763	NA	0.1067	NA	NA	
TCLP Limit (China)	50	0.3	3	50	NA	NA	10	NA	NA	
Air –cooled	0.02262	0.00146	0.104	NA	NA	<0.0005	0.00217	0.0055	NA	[1]
Water-cooled	0.02660	0.00113	0.0229	NA	NA	<0.0005	0.00081	0.0006	NA	
Composite-cooled	0.03165	0.0002	0.0315	NA	NA	NA	0.00026	NA	NA	
TCLP Limit (China)	100	1	5	100	5	0.1	5	5	NA	
Slag	NA	<0.01	<0.01	NA	NA	NA	<0.05	<0.01	<0.01	[4]
Dust from melting	NA	<0.01	0.02	NA	NA	NA	<0.05	0.03	0.85	
Slag	0.003	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	[3]
Standard limit	NA	1	5	15	NA	0.2	5	5	1	
Slag from BA(ppm)	0.150	NA	NA	4.54	0.88	NA	0.026	0.019	NA	[18]
Slag from FA (ppm)	0.075	NA	NA	0.366	0.032	NA	0.051	0.061	NA	
WAC (Italy) (ppm)	5	NA	NA	5	1	NA	1	0.2	NA	
Slag (mg/kg)	0.2	<0.0025	<0.007	0.076	0.023	0.0031	<0.016	<0.007	NA	[17]
Inert landfill WAC (London)	4	0.04	0.5	2	0.4	0.01	0.5	0.5	NA	

BDL –Below Detection Limit, NA – Not Available, ND – Not Detected, WAC – Waste Acceptance Criteria

5. Conclusion

Plasma melting offers a convenient treatment technique for detoxifying hazardous incinerator ashes. The technique used electric energy to generate high temperature plasma which melt incinerator ashes into vitreous slag that transform to glass ceramic upon cooling. The basicity of the ash affects the crystal formation of the slag. The lower the basicity the higher the chances of forming glassy vitreous matrix. Metals like Fe, Cu, Na, Ca, and Al are separated into ingot. Methods of cooling, water quenching or air cooling, determine the nature of crystal product developed from the vitreous slag. Products like gehlenite, wollastonite and diopside are formed through water quenching of slag while akermanite, mayenite and gehlenite are developed from gradual cooling in ambient air. Heavy metals present in the ashes are embedded within the crystalline structure of the glass ceramics, thereby preventing their leaching into the environment. Incinerator fly ash contained less silica materials than the bottom ash and therefore vitrification of fly ash requires addition of silica materials like glass cullet or magnesia. Additives like lime and colouring agents affect the crystal structure of glass ceramic formed. Products from the plasma melting of incinerator fly or bottom ashes can therefore be used in the building and construction industries. The flue gas from the treatment process can be free of dioxins and furans. This thermal process has thus not only makes waste harmless but generates wealth from it. However more work needs be done in aspects of regulation and product characterisation.

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