Thermal Plasma Treatment of Municipal Solid Waste Incineration Residue: A Review

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ABSTRACT— ***Incineration is the most common thermal method applied to treat generated municipal solid waste due to its ability to achieve volume and mass reduction of waste and energy recovery but this success comes along with the release and formation of bottom ash, fly ash and air pollution control residue that require proper treatment and management. This paper review the applicability of thermal plasma process in treating municipal solid waste residues (MSWI). Bottom ash, fly ash and mixture of bottom ash and fly ash has been subjected to thermal plasma treatment to study the slag reuse potential, volatilization and mobility of trace element, immobilisation of heavy metals and destruction of Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs). The predominant components in the residues are zinc and lead as well as oxides of aluminium, calcium and silicon (Al_2O_3, CaO and SiO_2).The need for environmentally acceptable and friendly treatment of waste and the benefit of high energy density, higher weight and volume reduction, elimination of landfill requirement and production of non-hazardous and reusable material from thermal plasma systems will continue to promotes its suitability for treatment of municipal solid waste incineration residue.***

Keywords— Thermal plasma, Fly ash, Incineration, Municipal solid waste

1. INTRODUCTION

As the global projection of Municipal solid Waste (MSW) is expected to reached 2.2 billion tonnes per year in 2025, it will continue to be a major environmental issue facing countries worldwide especially in developing countries [1, 2]. The annual growth rate of global municipal solid waste is projected to be around 3.2– 4.5% in developed nations and 2–3% in developing nations [3]. Municipal Solid Waste (MSW) refers to items such as product packaging, furniture, clothing, bottles, food waste/ scraps, newspapers, appliances, paint and batteries [4].The composition of MSW varies depending on region, income of generators, lifestyle/culture, climate, energy sources and economic affluence etc. but predominantly it is made up of 50% organic waste as presented in the world bank 2012 report on technical guidance of municipal solid waste [5]. Municipal solid has been defined differently by various countries [6] On a general perspective, MSW typically will consist of biodegradable waste, inert waste, electric and electronic (WEE), hazardous waste, toxic waste, medical waste and recyclable material. The composition of municipal solid waste varies depending on factors such as economic development, culture, climate and energy sources. Figure 1 is a representation of typical municipal solid waste composition by regions.

Basically, incineration involves combustion. The modern MSW incineration facility is mostly made up of three sections: incineration, energy recovery and air pollution control [7]. MSW is converted into ash, flue gas and heat. The ash is derived from the inorganic portion of the waste. Depending on the composition and degree of recovery of materials. It can achieve reduction of the solid mass of original waste by 80-85% and volume reduction by 95-96% but the treatment process is associated with environmental problem most especially air pollution[8].This is due to the presence of high concentration of heavy meals, dioxin and furans in fly ashes. The introduction of air pollution control devices e.g. dry/semi dry and wet scrubbers to treats toxic flue gases seriously reduce the problem but there a still concerns on the emission levels from incinerator of such persistent organic pollutants and heavy metal to the environment [9, 10]. Incineration is widely applied for municipal solid waste treatment most especially in countries with problem of land scarcity.

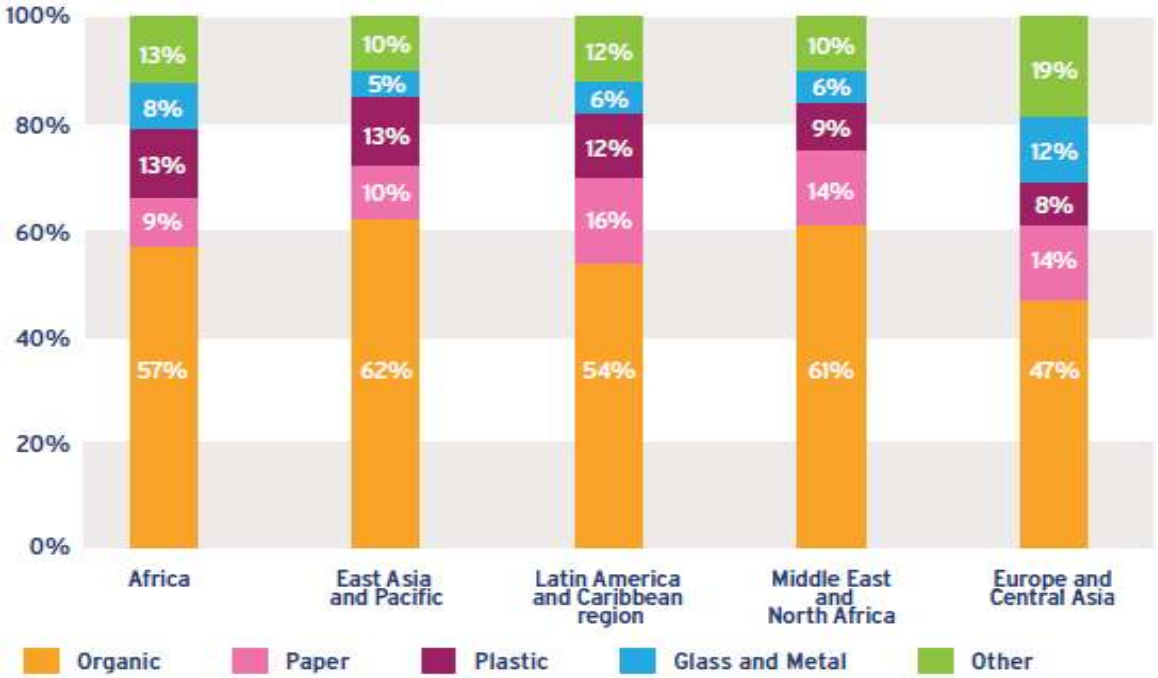

Figure 1:Typical global municipal solid waste composition by region [5].

1.1. Types of Incineration

There are basically three types of incineration in terms of operation technology. The mass burnt, modular combustors and fluidised bed combustors. In mass burnt unit the destruction of large volume of waste is done without pre-processing other than the removal of large items that cannot pass through the system. Its operation involves the introduction of excess air. The large mass burn units are characterised by low combustion temperatures. This is due in part to the high moisture, low heating value fuel, poor air/feed mixing as a result of a lack of feed processing, and lack of supplemental fuel [11]. Modular combustors are similar to mass burn units in terms of burning waste that are not pre-processed but mostly design to manage low quantity of waste per day. The most common of modular combustors is the starved air or control air type. Lastly, in fluidised bed combustors bed of sand is agitated by an upward flow of air which passes through a porous plate. The waste is shredded to obtain suitable size for efficient combustion of waste within the bed. A typical municipal solid waste incineration facility is shown in figure 2.

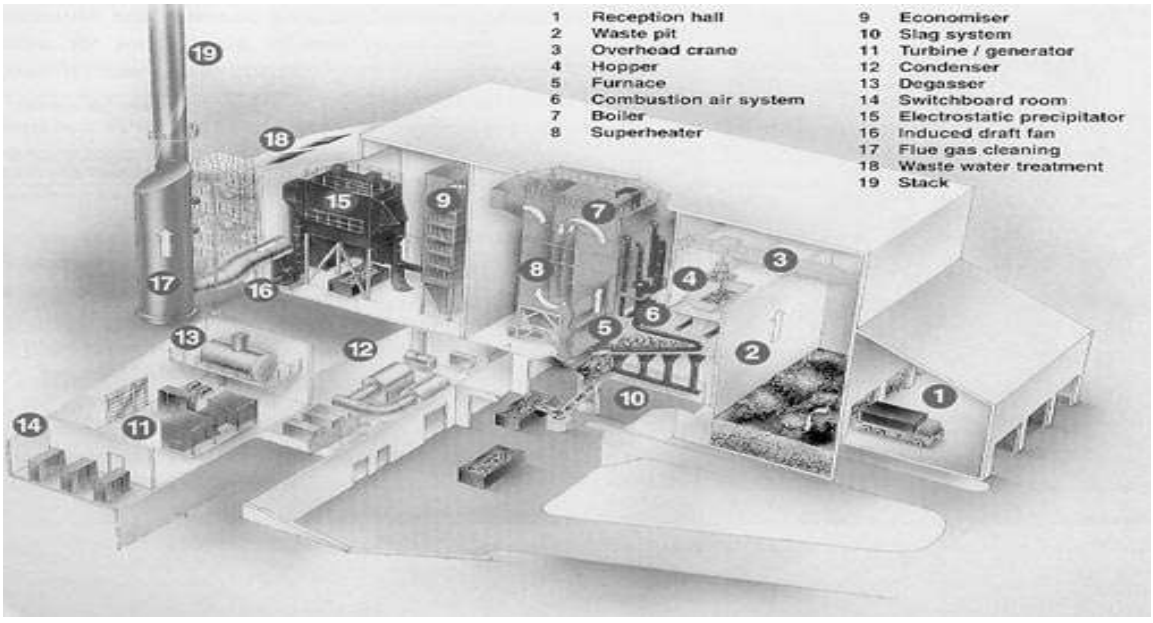

Figure 2: Typical waste to energy incinerator [12]

2. INCINERATION RESIDUES

2.1 Bottom Ash

Bottom Ash (BA) is referred to as grate ash discharged from the furnace grate and collected in the water quenching tank. During the process, the BA is combined with grate shifting (fine particles falling through the furnace) and heat recovery ash (particulate matter collected from the heat recovery system). BA is primarily a coarse, heterogeneous, non-combustible materials and unburned organic matter. According to [12] bottom ashes is of coarser dimensions, and the amount of chlorides and hazardous chemicals is significantly lower than in fly ashes [13].

2.2 Fly Ash

Fly Ash (FA) is the fine particulate matter found in the flue gases downstream of the heat recovery units which is removed before any further treatment of the gaseous effluents. Typical amount of fly ash produced by an MSW incinerator is in the order of 1–3% of the waste input mass on a wet basis [14]. Fly ashes from incinerators has high heavy metals, dioxin and furans [15-19].

2.3 Air Pollution Control Residue

Air Pollution Control Residue (APC) is basically the particulate material captured as a result of injection of reagent in the acid gas treatment units prior to effluent gas discharge into the atmosphere. Air pollution control (APC) residue is of fine particle size and generally contains high concentrations of heavy metals and soluble/volatile salts. They also contain hazardous organic compounds such as dioxins and furans. It can be in the form of solid, liquid or sludge, depending on whether dry, semi-dry or wet processes are adopted for air pollution control. APC residues are usually in the range of 2% to 5% of the original waste on a wet basis. [9, 20]. Its high alkalinity, high leachability of heavy metals and the high level of soluble anions, such as chlorides, make APC residues difficult to manage.

The physiochemical characteristics of municipal solid waste incineration residues varies. It depends on the nature of original waste, the type of incinerator and pollution control equipment [21, 22]. Previous researches indicate the major oxides found in ashes are SiO_2, Al_2O_3, CaO, Fe_2O_3, Na_2O, and K_2O. The most abundant oxides found in bottom ash and fly ash are SiO_2 (49 wt %) and CaO (46 wt %) respectively [23-29]. Table 1and 2 are showing the composition of oxides and elements in BA, FA and APC from municipal solid waste incinerator respectively.

Table 1: Typical composition of oxides in bottom ash, fly ash and air pollution control residue from municipal solid waste incineration [13, 24, 27]

Typical Composition of oxides in Bottom Ash, Fly Ash and Air pollution Control residue from Municipal Solid Waste Incineration (wt %)			
Oxides	Bottom Ash (BA)	Fly Ash (FA)	Air pollution Control Residue (APC)
CaO	14.4-51.4	12.45-46.1	13.9-38.74
SiO_2	2.25-47.8	0.13-24.84	6.19-33.6
Al_2O_3	0.18-17.0	0.14-12.7	3.64-11.6
Fe_2O_3	3.84-19.1	032-6.77	0.75-2.58
MgO	1.05-5.91	0.57-3.76	1.26-3.16
K_2O	0.6-2.6	2.03-15.24	2.6-8.77
Na_2O	1.42-8.20	2.71-9.17	2.2-14.0
SO_3	0.37-9.3	1.61-14.4	7.1-15.36
P_2O_5	0.9-5.24	0.26-2.7	1.06-2.81
MnO	0.085-0.3	0.04-0.2	0.06-0.12
ZnO	0.17-0.9	0.71-3.11	1.04-1.9
TiO_2	0.77-1.5	0.85-3.12	0.99-1.7

Table 2:The range of total content of elements in MSWI residues [10]

Element	Concentration (mg/kg)			
	Bottom Ash	Fly Ash	Dry/Semi Dry APC Residue	Wet APC Residues
Al	22,000 -73,000	49,000 - 90,000	12,000 - 83,000	21,000 - 39000
As	0.1-190	37 - 320	18 - 530	41 - 210
Ba	400 - 3000	330 - 3100	51 - 14,000	55 - 1600
Ca	370 - 123000	74,000 -130,000	110,000 - 350,000	87000 - 200,000
Cd	0.3 - 0.7	50 - 450	140 - 300	150-1400
Cl	800 - 4200	29,000 -210,000	62,000 - 380,000	17,000 -51000
Cr	23 - 3200	140 - 1100	73 - 570	80 - 560
Cu	190 - 8200	600 - 3200	16 -1700	440 - 2400
Fe	4100 -150,000	12,000 - 44,000	2600 -71000	20,000-97,000
Hg	0.02 - 8	0.7-30	0.1-51	2.2-2300
K	750 - 16000	22,000 - 62000	5900 - 40000	810-86000
Mg	400 -26000	11,000 - 19000	5100 - 14000	19,000-170,000
Element	Concentration (mg/kg)			
	Bottom Ash	Fly Ash	Dry/Semi Dry APC Residue	Wet APC Residues
Mn	80 -2400	800 - 1900	200 - 900	5000-12000
Mo	2 -280	15 - 150	9 - 29	2-44
Na	2800 - 42000	15000 -57,000	7600 - 29000	720-3400
Ni	7- 4200	60 - 260	19 - 710	20-310
Pb	100 - 13700	5300 - 26,000	2500 - 10000	3300-22,000
S	1000-5000	11,000 - 45000	1400 -25,000	2700-6000
Sb	10 - 430	260 -1100	300 -1100	80-200
Si	91,000 -308,000	95,000 -210,000	36000 - 120000	78000
V	20 - 120	29 - 150	8 - 62	25-86
Zn	610 -7800	9000 -70,000	7000 - 20,000	8100-53,000

3. THERMAL PLASMA TREATMENT OF BOTTOM ASH, FLY ASH AND AIR POLLUTION CONTROL RESIDUE

Thermal (equilibrium) plasmas and be referred to as partially or strongly ionised gas generated by electric arc at atmospheric pressure. It is characterised by a high-energy density and the quality of temperature of the heavy particles (atoms, molecules and ions) and electrons. Due to their very high mobility, the energy given to the plasma is captured by the electrons and transferred to the heavy particles by elastic collision (Boulos, 1991; Kogelschatz, 2004). Also because of the high electron number density, associated with operation at atmospheric pressure, elastic collision frequencies are very high and thermal equilibrium (all the species of the plasma, such as ions, atoms, electrons and neutral species, maintain the same temperature) is rapidly reached. plasma that have attained temperature of 10,000k and above and the energy transfer from the electrons to gas heating occurs fast enough for T_0 to equal the electron temperature T_e can be categorise as thermal plasma[30]. Examples of thermal plasma are those produced in radio frequency (RF) inductively coupled discharges and by direct current (DC) plasma torches (Boulos, 1996).

Thermal plasma technology can be applied to treat, recycle and utilise incineration ashes. Thermal plasma vitrification at about 1360^{o}c – 1500^{o}c can transform an inhomogeneous bottom ash into homogenous glassy slag. The vitrified bottom ash contain average percentage of 12.2% Al_2O_3, 52.1% SiO_2, 2.3% MgO, 4.2% Na_2O, 16.2% CaO and 7.7% Fe_2O_3, also 82% Fe and 12% Cu and small percentages of other elements such as P, S, C has been recovered [31-34]. Several researches focusing on volatisation and mobility of trace elements, reuse potential, removal of hazardous characteristics of incineration residues using thermal plasma has been conducted.

In 2015, treated fly ashes of MSWI in thermal plasma reactors of operating temperature between 1450^{o}C-1500^{o}C produced a stablise material that is safer for storage in landfills. The vitrified harmless slag was suitable for subsequent reuse[35, 36]. Researches has been conducted in the year 2013 and 2014 by [37, 38] to render fly ashes from municipal solid waste incinerator and medical waste incinerator harmless. A melting process based on a direct current thermal plasma torch was developed to convert fly ash from medical waste incineration into harmless slag [37]. Investigation was conducted on the density and micro-structure of the original ash and melted slag to evaluate the performance of the plasma melting process. The effect of the treatment on the destruction of PCDD/Fs and the immobilization of heavy metals was also examined. The working gas of the plasma torch was argon and its flow rate was varied from 12 to 14 L/min. The double arc plasma torch was operated in direct current mode with typically 20-30 V/100A for the first arc and

50 - 60 V/100A for the second arc. The temperature of the argon plasma jet near the torch exit is about 11,000 K, and the heat flux of the plasma jet around 65 kW/m^2 at 14 cm downstream from the plasma torch exit [39, 40]. Samples were collected from different medical waste incinerator FA1 and FA2.The physiochemical properties of the samples indicate major elements in FA1 were oxygen, calcium and chlorine, while oxygen, carbon and silicon were the major elements of FA2. Both fly ashes contained high concentrations of heavy metals, especially zinc and lead. Also the ash content (incombustible inorganics) of FA1 was 81.85%, much higher than that of FA2, which was only 34.45%.

The experimental results show that the decomposition rate of PCDD/Fs is over 99% in toxic equivalent quantity value and the leaching of heavy metals in the slag decreased significantly after treatment. The produced slag has a compact and homogeneous microstructure with density of up to 2.8 g/cm^3[37]. Previous researches carried out indicates that ashes brought out more than 90% of polychlorinated dibenzo-p-dioxins dibenzofurans (PCDD/Fs, as I-TEQ), polybrominated diphenyl ethers (PBDEs, as TEQs), and polybrominated dibenzo-pdioxins and dibenzofurans (PBDD/Fs) from an incinerator [41-43].

The mass distribution of metals and the crystalline characteristics of slag during the vitrification of incinerator fly ash from bag house filters of a municipal solid waste incinerator located in southern Taiwan were investigated [44]. The premixed powdery specimens were held in graphite crucibles, and then heated in a vitrification furnace (Dengyng DFH-30). The specimens were heated from 25 to 1000°C at a heating rate of 6 °C/min, from 1000°C to 1450°C with a heating rate of 4 °C/min, isothermal held at 1450°C for 0.5hr and cooled to room temperature without any convection. The vitrification shows, metals with low boiling points (Cd, Pb, and Zn) vaporized into flue gas as particulate phase. High levels of Pb and Zn of 315,000 mg/kg and 226,000 mg/kg respectively made the particulate phase worth reclaiming. Metals with high boiling points mainly stayed in the slag.

Major crystalline phases of the slag were 15.9% Ca_2SiO_4 and 12.1% often found in a thermal melting environment with a mass ratio of CaO/SiO_2 ~1[45, 46]. In 2010, it was demonstrated that glass derived from DC plasma treatment of APC residues can be used to form high strength geopolymer–glass composites [47]. The research investigated the optimisation and properties of geopolymers prepared from the glass. It also shows that High strength geopolymers can be formed and NaOH concentration of the activating solution significantly affects the properties. A mix prepared with S/L = 3.4, Si/Al = 2.6 and [NaOH] = 6M in the activating solution, produced high strength geopolymers with compressive strengths of ~130 MPa. This material had high density (2070 kg/m^3) and low porosity.

Treated fly ash from municipal solid waste (MSW) incinerator without additives in a DC arc plasma furnace achieved volume-reduction and recycling of vitrified slag [48]. This process uses extremely high-temperature in an oxygen-starved environment to completely decompose complex waste into very simple molecules. A novel crucible-type plasma furnace was used. The DC plasma arc, plasma gas flow rate and ash throughput were 100kW, 12 L/min and 0.0278 kg/s respectively. The heating rates of fly ash were controlled to about 10 K/min. The molten slag was kept above 1700 K for 10 min. The produced granulated slag was less than 1/3 of the original volume of the fly ash and 64% of the weight of the fly ash. The melting process metamorphosed fly ash to granulated slag that was less than 1/3 of the volume of the fly ash, and about 64% of the weight of the fly ash. The slag was subjected to different cooling methods. Water-cooled and composite-cooled slag showed more excellent resistance against the leaching of heavy metals as shown in Table 3.

Table: 3. Leaching test results for fly ash and various slag [48]

Samples	Toxicity Leachate (mg/l)					
	Zn	Cd	Cr	Pb	As	Hg
Fly ash	0.38	0.0013	1.41	12.19	0.011	0.011
Air-cooled slag	0.02262	0.001455	0.002168	0.104	0.0055	<0.0005
Water-cooled slag	0.02660	0.001134	0.000814	0.0229	0.0006	<0.0005
Composite-cooled slag	0.03165	0.000197	0.000258	0.0315	-	-
Upper limit by law	100	1	5	5	5	0.1

Heavy metals originated in the incinerated ash are confined in the treated silicate framework, hence yielding very low leachability results [49-51]. It also presented better resistance to the decomposition by an acid than the crystalline structure. Treated incinerated ashes, and slag has the potential to serve as a viable alternative for construction applications [52-54].

Again, Fly ash without additives was melted in a DC thermal plasma reactor[55]. The core of the reactor used is a Dc double anode plasma torch. Vitrification of the fly ash shows an obvious change in the microstructural and the mineralogical characterization, an excellent resistance against leaching of heavy metal ions and a significant decomposition rate (99.95%) of PCDD/Fs in TEQ in the produced slag. These results indicate that the thermal plasma vitrification is an alternative technology with high efficiency and energy to dispose MSWI fly ash. APC residues from waste to energy (WtE) plant in London UK were blended with silica (21.9wt %) and alumina (8.3 wt. %), and treated in a DC plasma transferred arc furnace. Leach testing demonstrated that the APC residue derived glass released only trace levels of chloride (0.2 mg/kg) and metals (lead (0.007 mg/kg) and zinc (0.02 mg/kg)[56]. A non-transferred plasma torch with a tungsten cathode and copper anode treated mixes of fly ash and sludge in Korea to determine the reduction in volume and removal of hazardous elements in fly ash and sludge from wastewater treatment on a laboratory scale. The leaching test on the vitrified slag showed that heavy metals leached below the regulatory limits.[50].

The incinerated ash from a MSW incinerator in Taipei was melted in a 100kW non-transferred arc plasma laboratory-scale torch at the Institute of Nuclear Energy Research (INER) in Taiwan [49, 57]. Argon was used for ignition of the plasma, and nitrogen as the carrier gas during treatment. Heavy metals originally in the incinerated ash were encapsulated in the vitrified silica network, resulting in very low leachability. Wet IBA from a MSW incinerator in Japan was treated in a DC graphite-electrode plasma melting furnace with nitrogen as the plasma gas [58, 59]. The concentration of lead, cadmium and Cr^{+6} in the slag was very low (Pb and Cd: 0.01mg/l) and 99.9% of dioxins and furans was destroyed. Jimbo in 1993 treated IBA and fly ash mixes in a DC transfer arc plasma furnace for over 28 months. The slag obtained had a lead content of less than 0.01mg/l with no traces of dioxin[60].

Fly ash from the municipal waste incinerator plant in Budapest was melted in a laboratory scale DC plasma furnace at 1600◦C [61]. Single-stage crystallisation heat treatments were performed on bulky samples in chamber furnaces at different temperatures. The microstructure of the vitrified product was investigated. The main crystalline phases obtained were wollastonite ($CaSiO_3$) (the majority) and anorthite ($CaAl_2Si_2O_8$). Also, Researches on the vaporisation behaviour of heavy metals produced by plasma treatment of incinerated ashes has been carried out [62].Table 4 is summary of thermal plasma treatment of municipal solid waste incineration residue highlighting focus of study.

Table 4: Summary of researches on thermal plasma treatment of MSW incineration residues

Type of incineration residue	**Focus of study**	**Reference**
Fly ash	Slag reuse potential, immobilisation of heavy metals and destruction of PCDD/Fs	[37]
Fly ash	Volatilisation and mobility of trace element/reuse potential	[44]
Air Pollution Control Residue	Generation of geopolymer-glass	[47]
Fly ash	Slag reuse potential	[48]
Fly ash	Slag reuse potential	[55]
Fly ash	Generation of glass-ceramics	[61]
Fly ash and sludge from waste water treatment	Slag reuse potential	[50]
Fly ash	Elimination of hazardous characteristics	[49]
Bottom ash	Slag reuse potential/process viability	[58]
Bottom ash	Mobility of trace elements	[63]
Fly ash	Slag reuse potential	[64]
Fly ash	Volatilisation of trace element	[65]
Fly ash and Bottom ash	Removal of hazardous characteristics/reuse potential	[59]
Fly ash and asbestos	Removal of hazardous	[66]
Fly ash from a power plant and Bottom ash from hospital incinerator	Reuse potential/volatilisation and mobility of trace element.	[67]
Fly ash	Volatilisation of trace elements	[68]

Treated municipal solid waste incineration residues are utilize for different purposes. Controlled addition of pretreated fly ash can be used to replace raw material in Portland cement production. Cement clinker using large amount of ash which is refer to ecocement has been developed in Japan [69, 70]. The addition of municipal solid waste incineration ash for clinker production shorten the setting time and decrease workability [71-73]. MSWI fly ash could

also be used as lightweight concrete aggregate by processing into pellets. This could be suitable for interior walls for insulating purposes (non-structural application).bottom ash used in the road base for construction did not affect the release of heavy metals. Fly ash has been utilised to produce stones for permeable pavement. Despite the low content of municipal solid waste incineration fly ash (15-30%) fusion or hydrothermal processes has been applied to synthesis different types of zeolites. Mixed fly ash of MSW and coal is more feasible in production of zeolite from MSWI ashes. Improved quality zeolite was produced [74].

The use of MSWI ashes for production of glasses, glass-ceramic and ceramics is possible at temperature > 1000^{o}C. Mixtures of fly ash and bottom ash has produced ceramic tile body[26]. When fly ash was mixed with cream coloured clay, fired clay, limestone in the ratio of 4:3:1:2, a high compressive strength and low water tile after sintering at 960^{o}C was obtained [27]. Investigations by [23, 29, 75, 76] have successfully indicated that vitrified ashes can be used as raw material for production of production of glass ceramic. Factors affecting the glass ceramic produced are heat treatment time and temperature. According to [77] the glasses obtained from vitrification process showed excellent resistance against leaching of heavy metal ions, an indication that the vitrification technique is effective for the stabilization and recycling of toxic incinerator fly ash. Table 5 is a summary of the Properties of glass–ceramics obtained after heat treatment of the vitrified product of plasma treatment (slag).

Table 5: Properties of glass-ceramic obtained after heat treatment of the vitrified product of plasma

Properties	Vitrified bottom ash +fly ash at 950^{o}C [78]	APC residue glass+ cullet glass [79]	Vitrified Air pollution Control Residue (APC) [80]	Vitrified fly ash (1050^{o}C)[61]	Vitrified ash incinerator (one step heat treatment at 850^{o}C) [49]
Compressive strength (MPa)	-		-	-	-
Flexural strength (MPa)	-	60	-	-	-
Four point bending strength (MPa)			81	-	-
Vickers hardness (MPa)	6203- 6864	5.4	6.0	-	-
Knoop hardness (GPa)	-	-	-	-	4.84
Mohs hardness	-	-	-	7.0	7.0
Chemical resistance (wt %)	5 wt% HAC, NaOH.			20 wt% HCl 0.45 20 wt% NaOH 2.67	
Water absorption (%)	0.19-0.61	< 6%	-	-	-
Water adsorption (%)	-	-		-	0.28
Main crystalline phases	Gehlenite, Akermanite, wollastonite	Gehlenite, wollastonite Anorthite	Anorthite wollastonite melilite, Kyanite	Anorthite wollastonite	Albita, anorthite,wollastonite cristobalite
Thermal expansion coefficient ($\times 10^{6}C^{-1}$)					9.85
Density (g/cm^{3})	2.35-2.50 (without cooling) 2.29-2.60 (cooling)	2.4	2.6		2.99

4. CONCLUSION

Several researches focusing on volatisation and mobility of trace elements, reuse potential, removal of hazardous characteristics of incineration residues using thermal plasma has been conducted on bottom ash, fly ash, mixtures of bottom ash and fly ash, mixtures of bottom ash and asbestos. It produced a homogeneous and inert slag and effectively destroyed PCDD/Fs and immobilised heavy metals. The properties of incineration residues promotes their reuse as adsorbent, construction material and for geotechnical purposes. Thermal plasma technology has therefore prove to be a highly efficient and capable of treating municipal solid waste incineration residue.

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