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Thermal Waste to Energy a Global Perspective, Environmental Standards and Thermal Waste to Energy Residues Transformation into eco-concrete

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ATTESTATION

I do hereby attest that I am the sole author of this thesis and that its contents are only the result of the readings and research I have done.

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Abstract

There are over 1700 Thermal Waste to Energy Plants worldwide a number that is increasing as more than 200 new facilities are currently under construction and can be operational by 2023 including the two largest plants in the world located in Dubai and Shenzhen China. Thermal Waste to Energy, also known as incineration with energy recovery, is a major and preferred waste treatment method in many developed countries and the most widely adopted technology that dominates the global Waste to Energy market. Most of all thermal Waste to Energy plants are located in developed countries, led by Japan, France, Germany and the United States.

Most Waste to Energy plants burn municipal solid waste, but some burn industrial waste or hazardous waste. In terms of volume, Waste to Energy plants incinerate waste reducing up to 90 percent of waste mass.

The resulting residue after the waste incineration process up to 25% of the total mass is divided into two waste streams Fly Ash and Bottom Ash, Fly Ash is classified as a hazardous waste due to the presence of high quantities of heavy metals and Bottom Ash although classified as non-hazardous waste it can be; in the USA both waste streams are combined and disposed of in landfills, in Canada these two waste streams are disposed separately in landfills, in Europe fly ash is disposed in specific landfills for hazardous waste and a percentage of bottom ash is used beneficially as a road subbase if it complies with the environmental regulations.

In this research work, world current residues management practice, existing regulations, and environmental consequences of MSWI residues beneficial uses are comprehensively reviewed worldwide with an emphasis in the fly ash acid treatment and the potential area of its utilization in eco-concrete. This research also entails a detailed chemical and microstructural characterization of MSWI Fly Ash and Bottom Ash produced from two Mass burner facilities in China.

The material characterization includes Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), and X-ray Diffraction (XRD) techniques. In addition, leaching tests as US EPA TCLP and China HJ/T 299-2007 have been conducted to investigate the environmental properties and demonstrate that Acid Fly Ash treatment is effective in transforming the heavy metals present in fly ash into metals resistant to leaching and that the combination of acid treatment plus the use of nano composites in combination with Portland cement are effective in encapsulating heavy metals preventing

heavy metals leaching allowing the beneficial use of all fresh Combined Ash (Fly Ash + Bottom Ash) in eco-concrete.

The final result shows that it is possible to transform at a low cost all the Fly Ash and Bottom Ash generated daily into eco-concrete while complying with all USA EPA environmental standards, EU environmental Standards and China environmental standards.

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LIST OF ABREVIATIONS

Cases

APC : Air Pollution Control 5
BC : British Columbia 9
BOT : Build Operate Transfer 30
CAA : Clain Air Act 15
CAGR : Compound annual growth rate 35
CEN : Committee for Standardization 76
DSWMC : Domestic Solid Waste Management Centre 31
ECS : Eddy Current Separation 82
EEP : Ethiopian Electrical Power 33
EfW : Energy from Waste 4
EFW : Enegy from Waste 8
FBC : Fluidized Bed Combustion 5
HMA : Hot Mix Asphalt 1
IC&I : Industrial, Commercial and Institutional. 9
JCPDS : Joint Committee on Powder Diffraction Standards 90
MACT : Maximum Achievable Control Technology 16
MDS : Magnetic Density Separation 82
MSW : Municipal Solid Waste 1
MSWI BA: Municipal Solid Waste Incineration Bottom Ash 2
MSWI FA : Municipal Solid Waste Incineration Fly Ash 2
MSWI : Municipal Solid Waste Incineration 1
Mt : Million tonnes 25
MWh : Mega Watt hour 5
NHSM : Non Hazardous Secondary Material 19
PCC : Portland Cement Concrete 2
PEI : Prince Edward Island 10
POC : Point of Contact 75
RCRA : Resource Conservation and Recovery Act 19
RDF : Refuse Derived Fuel 5
REO : Russian Ecological Operator 34
SEM : Scanning Electron Microscopy 2
TCLP : Toxicity Characteristic Leaching Procedure 2
TCLP : Toxicity Characteristic Leaching Procedure 72
WAC : Waste Acceptance Criteria 66
WtE : Waste to Energy 1
XRD : X-ray diffraction analysis 2

CHAPTER 1 INTRODUCTION

CHAPTER 1 INTRODUCTION

1.1 Problem Statement

Thermal Waste to Energy (WtE), also known as waste incineration with energy recovery, is a major and preferred waste treatment method in many developed countries and the most widely adopted technology that dominates the global WtE market. During the waste incineration process great amounts of residues and ash are generated, the amount of ash generated ranges from 15-25 percent (by weight) and from 5-15 percent (by volume) of the Municipal Solid Waste (MSW) processed. Generally, MSW combustion residues consist of two types of material: fly ash and bottom ash. Fly ash refers to the fine particles that are removed from the flue gas and includes residues from other air pollution control devices, such as scrubbers. Fly ash typically amounts to 10-20 percent by weight of the total ash. The rest of the MSW combustion ash is called bottom ash (80-90 percent by weight). In the USA the ash that remains from the MSW combustion process is combined and sent to landfills [1], in Canada, on the other hand the ash is disposed of in separate landfills [2], in Europe the percentage of bottom ash that complies with environmental regulations is used beneficially usually as road subbase, and in Singapore all the ash generated daily is combined and disposed of in the landfill [3].

As ash monofills around the world are reaching full capacity many countries have addressed the issue of beneficial utilization of MSWI ashes by establishing and executing strategic management plans and regulations [4] [5].

Many countries in the European Union have beneficially utilized only MWI bottom ash as a sustainable material complying with the set environmental criteria by regulators [6], however, a big percentage of the bottom ash is still disposed of in landfills [7] . In the U.S. on the other hand all the ash generated by the current 75 Waste to energy plants [8] (approximately 8 million tons a year) are combined and disposed of in landfills [9], Canada generates approximately 250,000 tons a year. In spite of successful demonstrations on the application of MSWI ashes in a number of construction projects [10], disposal of ashes in landfills has remained a common practice in the U.S., Canada, Singapore, Macao, etc., which leads to negative environmental impact associated with landfilling. Therefore, efforts are required to be taken to identify the potential area of beneficial utilization of MSWI ashes such as Hot-Mix Asphalt (HMA) and Portland cement concrete (PCC). Chemical and environmental properties associated with those applications are also needed to be addressed so that sustainable utilization of MSWI ash can be ensured.

1.2 Objectives and Overview

In this study, the current world situation in regards to Thermal Waste to Energy Residues management and environmental consequences were comprehensively reviewed, emphasizing the potential area of its utilization as per my research in concrete product. In order to find out the suitable applications of MSWI ashes utilization, characterization of chemical and microstructural properties was conducted with MSWI ashes from two of the incineration facilities in China. China has a large number of Thermal Waste to Energy Plants currently 400 but the central government has a goal to duplicate this number by 2022. This Thesis presents: (1) A global perspective of the current and future trends of the Thermal Waste to Energy Technology and sector. (2) The environmental regulations that apply to Thermal Waste to Energy Ash, whether it can be beneficially used or if it has to be landfilled and the type of landfill that ash should be disposed of in. (3) A comprehensive review on the MSWI ash beneficial uses, treatment and leaching. (4) Material characterization of MSWI bottom and fly ashes by spectroscopic techniques and microanalyses, and a comprehensive review of engineering properties, leaching properties and behaviors of PCC containing MSWI BA. Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), and X-ray Diffraction (XRD) techniques were employed. (5) An evaluation of Thermal Waste to Energy Bottom Ash and Combined Ash when used beneficially as aggregate in Portland Cement Concrete was done as well as the evaluation of phosphoric acid when use to treat fly ash. The expected outcomes of this research study are: 1. Comprehensive review of current management practice, existing regulations, and environmental consequences of MSWI ashes utilization; 2. Detailed chemical and microstructural characterization of MSWI BA and MSWI FA produced in China, using SEM, EDS, and XRD techniques; 3. Environmental properties and impacts, leaching tests as per US EPA TLCP, and as China HJ/T 299-2007 leaching test done on eco-concrete made with bottom ash and combined ash. 4. Latest test done in China for MSWI Combined Ash beneficial applications in concrete.

1.3 Organization of the Thesis

Apart from this chapter, the remainder of the thesis has been divided into seven chapters. Chapter 2 Exhibits the world current Waste to Energy Market, trends, future plants, Energy generated, etc. Chapter 3 represents the overview of the Municipal Solid Waste Incineration residues management and shows a brief discussion on the properties of MSWI ashes. Chapter 4 Presents the world regulation that applies for the beneficial uses of MSWI ashes and its disposals in landfills and the type of landfills. Chapter 5 Exhibits current MSWI ashes beneficial uses around the world, types of ash treatment and includes the review on the leaching test procedure commonly practiced in the U.S. and China when ash is used as a material replacement in concrete. Chapter 6 Includes the microstructural evaluation of MSWI ashes using SEM, compositional analysis using EDS, and mineralogical analysis using XRD techniques. Furthermore, it covers the chemical characterization of MSWI ashes by conducting laboratory chemistry experiment. Discusses the leaching evaluation of MSWI BA and MSW I. Combined Ash in PCC. Leaching characteristics of inorganic constituents from MSWI ashes when used in PCC have been investigated by using the TCLP test as per US EPA and HJ/T 299-2007 as per Chinese environmental regulation were conducted in the laboratory. Finally, chapter 7 Presents the latest development of fly ash treatment with phosphoric acid demonstrating a leaching reduction of heavy metals and the possible beneficial use of fly ash in combination with bottom ash in eco-concrete and a major conclusion of the study and also provides recommendations for the further study. Attempts are made to draw conclusions from various findings of the study and recommendations provide a basis of further study.

CHAPTER 2
WORLD THERMAL WASTE TO ENERGY A REVIEW

CHAPTER 2WORLD THERMAL WASTE TO ENERGY A REVIEW

2.1 Introduction

Many countries in the world use Thermal Waste to Energy plants (WtE) to capture the energy in Municipal Solid Waste. The use of waste to energy plants in some European countries and in Japan is relatively high, in part because those countries have little open space for landfills.

A Waste to Energy (WtE) plant is a waste management facility that combusts wastes to produce electricity. This type of power plant is every now and then known as an Energy from Waste (EfW) Plant, Thermal Waste to Energy Plant, Municipal Solid Waste Incineration to Energy Plant, or resource recovery plant.

Modern Waste to Energy plants are very different from the trash incinerators that were used in the past just a few decades ago, these types of incinerators did not remove any dangerous substances, endangered the health of plant workers and nearby resident and did not generate any energy.

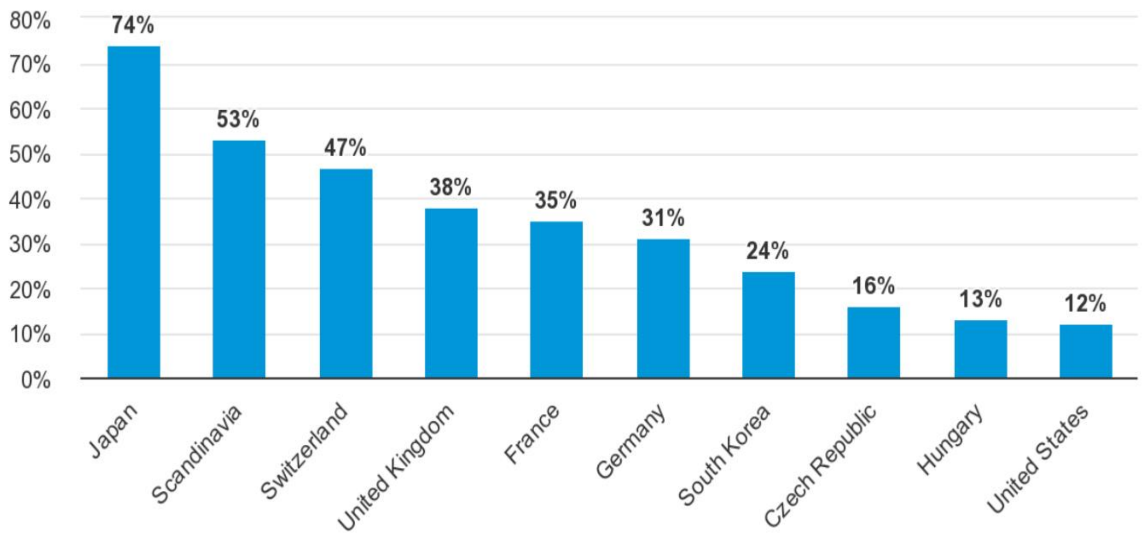


Figure 1 MSW incinerated with energy recovery selected countries

Percentage of total municipal solid waste that is burned with energy recovery in selected countries.

Note: Scandinavia includes Denmark Norway and Sweden. Data year for South Korea is 2016, Japan 2017 and for all other countries is 2018 [11].

Waste to Energy technology is getting attention because the potential of generating electricity the incineration of about 2,200 tons per day of waste will produce about 1200 MWh of electrical energy, in addition the incineration of waste reduces the waste mass by 80% to 90%.

Usually, Waste to Energy plants incinerate Municipal Solid Waste, but some Incinerate Industrial Waste, Waste Water Sludge, Hazardous Waste, etc. A current, well run Waste to Energy plant separates recyclable materials pre-incineration and incinerates waste that cannot be recycled.

The design of all Waste to Energy plants in general are very similar including biomass plants. First, the waste is brought to the facility. Then, the waste is sorted to remove recyclable and hazardous materials. The waste is then stored until it is time for burning. A few plants use gasification, but most combust the waste directly because it is a mature, efficient technology. The waste can be added to the boiler continuously or in batches, depending on the design of the plant.

There are three main types of WtE plant designs. These are mass burn, refuse derived fuel (RDF), and fluidized bed combustion (FBC). Mass burn plants burn the MSW as received at the plant, except to remove bulky items or other materials that cannot or should not be processed through the plant. Many of these plants process the ash to recover metals for recycling. RDF plants burn MSW processed to remove noncombustible materials and shredded into a more uniform fuel. The RDF may be injected into the plant's boiler above the grate to burn in semi-suspension or injected across the burning grate in a spreader stoker. Sometimes shredded RDF is densified into pellets or cubes and used as a partial substitute for coal. FBC burns RDF injected into a hot to fluidized bed of noncombustible granular material. Some consider FBCs to be RDF plants. All these plants produce ash and residues and the percentage will depend on the waste. Characteristics of the ash may vary among the designs depending on process efficiency, waste preprocessing, the air pollution control (APC) system, waste composition, and other site-specific factors.

The terms ash and residues are often used interchangeably. This, however, can be misleading. Ash refers to the matter that remains after complete combustion has taken place and is separate and different from APC residues. Residue includes unburned material, scrubber sludge, reaction products from the APC system, and other material that may end up in the final ash and residue stream. Consequently, from a technical viewpoint, residue includes the ash. Although technically there are more, three categories are routinely used to classify the residues as bottom ash, APC residues, and combined ash (the combination of bottom ash, APC residues, grate siftings, and heat recovery ash). Plants in the United States combine these streams for management in the plant. In most European countries and Canada, the bottom ash and the APC residues are collected separately, the same process takes place in Canada and Singapore, however, in Singapore although the residues are collected separately at the plant for ferrous and non-ferrous recovery, the two waste streams are combined and transported to the landfill.

Technically, ash and residues appear at several locations in the process. Bottom ash comprises most of the residue generated. The quantity of bottom ash in the residue depends on the combustion facility design, operating conditions, and characteristics of the waste being combusted for example newer plants in China tend to shred all the waste to be incinerated. Typically, about 80%–90% by weight of the residue produced is bottom ash (including grate siftings). Bottom ash is a heterogeneous mixture of slag, ferrous and nonferrous metals, ceramics, glass, other non-combustibles, high caliber plastics, and any unburned organics. After any large items are removed, it has the appearance of porous, grayish, silty sand and gravel.

The APC residues consist of very fine particles collected by the APC equipment and the residues from chemicals used to treat emissions. It makes up about 10%–20% by weight of the ash produced. Combined ash looks very similar to bottom ash because the bottom ash is the major ingredient. The chemical composition of the fractions will vary. Most metals occur as oxides with significant amounts of metal chlorides, metal sulfates, and metal carbonates. The ash also contains trace amounts of environmentally important metals such as Pb and Cd and may contain very small quantities of dioxins and furans. The ultimate fate of these constituents in the environment caused some concern about the wisdom of using the ash

In regards to waste mass reduction, Waste to Energy plants reduce the waste mass 80 to 90 percent of waste. Although, the residue ash (Bottom Ash) is classified as a non-hazardous waste after testing the ash if clean enough it can be used beneficially in the manufacturing of cinder blocks, artificial coral reefs, coastal erosion structures, pavers, road curves, for road construction as subbase, dam Embankment or as landfill sealing and closure [12].

Modern Waste to energy plants generate less air pollution than coal plants and classified carbon-negative as the processing of waste into biofuel releases considerably less carbon and methane into the air than having waste decay away in landfills.

The emission control of Waste to energy plants are designed to reduce the emission of air pollutants in the flue gases exhausted to the atmosphere, such as nitrogen oxides, sulfur oxides and particulates, and to destroy pollutants already present in the waste, using pollution control measures such as baghouses, scrubbers, and electrostatic precipitators. High temperature, efficient combustion, and effective scrubbing and controls can significantly reduce air pollution outputs while operating up to 98% below operational certificate limits [13] .

Figure 2 WTE Emissions Limits Burnaby Canada

Waste to energy plants generate fly ash and bottom ash. The total amount of ash generated by waste to energy plants ranges from 15% to 25% by weight of the original quantity of waste and depends on the type of waste incinerated, fly ash amounts to about 10% to 20% of the total ash. The fly ash is classified as hazardous waste as it constitutes by far a more of a potential health hazard than bottom ash as fly ash contains great amounts of heavy metals such as lead, cadmium, copper, and zinc as well as small amounts of dioxins and furans, chlorides and sulfates. The bottom ash on the other hand, may or may not contain significant levels of health hazardous materials thus is classified as a non-hazardous waste. In the United States, and perhaps in other countries as well, the law requires that the ash be tested for toxicity before disposal in landfills. If after testing the bottom ash is found to surpass the parameters for admittance in landfill, it can only be disposed of in lined landfills which are carefully designed to prevent pollutants in the ash from leaching into underground aquifers.

2.2 Waste to Energy in Canada

2.2.1 State of the Waste Recovery in Canada: Energy from Waste

Energy-from-Waste (EFW) facilities are considered the 4th “R” in the waste management hierarchy of “reduce”, “reuse”, “recycle”, and “recover”. EFW is a waste treatment that recovers energy in the form of electricity, heat, or steam from a waste source after recycling and diversion, except for anaerobic digestion which typically processes source separated organics.

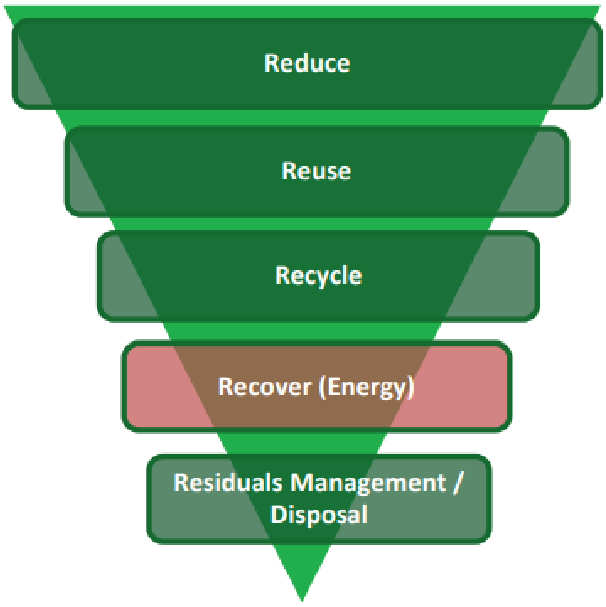


Figure 3 Waste Prevention and Reduction in the Waste Management Hierarchy

Technology options for EFW include thermal treatment (incineration with energy recovery), gasification [14], pyrolysis [15] and can be considered to include anaerobic digesters for organic waste streams (also called "biofuel facilities") which are capable of converting organic waste to energy (e.g., electricity, compressed natural gas, ethanol). Anaerobic digestion involves fermenting organic materials such as food waste, manure, sewage sludge, industrial effluent, forest and agricultural waste in an oxygen-deprived environment to produce biogas, compost and heat [16]. Some jurisdictions do not consider anaerobic digestion as an energy recovery technology; rather they consider it in the diversion category – while others do consider it as energy recovery. It can be considered as both.

In Canada there are five large EFW facilities operating that treat mixed MSW and recover heat or steam. There are an additional four large mixed MSW EFW facilities approved for construction in Ontario. There are two large anaerobic digestion facilities in BC and Ontario, with other large biofuel facilities planned in BC, Alberta, Ontario and Québec. These facilities process different combinations of food waste, wood waste, sewage sludge, or yard waste, and produce biofuel as a usable product. Only those that include processing waste from the MSW waste stream (i.e., residential and IC&I) sectors together have been identified in the following exhibit, however some jurisdictions also have industrial facilities such as paper mills or cement kilns that process MSW waste (e.g. tires) that have not been included in the following exhibit (an inventory of these facilities was not provided by jurisdictions for inclusion in this report). Similarly, facilities that primarily process sewage sludge and manure have not been inventoried [17].

Number of EFW Facilities Treating MSW in Operation and Planned for Construction

All existing large mixed EFW facilities (BC, Alberta, Ontario, Québec, and PEI) treat mixed non-hazardous MSW and generate electricity or steam. The two currently operational large MSW organics anaerobic treatment facilities are located in Richmond, BC (first commercial-scale high solids anaerobic digester facility in Canada funded in part by Natural Resources Canada's Clean Energy Fund[88]) and in Toronto (Dufferin facility). The City of Edmonton also has a large bio-fuels facility currently under construction for MSW (non-recyclable residuals). The city of Surrey, BC is planning a large biofuel facility utilizing the organics waste, and the Metro Vancouver plans to expand its EFW capacity with an additional EFW facility (but no facility currently planned). Typically, construction and operation of all EFW facilities in Canada would need a provincial or territorial approval to build, and operate. The following exhibit presents additional detail on the five large mixed EFW facilities in Canada.

Details	BC	AB	SK	MB	ON	QC	NB	NS	NL	PE	NU	NT	YT
# Large EFW Facilities treating MSW or Organics (>25t/day)	1 MSW 1 organics	1 MSW	-	-	1 MSW 1 organics	1	-	-	-	1 MSW	-	-	-
# Small EFW Facilities treating MSW / Organics (<10t/mo)	-	420[87]	-	-	-	2	-	-	-	-	-	-	-
NEW Mixed MSW EFW Facilities **Planned (Large or Small)**	-	1	-	-	4	2+	-	-	-	-	-	-	-
NEW Biofuel EFW Facilities **Planned** (Organics) ***Large or Small)***	1	1	-	-	1	7+	-	-	-	-	-	-	-

Table 1EFW Facilities treating MSW Canada

2.2.2 Existing Large EFW Facilities Primarily Treating Mixed MSW

2.2.2.1 Covanta Burnaby (Vancouver B.C.)

The Waste to Energy plant located in Burnaby owned by Metro Vancouver and operated by Covanta Holding Corporation, is located in Burnaby, British Columbia. The facility sustainably processes approximately 25 percent of Metro Vancouver's post-recycled waste, mainly from the North Shore, Burnaby and New Westminster.

Annual Performance

Every year, the Covanta Burnaby facility processes more than 281,000 tons of waste that would otherwise have ended up in landfills. The facility generates 23.9 megawatts of electricity 24/7 - enough to power 19,000 homes for a year and recovers 6,230 tons of metal for recycling annually - enough to build 5,000 cars [18].

Facility	Population Served	Waste Input	Annual Volume of Waste Processed	IBA 25% AVE year	IFA 3% AVE	Metals recovered %	Type of Energy Generated
BC (Burnaby) EFW Facility	450000	MSW / ICI non-hazardous, nonrecyclable residual waste	285,000 t/yr (780 t/d)	43,000	11,000	3.16	Electricity BC
(Wainwright) EFW Facility	10,000	MSW / ICI / biomedical nonrecyclable residual waste	11,000 t/yr (30 t/d)	2,750	330		Steam
ONTARIO							
• EMERALD EFW	1160000	MSW non-hazardous, nonrecyclable residual waste, commercial & Institutional	182,500 t/y (5oo t/d)	36,500	5,475		Electricity Ontario
• COVANTA DURAM YORK		MSW	140000 t/y (383 t/d)	30,000	4,200	2.36	
QC (Ville de Québec) EFW Facility "Limoilou incinerator"	500,000	MSW / ICI / Sludge nonhazardous, non-recyclable residual waste	300,000 t/yr (821 t/d)	75,000	2,250		Steam
PEI EFW Facility	65000	MSW non-hazardous, nonrecyclable, and sawmill residue	33,000 t/yr (90 t/d)	8,250	248		Steam

Table 2 Existing Large EFW in Canada

In regards to ash, Covanta Burnaby generates 43,000 tons a year of Bottom Ash which are acid treated and disposed of in the landfill, in addition to 11,000 of fly ash which are treated and transported to Oregon USA [19] .

2.2.2.2 Emerald Energy from Waste (Brampton Ontario)

Emerald Energy from Waste Inc. recovers thermal energy from solid non-hazardous waste from municipal (MSW) and industrial, commercial and institutional (IC&I) sources. The recovered thermal energy is converted to electricity and steam for use in our community.

The facility has 5 gasification units, each having a processing capacity of approximately 100 tons per day for a total processing capacity of 500 tons per day. Our facility has been in continuous operation since 1992, processing over 2.5 million tons of waste to date [20].

Emerald From Waste Brampton generates approximately 20% bottom ash (36,500 t/y) and 10% fly ash (3,500 t/y), all the ash generated is disposed of in landfills.

2.2.2.3 Covanta Durham York (Ontario)

Located in Courtice, Ontario, the Durham York Energy Centre is one of the newest Waste-to-Energy facilities in North America. The Facility is owned by the regional municipalities of Durham and York and serves residents of with reliable and sustainable waste management.

Every year, the Durham York facility processes more than 154,000 tons of waste that would otherwise have ended up in landfills.

Less waste in landfills reduce greenhouse gas emissions by 130,000 tons of CO_2. That’s like taking 25,000 passenger vehicles off the road for one year. The facility uses waste to produce 17.4 megawatts of electricity 24/7 - enough to power 10,000 homes for a year. Also, the facility recovers 4,250 tons of metal for recycling annually - enough to build 8,000 cars [21]. The Durham York generates approximately 20% in bottom ash (30,000 t/y) and 10% fly ash (15,000 t/y) all the ash generated in this facility is disposed of in landfills.

2.2.2.4 Wainwright Landfill Waste to Energy Plant

Located in Wainwright Edmonton Alberta, the facility incinerates 11,000 t/y of Municipal Solid Waste, commercial and institutional (IC&I) waste, biomedical non-recyclable residual waste and generates Steam for Industrial Use [22]. All the ash generated in this facility is disposed of in landfills.

2.2.2.5 Limoilou incinerator Quebec

Located in the Limoilou district, Quebec City's incinerator has been in operation since 1974. Its maximum waste treatment capacity is 312,000 tons annually. The incinerator receives household waste from the residential, institutional, commercial and industrial sectors of all of Quebec City and neighboring regional county municipalities (RCMs). The sludge from the two wastewater treatment plants is also dewatered, dried and incinerated there.

The incineration of garbage and sludge produces 65,000 tons per year of grate ash or bottom ash. Under an agreement between the city and the AIM company, it collects ferrous and non-ferrous metals (copper, zinc, aluminum). The purified clinker is thus used as a covering material for open-air landfills. The city is continuing its work on continuous process improvement. It aims to comply with the strictest industry standards in order to minimize the impact of the operation of the incinerator on the environment [23].

2.2.2.6 Prince Edward Island ENERGY SYSTEMS

Prince Edward Island is home to Canada’s longest-running, privately operated, biomass-fired district heating system. Operating since the 1980s, the system has expanded to serve over 100 customers in the downtown core of Charlottetown and contributed to the establishment of a local waste-wood fuel-supply market. With valuable agricultural and revenue-producing land being consumed for landfill, minimizing waste was an important priority. In addition, limiting use of imported fuel sources was also important for ensuring long-term energy price stability. Charlottetown is an excellent example of how provincial energy concerns and municipal waste management issues can be addressed by district energy systems.

The Charlottetown district energy system serves over 125 buildings, comprising a mix of residential, commercial, and institutional customers, by distributing approximately 1 million liters of hot water through a 17-km distribution system, and high-pressure steam through a 1 km distribution line to the Queen Elizabeth Hospital.

Within each customer's building is a heat transfer station with two heat exchangers: one for the building, which circulates water at 80°C, and another smaller one for domestic hot water that operates at 50°C.

Ash generated in Prince Edward Island is used beneficially as landfill cover but the MSW IFA is disposed in lined landfill [24].

2.3 Waste to Energy in the USA

The EPA developed the non-hazardous materials and waste management hierarchy [25] in recognition that no single waste management approach is suitable for managing all materials and waste streams in all circumstances. The hierarchy ranks the various management strategies from most to least environmentally preferred. The hierarchy places emphasis on reducing, reusing, and recycling as key to sustainable materials management.

Figure 4 USA EPA Waste Management Hierarchy

At an MSW combustion facility, MSW is unloaded from collection trucks and placed in a trash storage bunker. An overhead crane sorts the waste and then lifts it into a combustion chamber to be burned. The heat released from burning converts water to steam, which is then sent to a turbine generator to produce electricity.

A high-efficiency baghouse filtering system (APC) captures particulates. As the gas stream travels through these filters, more than 99 percent of particulate matter is removed. Captured fly ash particles fall into hoppers (funnel-shaped receptacles) and are transported by an enclosed conveyor system to the ash discharger. They are then wetted to prevent dust and mixed with the bottom ash from the grate. The facility transports the ash residue to an enclosed building where it is loaded into covered, leak-proof trucks and taken to a landfill designed to protect against groundwater contamination. Ash residue from the furnace can be processed for removal of recyclable scrap metals. Common technologies for the combustion of MSW include mass burn facilities, modular systems and refuse derived fuel systems.

Mass burn facilities are the most common type of combustion facility in the United States. The waste used to fuel the mass burn facility may or may not be sorted before it enters the combustion chamber. Many advanced municipalities separate the waste on the front end to save recyclable products.

Mass burn units burn MSW in a single combustion chamber under conditions of excess air. In combustion systems, excess air promotes mixing and turbulence to ensure that air can reach all parts of the waste. This is necessary because of the inconsistent nature of solid waste. Most mass-burn facilities burn MSW on a sloping, moving grate that vibrates or otherwise moves to agitate the waste and mix it with air.

Modular Systems burn unprocessed, mixed MSW. They differ from mass burn facilities in that they are much smaller and are portable. They can be moved from site to site.

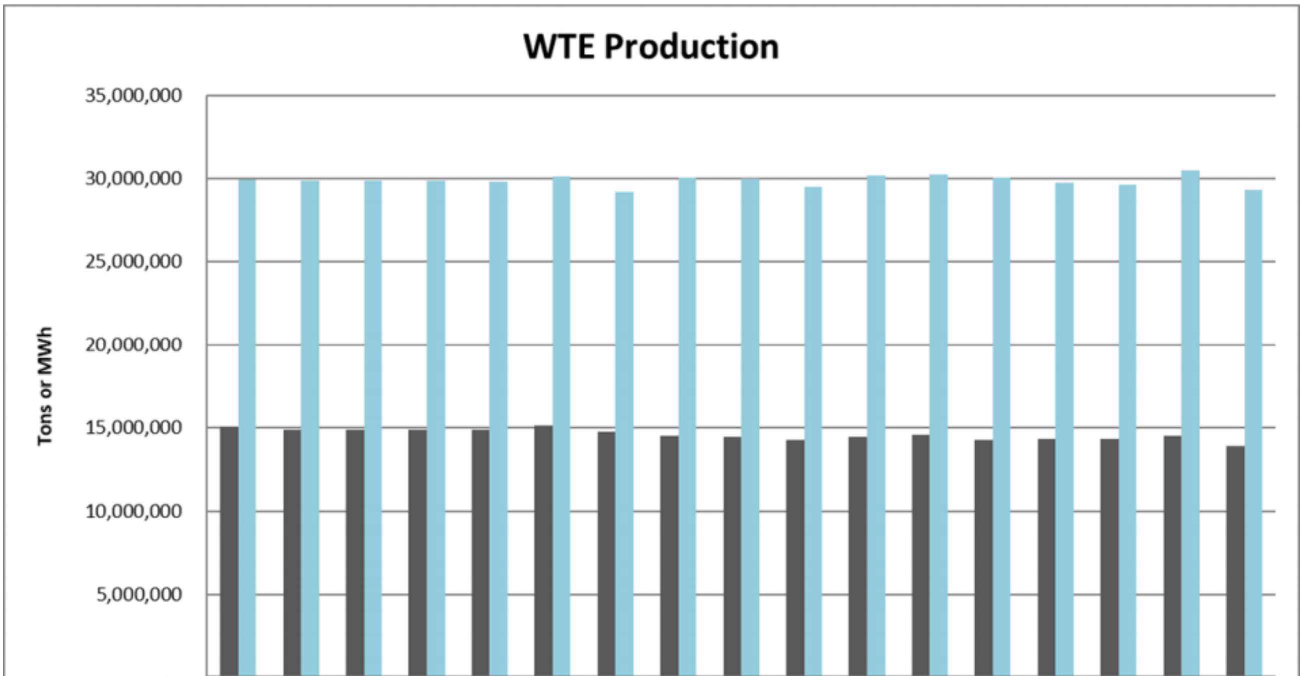
Figure 5 Modular Waste Incineration System [26]

Refuse derived fuel systems use mechanical methods to shred incoming MSW, separate out non-combustible materials, and produce a combustible mixture that is suitable as a fuel in a dedicated furnace or as a supplemental fuel in a conventional boiler system.

2.3.1 The History of Energy Recovery from Combustion

The first incinerator in the United States was built in 1885 on Governors Island in New York, NY. By the mid-20th Century hundreds of incinerators were in operation in the United States, but little was known about the environmental impacts of the water discharges and air emissions from these incinerators until the 1960s. When the Clean Air Act (CAA) came into effect in 1970, existing incineration facilities faced new standards that banned the uncontrolled burning of MSW and placed restrictions on particulate emissions. The facilities that did not install the technology needed to meet the CAA requirements closed.

Combustion of MSW grew in the 1980s. By the early 1990s, the United States combusted more than 15 percent of all MSW. The majority of non-hazardous waste incinerators were recovering energy by this time and had installed pollution control equipment. With the newly recognized threats posed by mercury and dioxin emissions, EPA enacted the Maximum Achievable Control Technology (MACT) regulations in the 1990s. As a result, most existing facilities had to be retrofitted with air pollution control systems or shut down.



	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Net Elec. Generation	15,033	14,886	14,877	14,871	14,878	15,080	14,748	14,519	14,438	14,218	14,422	14,565	14,214,	14,310,	14,300,	14,510,	13,876,
MSW Throughput	29,921	29,837	29,881	29,868	29,783	30,092	29,162	30,045	30,004	29,512	30,155	30,211	30,041	29,722	29,594	30,449	29,276

Table 3 WTE Energy generation ton per MWh

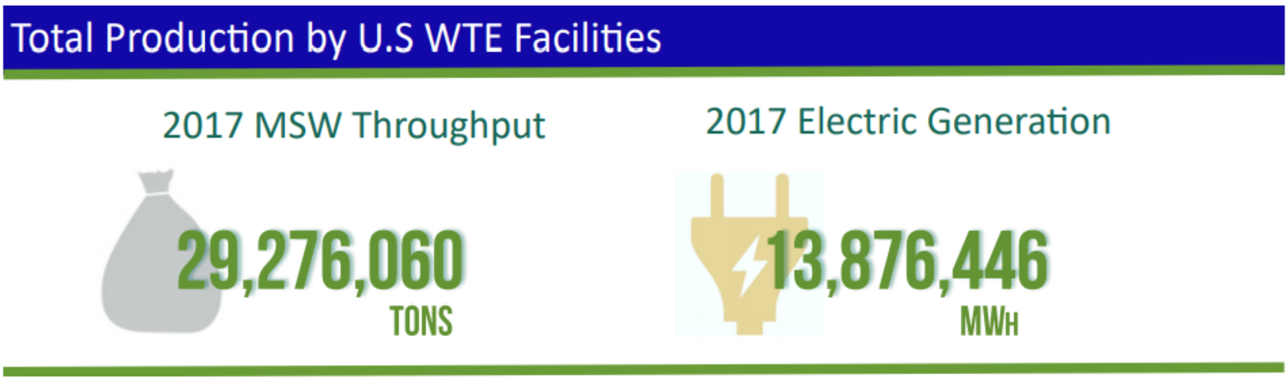


Figure 6 Total Production by US WTE Facilities

2.3.2 How much waste does America combust for energy recovery?

Currently, there are 75 facilities in the United States that recover energy from the combustion of municipal solid waste. These facilities exist in 25 states, mainly in the Northeast. A new facility was built in Palm Beach County, Florida in 2015 [26].

A typical waste to energy plant generates about 550 kilowatt hours (kWh) of energy per ton of waste. At an average price of four cents per kWh, revenues per ton of solid waste are often 20 to 30 dollars.

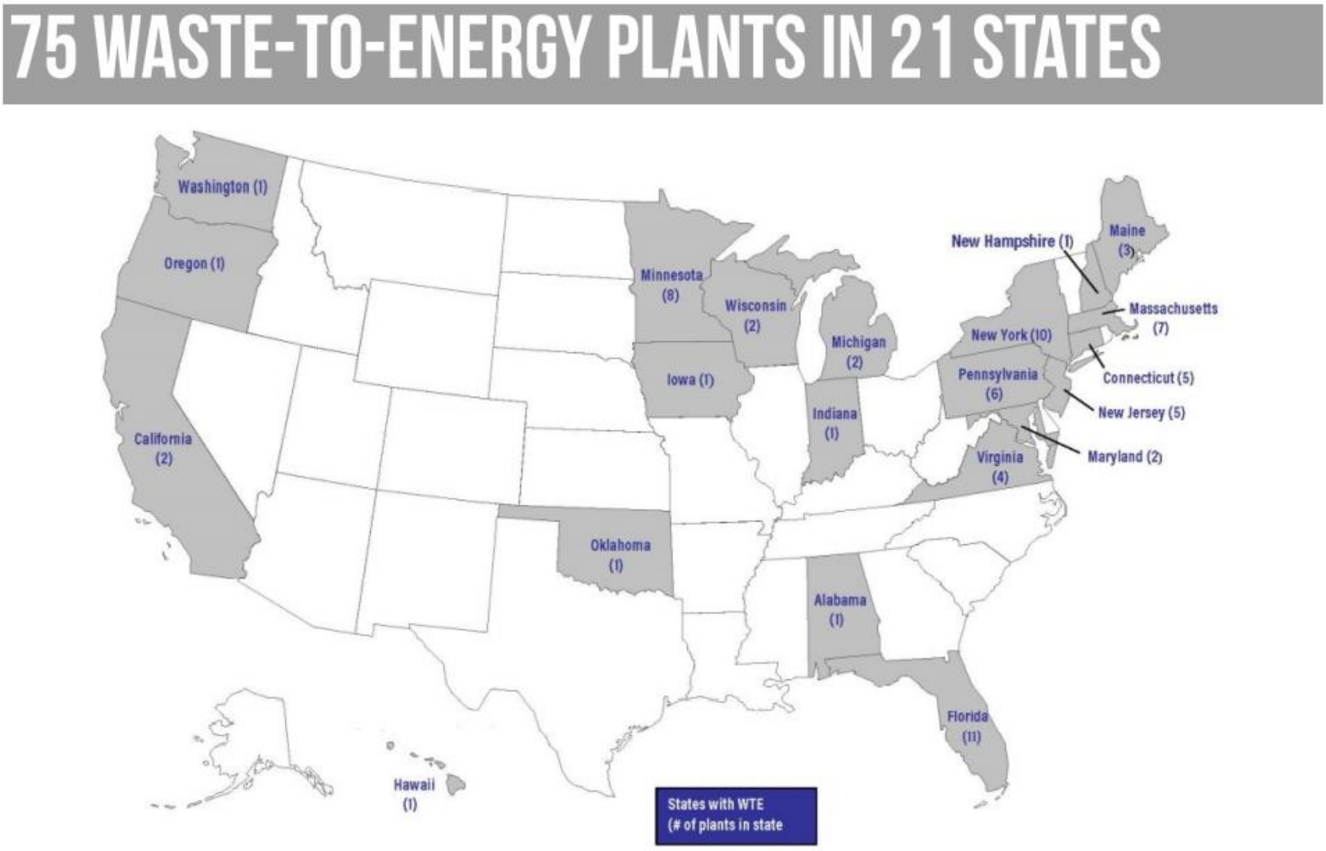


Figure 7 75 WTE Plants in 21 States

Why are MSW combustion facilities not more common in the United States?

According to the Advancing Sustainable Materials Management Facts and Figures Report, the United States combusted over 34 million tons of MSW with energy recovery in 2017 [27].

MSW combustion accounts for a small portion of American waste management for multiple reasons. Generally speaking, regions of the world where populations are dense and land is limited (e.g., many European countries, Japan, Singapore), have greater adoption of combustion with energy recovery due to space constraints. As the United States encompasses a large amount of land, space limitations have not been as important a factor in the adoption of combustion with energy recovery. Landfilling in the United States is often considered a more viable option, especially in the short term, due to the low economic cost of building an MSW landfill verses an MSW combustion facility.

Another factor in the slow growth rate of MSW combustion in the United States is public opposition to the facilities. These facilities have not always had air emission control equipment, thus gaining a reputation as high polluting. In addition, many communities do not want the increased traffic from trucks or to be adjacent to any facility handling municipal waste.

Additionally, the upfront money needed to build an MSW combustion facility can be significant and economic benefits may take several years to be fully realized. A new plant typically requires at least 100 million dollars to finance the construction; larger plants may require double to triple that amount. MSW Combustion facilities typically collect a tipping fee from the independent contractors that drop the waste off on a daily basis to recover costs. The facilities also receive income from utilities after the electricity generated from the waste is sold to the grid. A possible third stream of revenue for the facilities comes from the sale of both ferrous (iron) and non-ferrous scrap metal collected from the post-combusted ash stream.

What is the ash generated by combustion and what happens to it?

The amount of ash generated ranges from 15-25 percent (by weight) and from 5-15 percent (by volume) of the MSW processed. Generally, MSW combustion residues consist of two types of material: fly ash and bottom ash. Fly ash refers to the fine particles that are removed from the flue gas and includes residues from other air pollution control devices, such as scrubbers. Fly ash typically amounts to 10-20 percent by weight of the total ash. The rest of the MSW combustion ash is called bottom ash (80-90 percent by weight). The main chemical components of bottom ash are silica (sand and quartz), calcium, iron oxide, and aluminum oxide. Bottom ash usually has a moisture content of 22-62 percent by dry weight. The chemical composition of the ash varies depending on the original MSW feedstock and the combustion process. The ash that remains from the MSW combustion process is sent to landfills.

Which regulations apply to energy recovery from waste?

Energy recovery from waste is important in the development of sustainable energy policies. EPA continues to develop regulations that encourage energy recovery from hazardous materials or materials that might otherwise be disposed of as solid waste.

Identification of Non-Hazardous Materials that are Solid Waste

The 2011 non-hazardous secondary material (NHSM) final rule [28] under the Resource Conservation and Recovery Act (RCRA) identifies which non-hazardous secondary materials are, or are not, solid wastes when burned in combustion units. This determines which Clean Air Act emission standards a combustion unit is required to meet.

Does EPA consider burning for energy recovery to be waste minimization?

Waste minimization, the term employed in the RCRA statute, is defined to include both source reduction and certain types of environmentally sound recycling. EPA's highest priority is to achieve reductions through source reduction. However, if this is not achievable, then environmentally sound recycling is also an Agency priority.

Recycling activities closely resembling conventional waste treatment activities (such as burning for energy recovery) do not constitute waste minimization. Also, treatment for the purposes of destruction or disposal is not part of waste minimization, but is, rather, an activity that occurs after the opportunities for waste minimization have been pursued [29].

2.4 Waste to Energy in Bermudas

The opening or the Tynes Bay Waste Treatment Facility brought to a conclusion possibly the most complex and critical project ever undertaken by the Bermuda Government. Until this time, all of Bermuda's waste (garbage) was going to landfills, most notably the Marsh Folly site in Pembroke. In the early 1980's, with 80,000 tons of domestic and commercial waste being generated annually, the Island's only landfill site was nearing capacity and producing unacceptable problems for local residents. The Government at this time decided to replace landfill as a method for disposal of combustible waste with the provision of a municipal "waste-to-energy" mass burn incinerator.

In 1987 the Government engaged Von Roll Ltd. of Switzerland to design, procure and install the incinerator's mechanical and electrical plant. After a delay of three years due to environmental concerns, approval was given to restart the project. At the start of 1991 the Ministry project team faced the challenges of coordinating the design and the considerable task of bringing together the multi-national workforce to construct the $70 million facility on this small, isolated, mid-Atlantic Island.

2.4.1 Plant Operations:

The primary role of incineration in Bermuda's waste management plan is to reduce the volume of combustible waste by up to 90% to minimize the reliance on land filling as the primary means of solid waste disposal. A secondary and important function of the facility is to extract energy from the gasses to produce electricity for the facility and to export to the local power company (BELCO) grid.

In addition to the and valuable energy savings, there is an indirect benefit to Bermuda's economy by reducing diesel fuel imports and hence foreign currency requirements.

The facility has two streams each capable of incinerating 6 tons per hour. Each stream is designed for continuous operation. Incoming waste is inspected and weighed prior to discharge into the refuse bunker located in the tipping hall. The waste is mixed to provide a reasonably homogeneous material before it goes into the furnace. The temperature of combustion is controlled by the volume of air and the rate of feed through the combustion chamber. The grate in the combustion chamber both turns and tumbles the waste to facilitate complete burnout.

The sea water used for condensing the steam is drawn through the pumping station located on North Shore Road. Band screens, located in the for bay of the pumping station, prevent coarse sand particles, seaweed and other sea life from entering the pipes. The sea water is returned to the ocean at approximately 10 degrees above the ambient. This warmed water is dispersed into 8 m depth of ocean via a 35 m outfall through a diffuser angled at 10 degrees to the seabed.

2.4.2 Bottom Ash and Fly Ash

Ash that drops off the furnace grates (bottom ash) and the particulates removed by the electrostatic precipitators (fly ash) are transported to the quench tank. The combined wet ash is then conveyed to the ash bunker for storage. Ash handling equipment in the Ash Plant is used to process the ash. It is graded by passing over a 100mm screen, and ferrous material is removed with a magnetic separator. The ash is weighed and the moisture content determined prior to mixing with cement to form ash concrete to a strength of approximately 10 N/mm2.

This ash concrete is formed into 1 meter cube blocks, each weighing about 2 tons, which are used for shore protection and land reclamation at the Airport Waste Management Facility.

Before going ahead with the plan, the government decided to study what would happen to the blocks once they were in the ocean. What could happen to concrete blocks? Concrete is very similar to the material that forms the coral reef (calcium carbonate) and there are many organisms that can bore into, or eat the surface of the reef. If these organisms did eat the blocks, the toxic metals and other chemicals could kill these organisms or become part of the food chain and eventually end up threatening the health of other animals including humans!

The ash blocks were set down at about 30 ft in Castle Harbor near the airport where the landfill for the large items is located. Upon inspection it is seen that the blocks were covered with what looks like fuzz which is really a wide range of organisms that have colonized the surface, especially algae.

Artificial ash block (impact) and concrete-only (control) reefs were set up in Castle Harbor and in Tynes Bay near the incinerator and continue to be monitored on an annual basis. Aspects of the potential fate of chemicals from the blocks and effects on organisms have been studied since they were installed in the winter of 1992. So far there has been no clear evidence of increases in the levels of trace metals (copper, cadmium, lead, zinc and nickel) in sediments adjacent to the ash reefs compared to the concrete-only control reefs in either Castle Harbor or Tynes Bay. These results would indicate that the ash blocks may be only very slowly releasing contaminants into the environment [30].

Figure 8 Bermuda Artificial Coral Reefs made from WTE Ash

2.5 Waste to Energy in India

As 2019, 92 plants with aggregate capacity of around 250 MW have been set up in India for electricity generation from urban, agricultural and industrial waste. On an average, 100 tons per day of municipal solid waste (MSW) is required to generate 1 MW of power.
According to the Associated Chambers of Commerce and Industry's report “Value of Waste 2015”, investors valued WTE in India at almost $1.5 billion, around Rs 11,0000 crore, in 2017 And expected it to grow to about $11.7 billion by 2052.

The compositional characteristics of Municipal Solid Waste in India are very distinct compared to those in developed countries. Waste generated in India has a higher percentage of organic waste, more moisture content and low calorific value compared to waste generated in developed countries adversely impact the efficiency of electricity generation.

In India activists are flagging health risks arising from the huge amount of bottom ash being generated by these plants, although, worldwide bottom ash is classified as a non-hazardous waste but there are no comprehensive studies on the health impacts of WTE plants in India.

The major concern in India in regards to Waste to Energy development is that the Municipal Solid Waste (MSW) in India has low calorific value and has a high moisture content. Plants have to handle a vast quantity of mixed waste, housekeeping of this type of waste is extremely challenging leading to a lot of odor and visual pollution. Also, they have to reject about 30 per cent to 40 per cent of waste into landfills because they are either inert (construction debris and non-incinerable waste) or too poor in quality to be combustible.
The type of waste in India due to the high moisture and high percentage of organics are just not suitable for burning in these plants. To incinerate this type of waste, additional fuel is required increasing the plant’s operational costs while making the plants expensive to run. This has been the main reason why WTE plants in Kanpur, Bengaluru, Hyderabad, Lucknow, Vijayawada, Karimnagar, etc., had to be closed down [31].

On the environmental clearance, according to reports, WTE projects with a capacity of less than 15 MW do not require prior environmental clearance, thus air pollution may arise.

Figure 9 Air Pollution by small WTE plant in India

2.6 Waste to Energy in the he U.K.

The tonnage of Residual Waste processed at energy from waste (EfW) plants in the UK in 2020 increased 10.5% when compared with 2019. Residual waste is defined as non-hazardous, solid, combustible mixed waste which remains after recycling activities.

During 2020, UK EfW plants exported 7,762 gigawatt hours (GWh) of electricity, approximately 2.5% of the UK total net power generation, together with 1,651GWh of heat. Improved turbine availability and two new heat-exporting plants meant energy generation increased “significantly” for the UK.

The government report in regards to the Energy from Waste sector reads: “The UK continues to incinerate around 70,000 tonnes of residual waste a day, and exports and landfill options are in decline. The challenges of 2020 provided the EfW sector with the opportunity to demonstrate its operational resilience whilst highlighting that, in the understandable search for better carbon solutions for residual waste, stakeholders must be very careful not to lose sight of the critical need for operational reliability.

2.6.1 EFW Installed Capacity in the UK

At the end of 2020, there were 55 Energy from Waste plants which were fully operational or in late commissioning and a further 15 under construction.
The total headline capacity of EfW plants which were operational or under construction during 2020 increased by 1.7Mt when compared with 2019, to 20.20Mt. It is estimated that by 2025 the UK operational capacity will be 18.2Mt.

Data suggests that residual waste inputs to EfW plans in the UK represented 52% of the overall UK residual waste market, up from 46% in 2019.
It was estimated that exports of refuse derived fuel (RDF) from the UK in 2020 declined by around 31% when compared with 2019.

2.6.2 Market share

Viridor had the greatest market share by operator based on input tonnages in 2020 for the second year in a row. The waste management company processed more than 3 million tonnes of residual waste, representing a 21.8% share of the market.
Other companies to have a significant share of the market included Veolia (16.7%), Suez (15.5%) and WTI (13%) [32].

2.7 Waste to Energy in Europe

For decades, Europe has poured millions of tons of its trash into its 500 incinerators each year, often under the green-sounding label "waste to energy." Now, concerns about incineration’s outsized carbon footprint and fears it may undermine recycling are prompting European Union officials to ease their long-standing embrace of a technology that once seemed an appealing way to make waste disappear.

Capacity in Megawatts

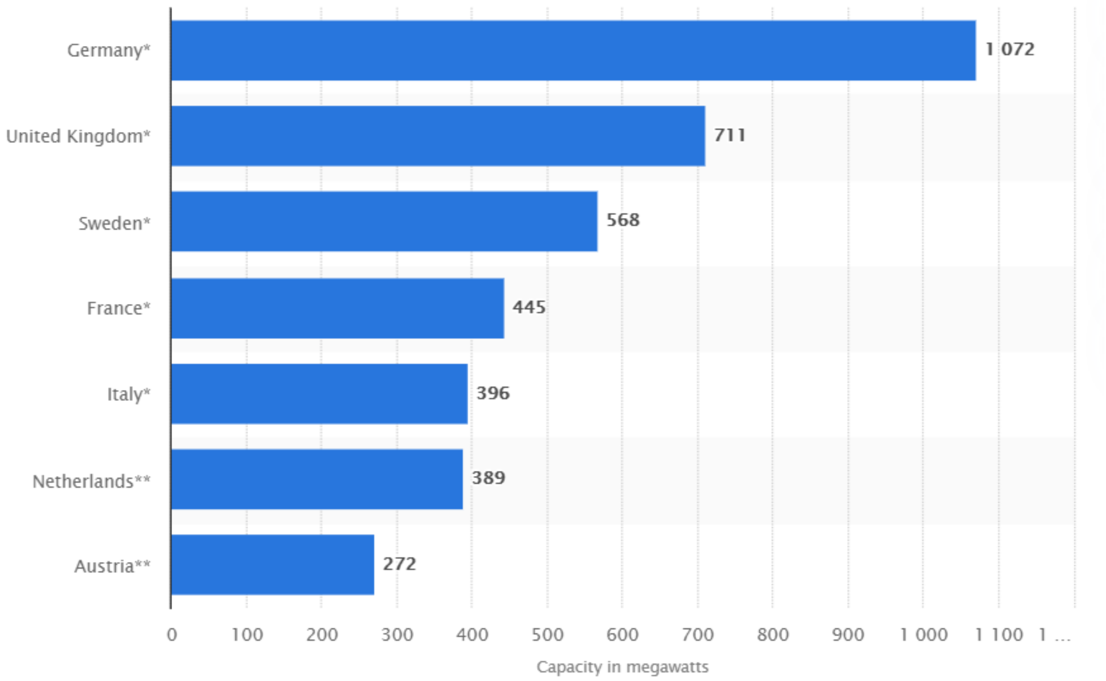


Figure 10 Capacity in MW generated in WtE in Europe

2.7.1 Number of Plants Per Country

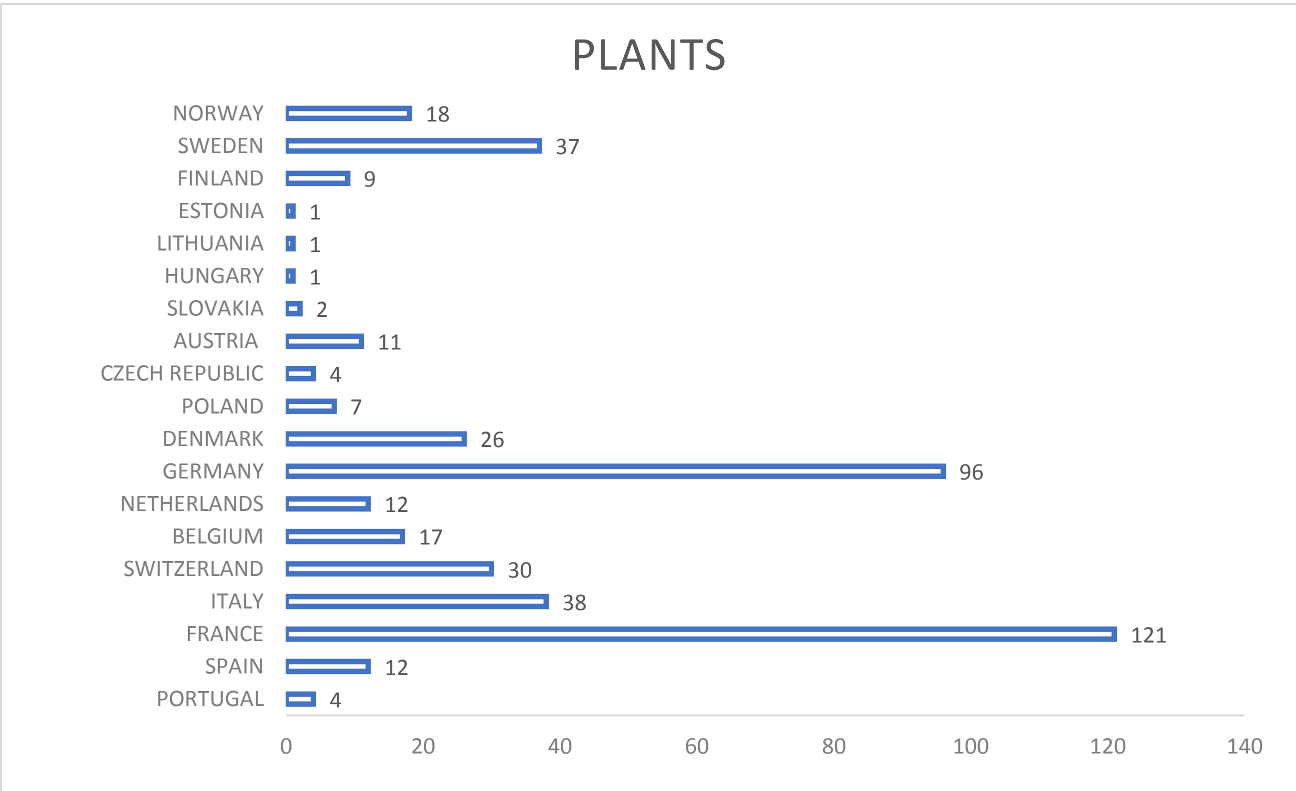


Figure 11 Number of WtE Plant per Country -Europe

The EU is in the process of cutting off funding for new incinerators, but there's little sign most existing ones — currently consuming 27 percent of the bloc's municipal waste — will close any time soon. And, even without EU financial support, new plants are in the works, many in southern and eastern European countries that historically have incinerated less than long-standing waste-to-energy proponents such as Germany, the Netherlands and the Scandinavian nations. Meanwhile, across the English Channel, post-Brexit Britain is charging ahead with proposals for dozens of new garbage-burning projects.

Without a more decisive change of course, critics argue, that adds up to an existential threat both to Europe's promise to slash carbon emissions to net-zero by midcentury and its dreams of a "circular economy" in which reuse and recycling largely take the place of waste disposal.

"Burning plastic in a climate emergency, that's insane," according to Waste to Energy technology critics over the UK decision to exclude incinerators from its new emissions trading system. Plastic, hard to recycle and ubiquitous in garbage, is made from fossil fuel derivatives and emits carbon dioxide when burned, accounting for a substantial chunk of incineration's climate damage.

Worries that incinerators sicken those who live near them — disproportionately poor and people of color — have long dogged the industry. Wealthy nations such as Sweden and Denmark, which rely heavily on waste-to-energy plants, say their sophisticated emissions treatment systems mean such concerns are misplaced. But critics note many nations lack the resources for the best pollution-control systems. Dangerous emissions such as dioxin and particulate matter sometimes go unreported, and enforcement is often porous, environmentalists say.

The climate concerns are newer, crystallized in a report the consulting firm Eunomia produced for ClientEarth, an advocacy group. It found that British incinerators' power generation was more carbon-intensive than electricity from natural gas, and second only to coal. Overall, European incinerators pumped out an estimated 95 million tons of carbon dioxide in 2018, about 2 percent of total emissions.

That footprint helped prompt EU officials to drop incineration from a draft of important green investment guidelines, known as the "sustainable finance taxonomy," expected to be formally adopted this month. Not only can trash-burning plants no longer get subsidies designated for environmentally beneficial projects, they also have been cut off from other major EU funding streams. And the European Parliament has urged member nations to minimize incineration.

In Brussels for example, according to Zero Waste Europe, “Leaders have started to understand that incineration is a big source of greenhouse gases."

Nonetheless, without incineration, landfill costs tend to rise, increasing the danger of European trash leaving the continent, and ultimately being burned in uncontrolled settings or littering beaches and waterways. Landfills have their own climate impact — any organic waste in them generates the potent greenhouse gas methane as it decays. What’s more, incinerator operators salvage metals from the ash left over after burning, allowing their reuse.

The EU’s shift comes after a building spree that doubled EU countries’ municipal waste incineration between 1995 and 2019, to 60 million tons annually. Such plants provide power to 18 million Europeans and heat to 15 million, the industry says.

Individual countries remain free to fund and commission new incinerators. Those plants still make money from waste-disposal fees and by selling electricity and, in some places, heat. In some countries, operators still can claim subsidies designed to support renewable energy, as long as they burn waste that has been collected in separate streams so recyclable or compostable material is not incinerated.

It all comes as the EU is pushing to reduce waste, particularly plastic, by ratcheting up targets for composting and recycling, mandating that plastic bottles contain 30 percent recycled content by 2030, and banning — as of July — single-use items such as cutlery, cups and stirrers. The EU also has adopted a new "circular economy" plan that aims in the longer term to encourage better product design so reuse and recycling are easier.

Continued incineration, critics argue, could threaten those goals. Once built, they say, incinerators cannibalize recycling, because municipal governments are often locked in by contracts that make it cheaper to get their rubbish burned than to sort it for recyclers.

One nation grappling with the legacy of its long embrace of incineration is Denmark. The country, one of Europe’s biggest waste producers, built so many incinerators that by 2018 it was importing a million tons of trash. The plants generate 5 percent of the country’s electricity and nearly a quarter of the heat in the local networks.

Pushing to meet ambitious carbon-cutting goals, Danish lawmakers agreed last year to shrink incineration capacity by 30 percent in a decade, with the closure of seven incinerators, while dramatically expanding recycling, Belgium is also seeking to reduce incineration capacity. Nonetheless, some countries are planning new plants such is the case for Greece, Bulgaria and Romania which landfill most of their waste, Italy and Spain may build new plants.

Poland has about nine incinerators, plus a similar number of cement plants that use processed waste as fuel, around 70 new projects seek approval including proposals to convert old coal plants to burn garbage instead. Poor environmental guidelines enforcement in Poland means emissions of toxins such as dioxins and furans often reach hazardous levels.

Britain, too, seems intent on pushing ahead with an expansion of burning, with dozens of new projects under consideration. Collectively, they would double current incineration capacity [33].

2.8 Waste to Energy Middle East

2.8.1 United Arab Emirates

Masdar, Abu Dhabi's renewable energy company, had signed a strategic partnership agreement with Bee'ah to develop the UAE's waste-to-energy (WtE) sector. This partnership will help contribute to the UAE Government's Vision 2021 which targets, among other goals, diverting waste from landfills by 75 per cent by 2021.

2.8.1.1 In Abu Dhabi

Abu Dhabi National Energy Corporation PJSC (Taqa), in cooperation with the Waste Management Center (Tadweer), is developing a 100 MW facility in Abu Dhabi, one of the largest in the world. The plant is scheduled to be up and running in 2017 to provide enough electricity for 20,000 homes in Abu Dhabi and reduce greenhouse gas emissions. It is expected to reduce carbon dioxide emissions by more than one million tons per year. The project is located near the Moussafah Seaport and covers an area of 100,000 square meters. It will become one of the largest waste incineration power generation facilities in the world.

2.8.1.2 In Dubai

Japan-headquartered Itochu and the Swiss subsidiary of Hitachi Zosen have secured a $1.1bn order to build and operate the largest planned waste-to-energy (WTE) plant in Dubai, according to a report by Tokyo-based media.

The scheme will have the capacity to treat 6,000t a day, equivalent to approximately half the city’s waste, and will have a power generation capacity of 200MW.

The contract is for 35 years with the plant scheduled for commercial operation by 2024.

MEED reported that the project stakeholders are expected to reach commercial close by the end of November for the planned build, operate, and transfer (BOT) contract for Dubai Municipality’s WTE power project that will be located in a waste landfill site in Warsan.

The special project will be owned by Itochu (20%), Hitachi Zosen Inova (10%), and Dubai Holding (31%). The other shareholders will maintain the remaining shares [34].

Figure 12 Dubai Plant Architectural Project

2.8.1.3 In Sharjah

The emirate of Sharjah set up a municipal waste management company Bee'ah (the Arabic word for environment) in 2007 in the form of a public-private partnership. In October 2011, Sharjah announced an ambitious plan for 100 per cent landfill diversion by 2015.

To attain this goal, Bee'ah developed a state-of-the-art waste management center to process and recycle waste. In 2012, the company introduced two-stream waste collection and a new tipping fee structure to incentivize waste reduction and to closely regulate landfill contents. Improved blue and green colored odor-proof bins have been deployed across the emirate.

In addition, Sharjah is constructing a Waste-to-Energy (WtE) plant in in Sajja area that will eventually convert 400,000 tonnes of waste per year into 80 megawatts (MW) of electricity.

The project will convert 99 per cent of organic waste into energy. After using some of the generated power for the plant's own needs, the electricity will be exported to Sharjah.

2.8.1.4 In Ras Al Khaimah

The Energy from Waste Program of the RAK Energy Efficiency and Renewables Strategy 2040 integrates seamlessly into the broader waste management strategy of Ras Al Khaimah. It focuses on promoting energy outcomes for the available waste, targeting at least 2% of the primary energy demand of Ras Al Khaimah to be fulfilled from waste by 2040.

The Energy from Waste Program is planned in two phases:

1) An initial phase of studies and pilots (2018 – 2020), when various diversion options and energy outcomes are explored for different waste streams and the best options are selected.

2) A subsequent phase of implementation (2021 onwards), when the waste treatment options selected in the first phase are implemented [35].

2.8.2 Qatar

Keppel Seghers, the environmental engineering arm of Keppel Integrated Engineering, was awarded two contracts by the Ministry of Municipal Affairs and Agriculture in Qatar (now known as Ministry of Municipality and Urban Planning) to design and build four Waste Transfer Stations and one Integrated Domestic Solid Waste Management Centre (DSWMC), and to operate and maintain the DSWMC for 20 years. Since October 2011, Keppel Seghers has formally handed over the DSWMC to its clients and has commenced the Operations and

Maintenance phase of this large Design-Build-Operate (DBO) project. The 300-ha modern DSWMC facility is located near Mesaieed, and is designed to treat up to 2,300 tonnes of mixed domestic solid waste per day, serving the waste treatment needs for the whole of Qatar. The DSWMC comprises state-of-the-art waste sorting and recycling facilities, an engineered landfill, a composting plant and a 1,500 tonnes per day Waste-to-Energy (WTE) incineration plant.

Rising energy prices and increasing worldwide commitment to reduce greenhouse gas emissions and to achieve landfill diversion are driving the development of new approaches to the management of solid waste. A modern integrated waste management policy is based on harnessing waste as a resource. As the first of its kind in the Middle East, the integrated DSWMC in Qatar is a visionary infrastructure project that showcases how the latest ideas on sustainable and resource conscious development can be put into practice. It combines the maximized recycling of used goods, water re-use, sorting and separate waste collection, and utilizes a well-organized and controlled waste stream which focuses on waste recovery. The integrated waste management chain can help to achieve up to 95% diversion from landfilling.

Benefits of Keppel Seghers' integrated waste management system:

• Maximum recovery of recyclable materials

• Maximum energy recovery in refuse-derived fuel

• Maximization of landfill diversion rate

• Minimal community impacts by state-of-the-art environmental controls.

Harnessing technological synergies

The strength of an integrated waste management concept is the combination of several technologies in one installation. The combination of pre-processing, mechanical and organic recycling and power-generating technologies offers synergy which would be unattainable if each technology was employed individually. This synergy leads to more energy and material recovery, and a maximum landfill diversion of up to 95 percent.

2.8.2.1 An integrated waste management system

Management system would be the pre-processing of waste received. Through pre-processing, materials suited for processes such as recycling and energy recovery through WTE technology are separated and transferred to their respective processing lines. This allows each process to achieve the highest performance, and obtain the maximum value out of each waste fraction

Flue gases from the waste incineration are cleaned with the removal of acidic components and metals through neutralization with hydrated lime and absorption by activated carbon to ensure compliance with stringent emission standards. Incinerator bottom ash (IBA) produced during incineration is processed at the IBA Treatment Plant to standardize the material and remove contaminants. The treatment plant is equipped with magnetic separators that separate ferrous metals from the IBA which are sent for recycling as well as screening and sieving [36].

2.9 Waste to Energy Africa

Ethiopia, in the Horn of Africa, is one of the fastest growing economies in the world. Along with economic growth comes growth in waste generation, not least in the densely populated capital of the country, Addis Ababa. So far, the waste generated by the more than 5 million inhabitants has been disposed of at an uncontrolled landfill.

To ensure sustainable management of the waste generated in Addis Ababa, the state-owned utility Ethiopian Electrical Power (EEP) decided to build a modern waste-to-energy facility. The facility is now in operation, and it will provide treatment for 1,400 tonnes of municipal waste per day, while at the same time generating 20 MW power to the grid. Also, it will transfer knowledge to the Ethiopians and serve as an inspiration to other cities in Africa.

The USD 120M EPC contract to build the plant was signed in 2013 between EEP and Cambridge Industries Ltd (CIL) (with its partner China National Electric Engineering Co. (CNEEC)). Subsequently, in 2014 Ramboll won an international bid for the Owner's Engineer role, including review of the contractor's designs, site supervision and assistance in the management of the EPC contract. Since the project was initiated, a total of about 30 Ramboll experts have been involved in the project, delivering 15,000 hours on site in Ethiopia and about 3,500 hours from home office in Denmark.

The facility has been designed and built to operate according to European emission standards [37].

2.9.1 Project facts

- Capacity: 400 000 tonnes per annum
- Waste: Municipal Solid Waste (MSW)

- Furnace/boiler: 2 grate fired lines, vertical economizer section
- Energy production: 20 MW power
- Steam parameters: 60 bar/420˚C
- Flue gas treatment: SNCR, dry FGT system (lime milk in reaction tower), baghouse filter
- Procurement: EPC
- Commissioning: 2018
- Bottom Ash transformation into bricks

2.10 Waste to Energy Russia

2.10.1 Current situation Russia

Russia does currently not have a tradition of recycling, waste separation, and/or waste incineration. Meanwhile, the existing landfills are increasingly reaching their capacity limits. Moreover, many of Russia's landfills are outdated, leading to a number of challenges for the local population and the environment, such as bad smells, pollution of ground water and even release of toxic gasses. In recent years, the issue of waste management, specifically the growing landfill troubles, has become a concern to both the public and the government. In 2018, the government therefore introduced the National Project 'Ecology' to better protect the environment. Part of this plan is to introduce a solid waste management system for industrial- and household waste and to liquidate all unauthorized landfills in cities by 2024.

2.10.2 Russian Ecology Project

The Russian government has launched the National Ecology Project to improve environmental protection in Russia towards 2024. The project focuses on different areas, among which the quality of air and water, sewage in rivers, forest preservation and waste management. In order to implement the Ecology project, the state-owned company Russian Ecological Operator (REO), its core tasks are to:

• Ensure sound regulation of household waste in practice (separation, processing, recycling);

• Build adequate infrastructure for waste management;

• Raise awareness among consumers and producers.

REO currently prepares the Federal Scheme for Solid Waste Management, to be adopted in November 2020, in which it revises the targets for waste management in 2024. With this scheme, the government raises its targets and aims to recycle 36 percent (7% in 2019) and to sort 100 percent (2019 12%) of household waste in 2024. This should also lead to a reduction in landfilling waste in 2024, from 64% to 50%. Despite these ambitions, this will require the opening of another 348 landfills in Russia in the coming years.

In addition, and to ensure a transition from landfilling to processing waste, the Russian government plans to build 361 waste separation- and processing plants (composting and biofuels) and 154 plants for incineration and waste to energy by 2024. According to REO, more than 5 billion euro will be invested in the Russian waste sector until 2024 [38].

2.11 Waste to Energy Asia Pacific

2.11.1 Japan

2.11.1.1 Market Overview

Japan dominated over 60% of the Asia-Pacific industry for Waste-to-Energy (WtE) incineration in 2019, and the country's waste-to-energy market is expected to register a CAGR of more than 12% during the forecast period, 2020-2025. Factors, such as economic development, industrialization, and increasing population levels in Japan, problems related to the expanded consumption and depletion of resources, and the increased generation of waste and increasing focus on non-fossil fuel sources of energy have been driving the adoption of the waste-to-energy market in the country. However, the market studied has been restrained by the increasing emission of harmful gases and the expensive nature of incinerators, particularly as energy prices decline, and several plants have been unable to cover operating costs.

- Thermal technology is expected to dominate the waste to energy market. The emerging waste to energy technologies, such as stoker furnace technologies, which have been more efficient in terms of electricity generation, with additional benefits of no emission discharge and effluence problems at plant sites, are expected to create significant opportunities for the market players, over the coming years [39].

In the fiscal year 2019, more than 1.06 thousand waste incineration plants operated in Japan. Even though the number of waste incineration plants has decreased continuously since fiscal 2010, incineration remains the most widely used waste treatment method.

Number of waste incineration plants in Japan from fiscal year 2010 to 2019

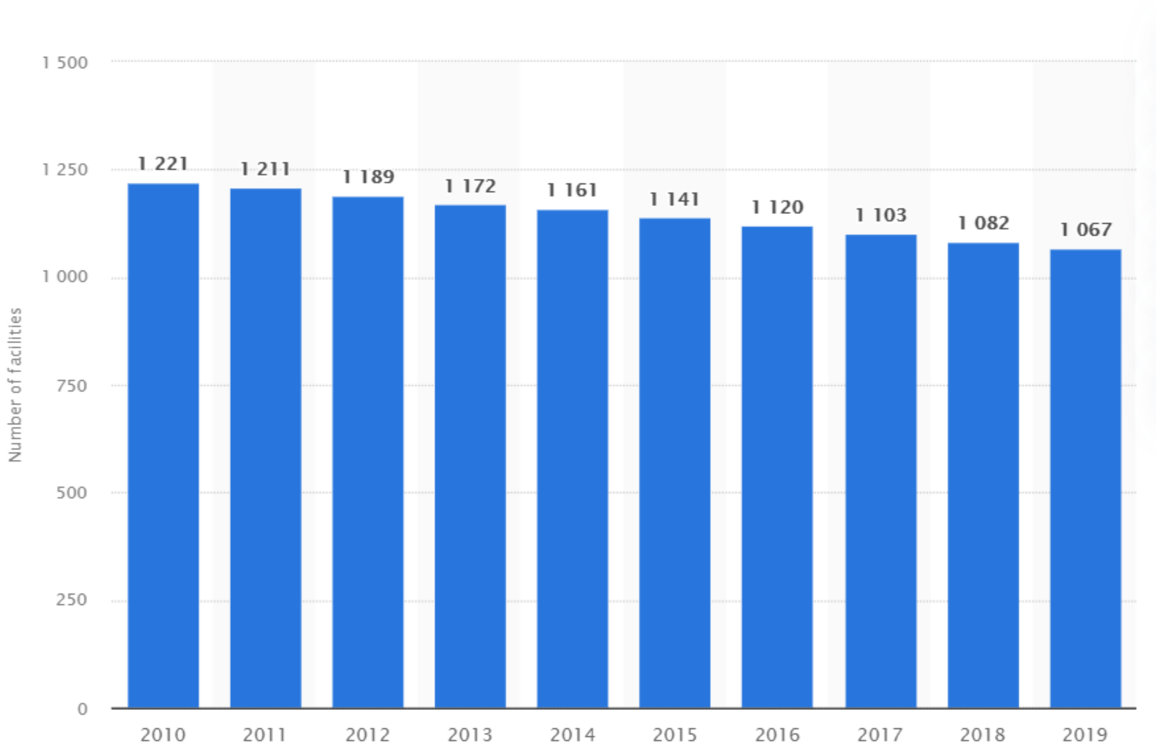


Figure 13 Number of Incinerators in Japan 2021

2.11.1.2 Waste management in Japan

Most of the waste collected in Japan is processed in incineration or recycling facilities or is disposed of at landfills. Plastic, paper, PET bottles, aluminum, and glass are collected separately to be recycled. While the rate of recycled plastic waste increased up to over 80 percent, the recycling rate of Japan's total waste has remained at around 20 percent throughout the past decade. Despite the decreasing amount of municipal waste disposed at landfills, Japan is facing a shortage of landfill sites as the remaining capacity of landfill sites for final waste disposal is shrinking.

2.11.1.3 Waste incineration in Japan

With an incineration rate of municipal waste of over 70 percent, incineration is the leading waste treatment method in Japan, as it can easily reduce the volume of waste. Thermal recycling was the main method to recycle plastic waste. With this method, the waste is incinerated to generate energy. Despite the filtering technologies, which avoids the release of huge amounts of fumes, the incineration process produces greenhouse gases that contribute to air pollution and climate change [40].

2.11.2 China

2.11.2.1 Market Overview

China waste to energy market is expected to grow at a CAGR of more than 4.75% during the forecast period 2020-2025. With the increasing rate of municipal waste generation, around the country are emphasizing reducing the waste by utilizing it to generate energy in the form of methane. Using the municipal waste to generate substantial energy in the form of heat and electricity can help to stabilize the increasing carbon footprint, that is getting generated by burning various fossil fuels such as coal and natural gas to produce energy. Organic waste, a form of municipal waste, is the largest form of waste that is mostly getting generated from the developing country, accounts for nearly 56% of the total waste generates annually in the country. Waste to Energy (WtE) implies a set of technologies that treat municipal waste to extract energy in the form of heat and electricity. Uses of the technologies also help to obtain biogas as an alternate form of fuel. The drivers of the market are the increasing dumping and open burning of wastes that directly or indirectly impact human health and the environment. However, WtE plants produce ash that needs to be disposed of safely, usually in landfills that are lined with barriers to prevent groundwater contamination.

- In 2020, thermal based technology is expected to dominate the China waste to energy market.
- Also, municipalities in the state have moved toward both public and private companies to meet constraints related to budgets and increase efficiency for managing the WTE technologies.
- Moreover, daily per capita waste generation in the region is expected to get an increase of nearly 40% by 2050. Thus, increasing municipal waste volume and increasing demand for energy in the region is expected to create an opportunity for the waste-to-energy market in the near future.

2.11.2.2 Thermal Based Waste to Energy Conversion to Dominate the Market

China is one of the prominent countries, that has installed the world's largest incineration plant (The Shenzhen East waste-to-energy plant) in 2019. The plant has a capacity of processing 2.7 million tonnes of waste per year and is capable of generating 1.5 billion kilowatt-hours of power per year. It is estimated that plants, which utilize cogeneration of thermal power (heating and cooling), together with electricity generation can reach optimum efficiencies of 80%.

In the present scenario, incineration is the most well-known waste-to-energy technology for Municipal Solid Waste (MSW) processing, however, waste-to-energy technologies, particularly incineration, produce pollution and carry potential health safety risks.

To reduce particulate and gas-phase emissions, incineration plant owners have adopted a series of process units for cleaning the flue gas stream, which has, in turn, led to a significant improvement in terms of environmental sustainability.

2.11.2.3 Increasing Investments to Drive the Market

China is the second-largest producer of municipal waste in the world that initiated waste sorting plans during 2017 and aims to recycle 35% of waste in 46 major cities, including Shanghai, by the end of 2020.

In China, the number of incineration plants has increased from 74, in 2008, to around 400, in 2018. Beijing is planning to double its incineration capacity and to burn 54% of the municipal wastes, by the end of 2020. Under Chinese President Xi Jinping's plan to tackle pollution, the incineration industry is expected to continue its expansion, to replace stinky, polluting, land-intensive garbage dumps. Moreover, with its burgeoning economy producing vast quantities of garbage (increasing 8-10% annually), China is turning to new facilities that burn solid waste to produce electricity.

As per the International Energy Agency (IEA), China has around 7.3 gigawatts of installed waste to energy capacity, with its 339 plants during 2017. The country's waste to energy has grown by 1 GW per year on average from the last five years and is expected to continue the growth with rising municipal waste [41].

2.11.3 South East Asia

The rapid pace of urbanization and industrialization in Southeast Asia has led to a big surge in the volume of waste generated in the region. Major cities in several countries are running out of landfill sites, which is currently the most commonly used method for waste disposal. Moreover, the region's urban population is projected to rise to nearly 400 million by 2030, thus further deepening its waste woes. With increasingly limited land availability and steady growth of cities, the development of waste-to-energy (WtE) plants is being seen as an effective solution by several countries to handle their waste. In the coming years, the WtE segment is expected to play a crucial role in serving the twin goals of waste and energy management in the region. A look at some of major operational and upcoming WtE projects in the region [42] .

2.11.3.1 Singapore

Singapore has been a forerunner in the development of WtE plants in Southeast Asia. The country's first WtE plant, the Ulu Pandan plant, was set up in the year 1979. However, it was decommissioned in 2009 and replaced by the Keppel Seghers Tuas Plant (KSTP). Currently, there are four operational WtE plants in Singapore – Tuas, Senoko, Tuas South and KSTP – with a capacity to produce 259 MW of electricity per day. The Tuas South incineration plant is the country's largest WtE facility with the capacity to process 3,000 tonnes per day (tpd) of solid waste. The Tuas, Senoko and KSTP facilities have capacities of 1,700 tpd, 2,400 tpd and 800 tpd respectively. These plants together process around 37 per cent of the total waste generated in the country.

Moreover, two WtE plants are currently under development. The TuasOne WtE facility with a capacity of 3,600 tpd is expected to be completed by January 2021. Further, the upcoming Integrated Waste Management Facility will be designed with an incineration capacity of 5,800 tpd, making it one of the largest in the world. In April 2020, the National Environment Agency awarded Keppel Corporation-led consortium the contract for the first phase of the project. The group will design and build a 2,900 tpd WtE facility and a 250 tpd material recovery facility [43].

2.11.3.2 Indonesia

Indonesia, one of the largest waste producers in Southeast Asia, also aims to handle its waste management issues through the creation of WtE facilities. Currently, around 64 million tonnes of solid waste is produced annually in the country with more than 75 per cent of it being disposed of in landfills. However, several of its landfills are running out of space. In fact, the country's largest landfill site, Bantargebang, which caters to the capital city of Jakarta is expected to reach its full capacity by as early as 2021. In March 2017, the government launched a pilot project to develop a WtE facility at the Bantargebang landfill. The work on the plant was completed in March 2019. The facility can process 100 tonnes of waste on a daily basis and produce 700 kWh of electricity. Another facility, the Sunter WtE plant, with a capacity of 2,200 tpd is also being developed in Jakarta. It is expected to be completed by 2021. Further, the country is also moving forward with development of 12 more WtE plants to tackle waste volumes in major cities such as Jakarta, Palembang Surabaya, Bekasi, etc. These plants are due to be operational by 2022 and will be able to generate 234 MW of electricity by using 16,000 tpd of waste [44].

2.11.3.3Malaysia

The development of WtE plants has gained momentum in Malaysia, which too relies on landfills for waste disposal. The country's first WtE plant, located at Tanah Merah in the state of Negeri Sembilan, is expected to commence operations in 2020. The plant will be able to handle 1,000 tpd of waste and produce 20-25 MW of electricity to power 25,000 households. Further, there are also plans to develop a WtE facility at Jeram in Selangor. The plant, which is expected to be completed by 2022, will be one of the biggest incinerators in Malaysia. Besides, WtE facilities are also being considered for the states of Johor, Kedah and Melaka [44].

2.11.3.4 Thailand

In Thailand, around 50 per cent of the total waste generated is disposed of in landfills. To solve the country's waste management problems, the government is promoting the development of various WtE plants including incineration, gasification, fermentation, etc., by offering various subsidies and tax incentives. Further, the government has also increased the power purchase quota under the Power Development Plan 2018-2037 from 500 MW to 900 MW to boost investments. Currently, there are 33 operational WtE plants in the country with an overall power generation capacity of 283 MW [44].

2.11.3.5 Myanmar

Myanmar's first WtE plant, located in Yangon, commenced commercial operations in 2017. The 760-kW plant has a capacity to treat 60 tpd of waste. Further, a second WtE project is currently under implementation in Yangon. The construction of the plant is expected to begin in 2020. Upon completion in 2022 the facility will be able to process 1,000 tonnes of the 2,500 tpd of waste produced in Yangon daily. It will be located at the Htein Pin landfill in the Hlaing Tharyar township of the city. The plant will be able to produce 30 tonnes of compressed natural gas daily, 40 tonnes of liquefied carbon dioxide, 180 tonnes of derivative waste fuel and 250 tonnes of compost [44].

2.11.3.6 Cambodia

In Cambodia, the Ministry of Mines and Energy, has launched a project to convert waste into energy in Phnom Penh city. The project is expected to get technical support from the Asian Development Bank. Besides, the development of WtE plants has also been prioritsed under the country's draft national policy on managing and processing waste materials [44].

2.11.3.7 Philippines

The country's first WtE plant was established in the year 2018 in Lapu-Lapu City in Cebu. The facility can generate 3 MW of power of which 1 MW of power is used to meet its energy requirements. Besides, several WtE projects are currently being undertaken in the Philippines. A WtE facility involving an investment of PhP 2.1 billion will be developed in Puerto Princesa City in Palawan. It will use 110 tpd as fuel or feedstock to generate 5.5 MW of electricity. Further, another plant worth PhP 2.5 billion will be set up in Tugbok district of Davao City. The plant will be able to process 600 tpd of waste and is expected to be completed by 2021[44].

2.11.3.8 Vietnam

In Vietnam, where more than 70 per cent of the waste is currently dumped in landfills, the development of WtE plants is being considered as a potential solution for waste management. It is estimated that with WtE facilities in place, the country can produce around 6 billion kWh of energy by 2050 just from waste. Currently, the WtE plants in Vietnam include the Nam Son facility in Hanoi with a capacity of 1.93 MW and the Go Cat waste handling project in Ho Chi Minh City with a capacity of 2.4 MW. Future WtE projects in the country will focus on increasing the number and capacity of plants in Hanoi, Ho Chi Minh City and the Mekong Delta [45].

2.11.4 Australia

The Kwinana Waste to Energy project will develop a waste processing facility which will use moving grate technology to process approximately 400,000 tonnes of municipal solid waste, commercial and industrial waste and/or pre-sorted construction and demolition waste per annum to produce approximately 36 MW of baseload power for export to the grid.

2.11.4.1 How the project works

The Kwinana Waste to Energy project will use Keppel Seghers moving grate technology, which thermally treats the waste and converts the recovered energy into steam to produce electricity. Metallic materials will be recovered and recycled, while other by-products will be reused as construction materials. Read more about bioenergy and energy from waste.

2.11.4.2 Area of innovation

The Kwinana Waste to Energy facility is an important and significant renewable energy project for Western Australia and Australia. It will be the first thermal utility-scale Waste to Energy facility constructed in the nation, diverting approximately 25 per cent of Perth's post-recycling rubbish from landfill sites.

Kwinana WTE Project Co commissioned a Life Cycle Assessment (LCA) of their proposed Kwinana Waste to Energy plant (WtE Plant) to meet funding requirements of the Australian Renewable Energy Agency (ARENA). The WtE Plant will be located in Kwinana, Australia. It will have two lines, each line estimated to generate 138,220 MWh of electricity annually from 25,000 kg per hour of municipal solid waste. The Western Australian grid is primarily supplied by black coal and gas, with a small portion of wind as illustrated in Figure 1.

The objective of the LCA study is to meet the requirements of ARENA, which are to show the overall environmental impact profile, primarily for embodied fossil energy and GHG balance and to provide a benchmark on fossil energy used, energy return on energy invested (EROEI), and GHG performance.

Whilst the Western Australian market is supplied with a blend of fuel types, the functional unit of the study is to compare the cradle to grave impacts of 1 MWh of electricity supplied to the Western Australian grid from proposed WtE Plant electricity production versus electricity production using black coal. The WtE Plant impacts include collection and transportation of the municipal solid waste as well as the displacement of municipal solid waste to landfill per the ARENA requirements [46].

CHAPTER 3 MUNICIPAL SOLID WASTE COMBUSTOR RESIDUES MANAGEMENT

List of Elements

Symbol	Element
Ag	Silver
Al	Aluminium
As	Arsenic
Au	Gold
B	Boron
Ba	Barium
Be	Berylium
Bi	Bismuth
Br	Bromine
C	Carbon
Ca	Calcium
Cd	Cadmium
Ce	Cerium
Cl	Chlorine
Co	Cobalt
Cr	Chromium
Cs	Cesium
Cu	Copper
Dy	Dysprosium
Eu	Europium
Fe	Iron
Hf	Hafnium
Hg	Mercury
I	Iodine
In	Indium
K	Potassium
La	Lanthanum
Li	Lithium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
Na	Sodium
Nd	Neodymium
Ni	Nickel
O	Oxygen
P	Phosphorus
Pb	Lead
Rb	Rubidium
S	Sulfur
Sb	Antimony
Sc	Scandium
Se	Selenium
Si	Silicon
Sm	Samarium
Sn	Tin
Sr	Strontium
Ta	Tantalum
Tb	Terbium
Th	Thorium
Ti	Thallium
U	Uranium
V	Vanadium
W	Tungsten
Y	Yttrium
Yb	Ytterbium
Zn	Zinc
Zr	Zirconium

Table 4 List of Elements

CHAPTER 3 MUNICIPAL SOLID WASTE COMBUSTOR RESIDUES MANAGEMENT

3.1 Introduction

As the amount of municipal solid waste (MSW) generated in the world continues to increase emerging concerns about municipal solid waste management tend to adopt waste reducing technologies such as waste incineration. In the United States for example, the total generation in 2018 of municipal solid waste was 292.4 million tons or 4.9 pounds per person per day [47]. In the USA many municipalities opted for incineration technology to manage the municipal solid waste generated by Americans, today there are 75 plants that incinerate approximately 29 million tons of municipal solid waste a year and in the process generate 13.8 million MWh of electricity [48].

In the world over 1700 Waste to Energy plants incinerate municipal solid waste to manage the huge amounts of waste generated by humans a number that is increasing as many countries are adopting Waste to Energy technology as the best technology to manage waste that cannot be recycled and, in the process, generate electricity. During the incineration process great percentages of residues and ash are generated, the terms ash and residues are often used interchangeably. This, however, can be misleading. Ash refers to the matter that remains after complete combustion and is separate and different from APC residues. Residue includes unburned material, scrubber sludge, reaction products from the APC system, and other material that may end up in the final ash and residue stream. Therefore, from a technical viewpoint, residue includes the ash. However, many people use the word ash to refer to the total ash and residue stream leaving the plant [49].

The amount of ash generated ranges from 15-25 percent (by weight) and from 5-15 percent (by volume) of the MSW processed. Generally, MSW combustion residues consist of two types of material: fly ash and bottom ash. Fly ash refers to the fine particles that are removed from the flue gas and includes residues from other air pollution control devices, such as scrubbers. Fly ash typically amounts to 10-20 percent by weight of the total ash. The rest of the MSW combustion ash is called bottom ash (80-90 percent by weight). The main chemical components of bottom ash are silica (sand and quartz), calcium, iron oxide, and aluminum oxide. Bottom ash usually has a moisture content of 22-62 percent by dry weight. The chemical composition of the ash varies depending on the original MSW feedstock and the combustion process. The ash that remains from the MSW combustion process is sent to landfills [50].

Every country manages their ash in different ways, for example, Canada landfills all the ash generated daily by disposing of it in separate landfills, the USA on the other hand, combines the ash and disposes of it in landfills which is third largest sources of greenhouse gas emission in the U.S. [51]. In regards to Europe, many European and Asian have addressed the issue of potential reuse of MSWI ashes by executing strategic management plans, and especially, utilizing the Bottom Ash as a beneficial material based on environmental criteria set by their strategic regulations.

In this chapter, relevant literature on incineration of Municipal Solid Waste (MSW), incineration technologies, and chemical and physical properties of MSWI ashes have been thoroughly reviewed. This chapter also provides extensive review of Bottom Ash and Fly Ash management practices and environmental regulations in the USA, Canada, European and Asian countries.

3.2 Municipal Solid Waste Incineration Ash

During the Municipal Solid Waste Incineration process, Incineration Bottom Ash (IBA), Incineration Fly Ash (IFA), and air pollution control (APC) residue are the main products of incineration. Bottom Ash is referred to as grate ash discharged from the furnace grate and collected in the water quenching tank. During the process, the Bottom Ash is combined with grate shifting (fine particles falling through the furnace) and heat recovery ash (particulate matter collected from the heat recovery system).

Fly Ash consists of fine particles carried over the furnace and separated prior injecting sorbents to treat the gaseous effluent. Gas condensate and reaction products are produced from APC devices, such as electrostatic precipitator, scrubber, etc. APC residue is then produced by combining the generated Fly Ash, sorbents, gas condensates, and reaction products together in APC devices.

Management of ash differs from county to county, in the U.S. for example, most Waste to Energy plants combine the IBA and IFA from APC devices in one stream [52] referred to as combined ash, unlike European countries where ashes are separately managed and used for road subbase [53], or China that makes bricks with the Bottom Ash.

3.3 Overview of Thermal Waste to Energy Technology

Municipal Solid Waste and some Industrial Waste has been converted into a beneficial material for the last 100 years. Incineration of municipal solid waste with energy recovery or Thermal Waste to Energy has been accepted worldwide as a safe, effective, and environmentally sound technology. The established large-scale waste processing technologies are:

1. Mass Burn (MB) Incinerator
2. Modular Incinerators
3. Refuse-Derived Fuel (RDF) Incinerator
4. Fluidized Bed Incinerator

3.3.1 Mass Burn (MB) Incinerator

Mass Burn incinerators, combust MSW without prior processing or separation scheme. Most mass burn plants, however, separate the non-combustible steel and iron for recycling using magnetic separation processes before the incineration [54]. In a typical Mass Burn Incinerator (Figure 14), the Municipal Solid Waste or waste to be incinerated is collected onto a tipping floor or storage pit so that sufficient waste input is ensured for continuous operation of incineration. The storage pit also facilitates the removal of large non-combustible materials (metals, rocks, ceramics) from the waste and uniform mixing of waste. The fairly mixed waste is then transferred to charging hopper which is used for maintaining a continuous feeding of waste into the incinerator. Waste then undergoes gravity fall onto the grate system (also referred to as moving stoker) at the bottom of incineration chamber where incineration takes place.

In general, the system of grates in large-scale Mass Burn Incinerators like the ones in China that incinerate 5,000 tons of waste per day are movable (vibrating, rocking, reciprocating, or rotating) to provide agitation to the wastes, thereby promoting combustion the removal of the residue from the incineration chamber.

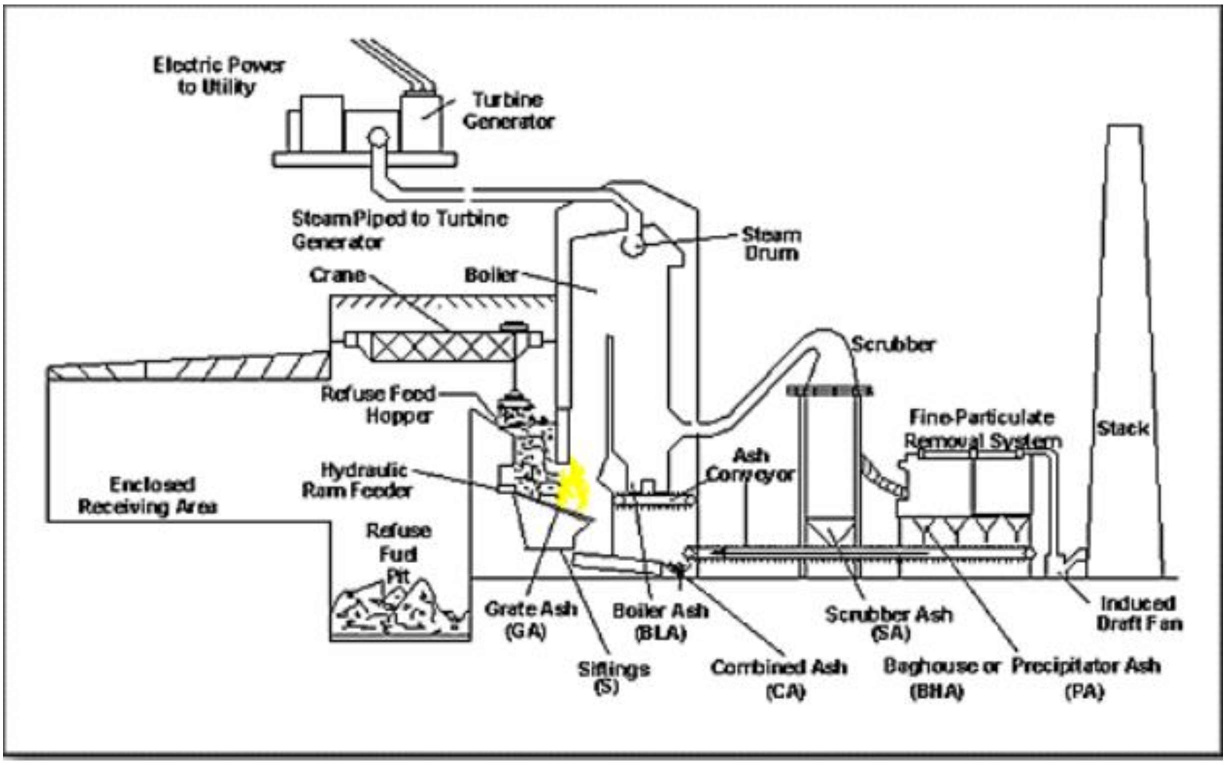


Figure 14 Mass burn WtE facility- typical cross section and ash streams [112].

3.3.2 Modular Incinerators

Modular incinerators are small scale mass burn facilities with a capacity of 15 to 100 tons of waste incineration per day. Modular incineration facilitates two combustion chambers where gases generated in the primary chamber are transferred to the secondary chamber in order to ensure complete incineration [55].

Figure 15 Modular Incinerator Phoenix Waste Solutions [140]

3.3.3 Refuse Derive Fuel (RDF) Incinerators

In the U.S. there are 13 Municipal Solid Waste Incinerators that use Refuse Derive Fuel (RDF) [56]. RDF incineration process offers extensive preprocessing of solid waste before its incineration. Pre-processing allows the removal of non-combustible items, such as glass, ceramics, metals and other recyclable and non-incinerable materials. The residual solid waste is then shredded into smaller pieces for easier incineration. Sometimes RDF materials are compacted at high pressure to produce fuel pellets. The unique feature of RDF systems is in the pre-processing of waste as seen in the following diagram of a typical RDF processing facility. Entering MSW passes through pre-trommel, followed by passing through secondary trammel, and then going to the shredder. A magnetic separator removes ferrous metals and the balance of the material is fired in the furnace. Due to the processing of waste input, RDF process entails the reduced potential of the heavy metal emissions from the incinerators.

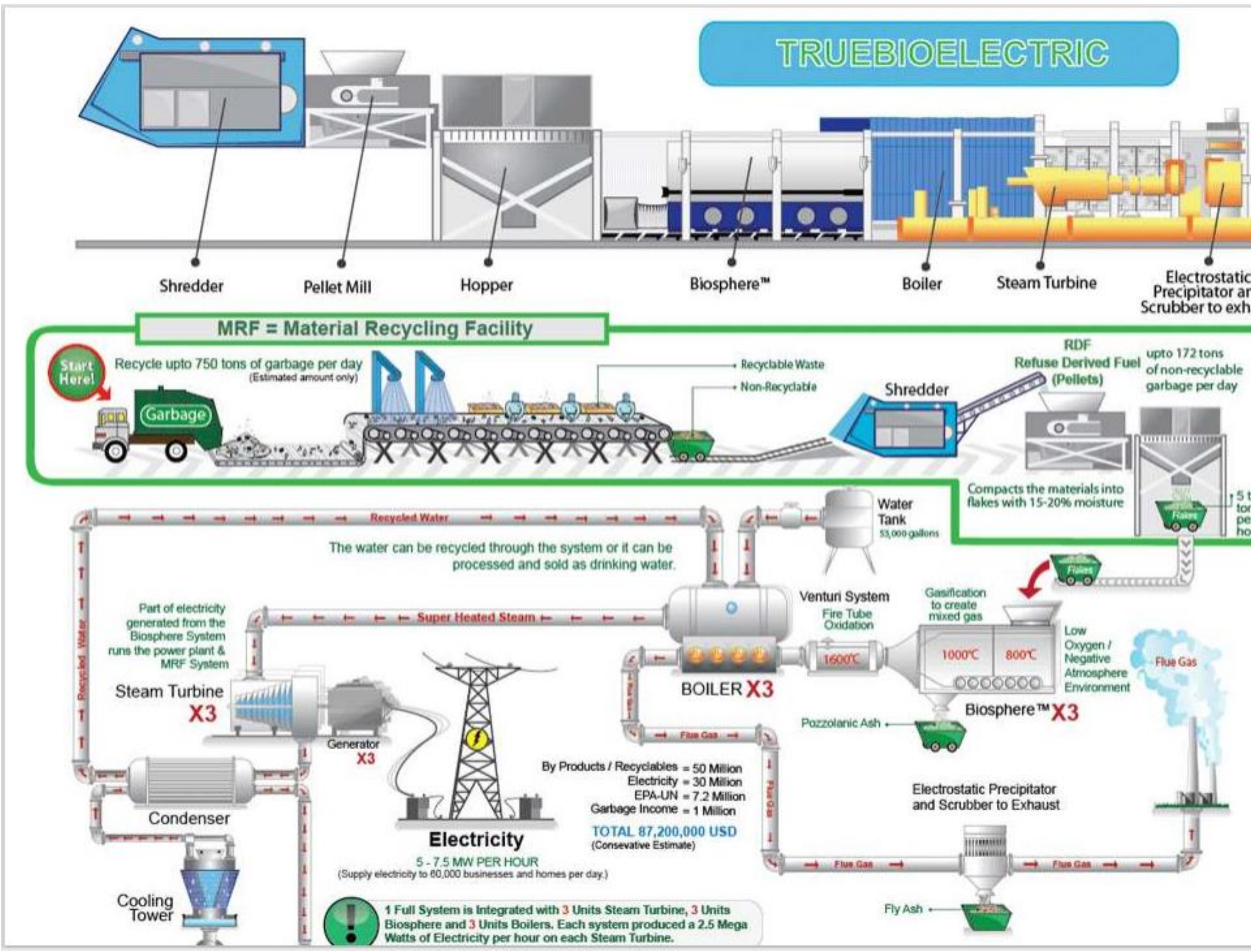


Figure 16 Refuse Derive Waste to Energy Plant [141]

3.3.4 Fluidized Bed Incinerators

During the waste incineration process in a fluidized bed incinerator, solid waste is incinerated within a chamber containing a high temperature bed of a fluidized, granular, noncombustible medium, such as sand. This technique allows almost complete incineration of solid waste by providing close contact with hot bed medium in the incineration chamber which results in little residual unburned carbon. Design concept for fluidized bed incineration requires particulate type feed input. Residual Derive Fuel is the typical form of solid waste that is supplied to fluidize bed combustion units. Although fluidized bed incinerator is associated with higher cost than Mass Burn Incinerators, it certainly offers few advantages over the latter in terms of higher thermal efficiency, lower unburned residual ash and low emission of air pollutants [57].

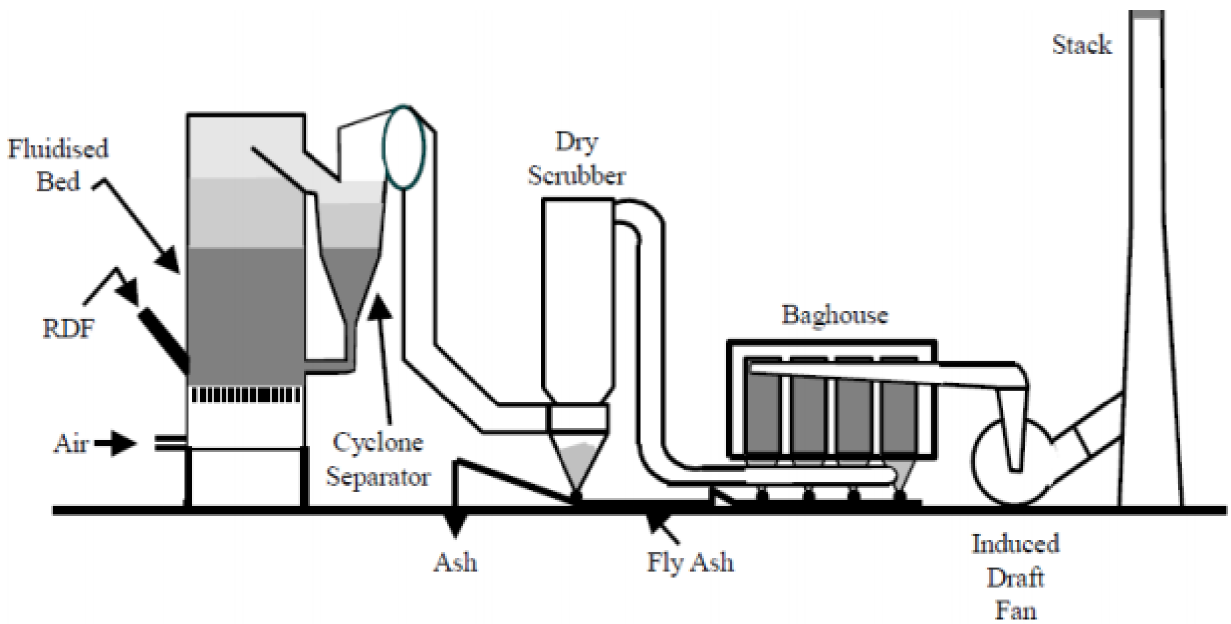


Figure 17 RDF-fired circulating fluidized bed combustion system

3.4 Properties of Municipal Solid Waste Incineration Ash

Based on historical data [58], table 18 summarizes Composition Ranges of Bottom Ash from All Types of WTE Facilities, and Fly Ash Dry/Semi-Dry, and Wet APC System Residues from Mass Burn WTE Facilities.

Element	BA	FA	APC residue (dry/semi dry system)	Wet APC residue (excluding FA)
Ag	0.29-37	2.3-100	0.9-60	-
Al	22,000-73,000	49,000-90,000	12,000-83,000	21,000-39,000
As	0.12-190	37-320	18-530	41-210
B	38-310	-	-	-
Ba	400-3,000	330-3,100	51-14,000	55-1,600
C	10,000-60,000	-	-	-
Ca	37,000-120,000	74,000-130,000	110,000-350,000	87,000-200,000
Cd	0.3-71	50-450	140-300	150-1,400
Cl	800-4,200	29,000-210,000	62,000-380,000	17,000-51,000
Co	6-350	13-87	4-300	0.5-20
Cr	23-3,200	140-1,100	73-570	80-560
Cu	190-8,200	600-3,200	16-1,700	440-2,400
Fe	4,100-150,000	12,000-4,4000	2,600-71,000	20,000-97,000
Hg	0.02-7.8	0.7-30	0.1-51	2.2-2,300
K	750-16,000	22,000-62,000	5,900-40,000	810-8,600
Mg	400-26,000	11,000-19,000	5,100-14,000	19,000-17,0000
Mn	83-2,400	800-1,900	200-900	5,000-12,000
Mo	2.5-280	15-150	9.3-29	1.8-44
N	110-900	-	-	1,600
Na	2,900-42,000	15,000-57,000	7,600-29,000	720-3,400
Ni	7-4,300	60-260	19-710	20-310
O	400,000-500,000	-	-	-
P	1,400-6,400	4,800-9,600	1,700-4,600	-
Pb	98-14,000	5,300-26,000	2,500-1,0000	3,300-22,000
S	1,000-5,000	11,000-45,000	1,400-2,5000	2,700-6,000
Sb	10-430	260-1,100	300-1,100	80-200
Se	0.05-10	0.4-31	0.7-29	-
Si	91,000-310,000	95,000-210,000	36,000-120,000	78,000
Sn	2-380	550-2,000	620-1,400	340-450
Sr	85-1,000	40-640	400-500	5-300
Ti	2,600-9,500	6,800-14,000	700-5,700	1,400-4,300
V	20-120	29-150	8-62	25-86
Zn	610-7,800	9,000-70,000	7,000-20,000	8,100-53,000

Table 5 Composition Ranges of Bottom Ash and Fly Ash [10]

3.4.1 MSWI Bottom Ash

Municipal Solid Waste Incineration Bottom Ash (WSI BA) is the major by-product residue of the MSW Incineration process (85-95 wt. %), Bottom ash is similar in appearance to a porous, grayish, silty sand with gravel material, containing primarily glasses, ceramics, minerals, ferrous and non-ferrous materials with small contents of unburned materials, and organic carbon [10]. Major forms of compounds are oxides, hydroxides, and carbonates. According to research studies using different spectroscopic analyses [59], the main compounds (> 10 wt. %) of IBA are SiO_2, CaO, Fe_2O_3, and Al_2O_3, whereas Na_2O, K_2O, MgO, and TiO_2 are found in minor concentrations (0.4-5.0 wt. %), as predominant form of oxides. SiO_2 is found to be predominant compound in BA, which constitutes up to 49% [60]

Ba, Zn, Ba, Zn, Cl, Mn, and Pb are trace elements (< 1 wt. %) as shown in Table 5. S is found in minor concentrations in the fine fractions (< 1 mm) [61]. The presence of trace and minor elements (Pb, Cl, and S) in smaller particles is reported to be attributed to the deposition of such elements onto particles with higher surface area [10]. The BA has a pH ranging from 10.5 to 12.2, partly due to the presence of hydroxide formation of CaO [10].

In regards to the utilization of IBA, important properties of IBA are loss on ignition (LOI) and presence of metallic Al. A study in Denmark [10] reported that the mean value of IBA LOI varies from 1.9 to 6.3% based on the efficiency of the incineration process. Modern MSWI plants facilitate proper incineration that results in lower LOI, where the LOI less than 3% is indicative to satisfactory burn out [10]. On the other hand, the presence of metallic Al is one of the biggest hindrances of BA utilization in PCC due to the evolution of hydrogen gas originated from the reaction of metallic Al [62] [63] [64] [65]. Despite of the fact that the IBA has considerable number of heavy metals specially Zinc, due to the relatively low level of leaching potential, IBA is often classified as a non-hazardous waste and a benign material. The aging and weathering processes of IBA can further reduce the reactivity and potential of heavy metal release by the reaction between CO2 and water, which form stable complex compounds in BA [66] [67]. Aging is also known to transform metallic Al to stable Al2O3, thereby reduce the potential of hydrogen gas formation [12] [68]. Therefore, the aging and weathering of BA can eventually improve the quality of BA, making its recycling a viable option in the area of road construction material.

3.4.2 MSWI Fly Ash

In general, MSW Incineration Fly Ash is referred to as the entire ash residues from the APC devices. Hence, properties of FA greatly vary with different APC systems, such as dry/semi-dry or wet scrubber equipped with electrostatic precipitator or fabric filter [62]. The MSW IFA is characterized with fine particulate matters, dusty appearance with gray to dark gray color [62] [69]. The MSW IFA mostly contains oxide form of calcium, different metal salts, chloride compounds, and heavy metals [62] [70]. The major elements found in MSW IFA are O, Cl, Ca, Fe, Al, Na, K, Ph, Zn, and S, whereas trace elements are Hg, Cd, Cr, Ni, As, and Co as listed in Table 5 CaO is found to be predominant compound in MSW IFA, which constitutes up to 46% [70]. When MSW IFA is subjected to a treatment with lime (CaO) scrubber, Ca (OH)2 is obtained as end product [62].

MSW IFA is generally considered more toxic material than MSW IBA and it is classified as a hazardous waste, because the MSW IFA comprises higher concentration of heavy metals, salts, and organic micro-pollutants due to the volatilization and condensation of different elements during the incineration [62] [71] [72]. Due to the presence of highly soluble salts, Cl, and heavy metals, the MSW IFA is not considered for direct utilization as transportation materials [62] [10] [73]. Especially, high content of Cl in FA may increase corrosion probability of reinforced concrete structure when mixed with cement. In addition, when the MSW IFA with lime scrubber treatment is incorporated in construction materials, the workability is considerably reduced due to the high-water absorption characteristic of hygroscopic $CaCl_2$ [10]. Moreover, similar to the MSW IBA, large content of metallic Al in FA makes the utilization of MSW IFA uncertain [74].

The presence of readily soluble salt, such as Cl and Na in MSW IFA can significantly contaminate drinking water system [60] [71]. Although dioxin and furan do not leach easily, high potential of heavy metals and trace metals is another concern that can pose a threat to human health [75] [76]. In order to reduce the adverse effect of MSW IFA, different treatment techniques are being practiced. These treatments are (1) extraction and separation using water or acid [77] [12], (2) chemical stabilization using carbon dioxide/phosphoric acid (CO_2/H_3PO_4), ferrous sulfate ($FeSO_4$), sodium sulfide (Na_2S), and orthophosphate

(PO_4^{3-}) [62], (3) solidification using lime, cement, asphalt, and gypsum, and (4) thermal treatment, such as vitrification and pyrolysis [62] [78].

3.4.3 Leaching of MSWI Ashes

Due to the presence of heavy soluble salt and heavy metals in MSWI ashes, leaching properties of MSW IBA, IFA, and combined ash have been considered as one of the most critical parameters for years in order to utilize MSWI ashes without impairing the environment, [79] [80]. Different countries implemented their own standard procedure of leaching test and set threshold limit for toxic elements to evaluate the leaching potential of heavy metals and soluble salts when the MSWI ashes are either landfilled or in contact with soil and water [5] [81].

Evaluation of leaching from MSWI ashes, leachate, and run off from landfill and application 7 sites have been performed mostly in European countries [62] [82], but also at small extent in the U.S. [10] [83]. Leaching test results reveals that MSW IFA contains significantly higher soluble salt content (i.e., Na, K, Ca, Cl) and toxic elements (i.e., Pb, Zn, Cr, Ni, Cu) with compared to MSW IBA [84] [85]. Oxyanions, such as Zn and Pb are termed as amphoteric, which are characterized with high leaching potential at both high and low pH. Release of such amphoteric heavy metals from MSW IFA can be significantly increased due to the high pH of MSW IFA originated from APC devices containing lime solution [86]. Substantial Pb leaching has also been confirmed by the researchers in Korea and Japan [87]. Danish researchers [88] evaluated MSW IBA and MSW IFA from 25 MSWI plants from 1998 to 2010 and reported that the MSW IFA is likely to exceed the leaching limit values for Cl, SO4, Cd, Cr, Hg, Mo, Pb, and Zn whereas the MSW IBA is likely to exceed limit values for Cl, SO4, Cu, Mo, Sb, and Se.

Weathering and carbonation of MSW IBA [89] [90] [91] and MSW IFA [92] are beneficial for the application of the ashes, because these treatments reduce the pH of the ashes and toxic metal release. Although carbonation technique is less effective in the leaching of Mo and Sb, it is effective for the Cu release [93]. Although Cu in the leachate is bound in neutral and basic condition; in acidic condition, Cu exists as highly mobile ions that substantially increase its leaching [94] [95]. Therefore, Cu release is considered to be a critical concern. Dissolved organic carbon is believed to be responsible for Cu and Ni release due to the potential complexation of these metals [96] [97]. Similarly, Zn leaching also follows the same characteristics of Cu when BA is in acidic condition [94].

Leaching tests have been conducted to evaluate toxic elements release from the leachate of MSW IBA, MSW IFA, and combined ash when used as base or sub-base course in asphalt pavement [98] [99], Portland Cement Concrete product [64] [74] [80] [100], and embankment fill [101] [102]. The U.S. studies reported that heavy metal concentration in leachate mostly meets the leaching requirements [103] and often meets the U.S. drinking water standard [104]. It was also reported that the concentration of dioxin and furan, especially in MSW IFA, does not pose any threat in regard of the environment and health [105]. However, although heavy metal concentrations in ash leachate are found mostly below the threshold limits in the U.S., salt concentration was reported to be much higher than the limit of the drinking water standard [106] [107].

Researchers confirmed significant reduction of leaching potential of MSW IBA, MSW IFA, and combined ash when incorporated with cement and concrete [80] [98] [108] [100]. Spanish researchers formulated granulated material with combined ash and cement to use as secondary building material [108]. In this research study, batch leaching tests were performed to evaluate leaching behavior of MSW IBA, APC, and combined ash containing concrete. Concrete mixtures were prepared with 10% cement, 10% APC, and 80% BA by weight. The test results are provided in Table 2.2 with threshold values established by utilization criteria [109] and three categories of landfill criteria [110] set by Spanish Government for MSWI BA utilization as secondary building material. It is indicated that a significant reduction of leaching was observed for the combined ash mixed concrete formulation and heavy metal concentrations were below the criteria of utilization. A considerable reduction in leaching of heavy metals from MSWI ashes by chemically encapsulating within concrete has also been confirmed by many other researchers [80] [98] [111] [100].

Element	BA	APC	Combined ash	Concrete with combined ash	Criteria for utilization[a]	Criteria for landfill[b]		
						Inert	Non-hazardous	Hazardous
As	0.003	0.004	0.003	0.001	1.0	0.50	2	25
Ba	0.504	43.682	5.302	15.04	-	20.0	100	300
Cd	0.043	0.040	0.043	0.026	1.0	0.04	1	5
Cr	0.390	3.643	0.751	0.050	5.0	0.50	10	70
Cu	0.989	4.999	1.435	0.938	20	2.00	50	100
Hg	<0.01	<0.01	0.010	<0.010	0.2	0.01	0.2	2
Mo	0.401	2.611	0.647	0.117	-	0.50	10	30
Ni	0.060	1.290	0.197	0.170	5.0	0.40	10	40
Pb	0.079	138.284	15.435	2.139	5.0	0.50	10	50
Sb	0.460	0.040	0.413	0.079	-	0.06	0.7	5
Se	0.007	0.092	0.016	<LOD[c]	-	0.10	0.5	7
Zn	0.818	35.083	4.625	1.008	20.0	4.00	50	200

Table 6 : Leaching results for MSWI BA, APC residue

Leaching results for MSWI BA, APC residue, and formulated concrete mixture (mg/kg) [108]

[a] Spanish utilization criterion [109]

[b] Spanish landfill criteria [110]

[c] LOD = limit of detection

3.4.4 MSWI Ash Beneficial Uses

Municipal Solid Waste IBA and IFA have been used as partial replacement of cement in order to investigate their effect on the cement paste and PCC [64] [112] [113] [100] [114] [115]. Although sometimes IFA is considered to have similar properties with cement [70] [116] [117], experimental observation reveals that both ashes contain considerable amount of metallic Al that results in hydrogen gas evolution, cracks, and voids in cement paste specimens [64] [118] [119] [113]. In addition, IFA contains significant amount of Cl, which may increase corrosion probability of reinforcing steel in reinforced concrete structure.

3.5 Management Practices of MSW Incineration Bottom Ash

Beneficial uses of MSWI ash has been well established in European countries. Applications of MSWI ashes in road construction materials as subbase layer, in asphalt paving and PCC have been common practice [62] [120] [121]. These applications are not only promising from structural integrity standpoint, but also effective from environmental safety perspective. In the ash utilization into concrete, concrete captures the heavy metals in physical and chemical manner and they are transformed into more stable and insoluble compounds, making it less vulnerable to potential contamination [122]. Leaching potential from ash residue can be reduced significantly by being physically encapsulated in asphalt [123].

Confederation of European Waste-to-Energy Plants (CEWEP) [124] reported that around 500 WTE plants turn the non-recyclable waste into secure energy and valuable raw materials in an environmentally safe manner in Europe as 2021, Waste-to-Energy helps reach the targets set in the EU Landfill Directive that aims to reduce the amount of waste being landfilled (Benefits of diverting waste from landfills). Waste-to-Energy and Recycling are complementary waste treatment methods in integrated waste management systems. Household and similar waste should be sorted at source and the clean materials should be sent to high quality recycling. The remaining waste, that cannot be recycled in a technically or economically viable way, should be used to generate energy.

The managements of MSWI ash in several countries, including European countries, Japan, and U.S. are summarized below.

3.5.1 United States

In the USA the common practice is to combine the ash at the plant for disposal in landfills. Predominant method for the management of combined ash is disposal in monofill, lined with clay, synthetic liners, or a combination of those methods that is associated with the facility for leachate collection and treatment scheme [12]. Currently, there is no recycling of MSWI ash; instead, ash management only involves with preprocessing, such as recovery of ferrous metals using magnetic separators and non-ferrous metals using an eddy current in facilities incorporated with incineration plants [5] [10]. Although currently there is no recycling of combined ash or BA as a road construction material, field research and demonstration projects for the beneficial use of ash have been conducted over 25 years in the U.S. [12]: (1) geotechnical applications, including base and subbase, embankment [125] [126], (2) hot-mix asphalt [80, 86], and (3) Portland cement concrete [10]]. IBA and combined ash used as asphalt pavement aggregate, Portland cement concrete, block aggregate, structural fill, landfill cover, and road base as gravel replacement in the U.S. are summarized in Table 7 [10].

Utilization area	Location	Description	Report
Concrete	Albany, NY	After ferrous removal and size reduction at smaller than ¾ inch, BA replaced all coarse and partial fine aggregate in concrete block foundation	Excellent, no ground, water and air pollution
	Rochester, MA	Boiler Aggregate, BA processed by ferrous removal and screening, used in concrete block for building frontage and concrete curbing	No environmental risk
	Long Island, NY	Processed after ferrous recovery and screened to size, stabilized BA and combined ash (85% ash and 15% type II Portland cement) used in masonry blocks and artificial reef	Blocks were stronger than original concrete blocks. No ground or water pollution
	Montgomery County, OH	BA, before and after ferrous removal, used as aggregate in building blocks. Spalling was observed due the ferrous metal for the former condition	Ferrous metal recovery is effective before use of BA in block manufacturing
	Los Angeles, CA	90% ash, smaller than 1 inch, mixed with 10% type II Portland cement. Cured blocks were crushed to gravel size aggregate to use as road surface	Satisfactorily acceptable
	Ruskin, FL	Ash used as partial replacement of coarse aggregate in Portland cement mix	Acceptable
	Islip, NY	Combined ash treated with Portland cement in a patented process, named as Rolite, used as gas venting layer at landfill and lightweight fill in closed area	Acceptable
	Palm Beach, FL	waste tire-clad and concrete log with ash aggregate content, named as Tirelog, used as reef barrier and highway guard rail	Feasible
Landfill Cover	Honolulu, HI	Combined ash used as landfill cover at landfill	Very well performance
	Blydenburgh, NY	Portland cement treated combined ash, Rolite was used as landfill cover	Feasible
Embankment Fill	Pinellas County, FL	Phosphate treated (WES-PHix process) combined ash was used as embankment fill	Acceptable

Table 7 Research projects on MSWI ash in the U. S [10].

3.5.2 Canada

In Canada there are 5 large waste to energy plants that incinerate 951,000 tons a year or Municipal Solid Waste [17]. Waste to Energy facilities dispose the ash in different landfills, after sampling, bottom ash will be hauled directly for disposal unless the 6-week rolling average is above 80% of the TCLP standard [127] or it is used beneficially as a landfill cover of in the construction of waste transfer stations [128].

3.5.3 The Netherlands

The present incineration capacity of the Dutch EfW installations amounts to more than 7.5 M Tonnes / year. The "free" capacity at this moment is around 15 – 20 %; the free capacity is filled by imported RDF (primarily from UK). The Dutch policy to increase recycling and separate collection of separate streams leads to an increase of:

• The "free" capacity and dependency on waste imports • The opposition to accept long term future utilization of "complex" and partly "English" IBA in road construction [129]as a subbase fig 18.

The special use of IBA in the Netherlands has the following strong drawbacks:

• Continuous aftercare of isolation construction • Risk that construction will sink below ground water level • Complicated processing of IBA in the construction • risk for planning of construction phase [53].

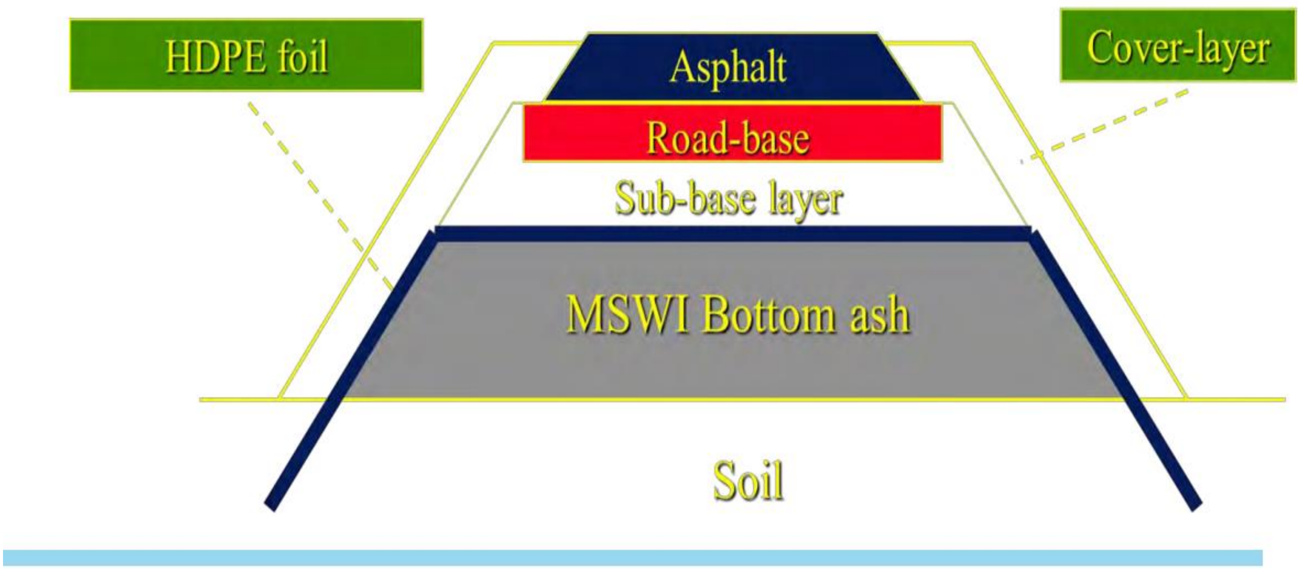


Figure 18 Bottom use as road subbase Netherlands [129]

3.5.4 Germany

Germany recycles about 65% of its MSW IBA generated, while landfills 28% after the reduction of salt content by water quenching, followed by ferrous and non-ferrous metal recovery and 3–19-month maturation [12]. A reduction in leaching potential makes BA suitable for the utilization as road construction and secondary building materials [12]. Salt content of ash and dry scrubber residues are subjected to backfill in the old mines to prevent subsidence. Small quantity of APC residue is disposed into landfill after stabilization.

3.5.5 France

France recycles 79% of IBA produced in the civil constructions [77]. BA treatments involve ferrous and non-ferrous metal removal, size reduction, and sometimes cement stabilization [77]. APC residue is managed mostly by stabilization with either cement or treatment with NaHCO3; it is then disposed of in a landfill designated for hazardous waste [81]. Thermal treatment is also considered as a new option for ash treatment, which is not very common, yet [78].

3.5.7 Sweden

Having enough natural resources accompanied by less incentive of ash utilization, BA and FA are collected separately, and BA is disposed into the landfills without any treatment. On the other hand, FA is disposed in the special lined landfill or cell after treatments. Sweden exports their APC residues to Norway for neutralization of acid waste and landfilling after solidification and stabilization [10].

3.5.8 Japan

Due to a very large number of incinerators, a great amount of as is being producing, and lack of land space for landfilling makes Japan to predominantly practice thermal and melting treatment of MSWI combined ashes [130] [131]. IFA is permitted to be disposed in landfill after melting, followed by solidification or stabilization with cement or 20 chemicals and acid or solvent extraction [77]. Molten slag produced from the melting processes are considered for civil engineering application, such as filler material, interlocking blocks, roadbeds, and aggregate for asphalt paving [10].

3.5.6 Singapore

Sustainable solid waste management involves the people, private and public sectors. Working hand in hand with these key stakeholders, NEA has developed a range of initiatives and programs to curb waste growth.

At source where the waste is generated, recyclables are sorted and retrieved for processing to conserve resources. The remaining waste is collected and sent to waste-to-energy plants for incineration. Incineration reduces the waste by up to 90 per cent, saving landfill space, and the heat is recovered to produce steam that propels turbine-generators to generate electricity, providing up to 3% of the island's electricity needs.

The incineration ash and other non-incinerable wastes are then transported to the Tuas Marine Transfer Station (TMTS) from where they are barged to Semakau Landfill for final disposal [132].

3.5.6 Denmark

MSW IBA is considered as a suitable gravel substitute as subbase material when used with asphalt or concrete cover to avoid a direct contact with soil and water [10]. Denmark aimed at recycling 98% of BA into building and road construction and embankment fill after screening, crushing, and ferrous metal recovery [10]. APC residues, including FA and acid cleaning end product are considered as special hazardous waste, required to landfill after treatments [77]. Denmark exports APC residue to Norway for the use in neutralizing acid waste or to Germany in order to use as backfill in salt mines [77].

CHAPTER 4 ENVIRONMENTAL REGULATIONS

4.1 Introduction

European countries and Canada have implemented more strategic and scientific regulations for MSWI ash management compared to those of U.S. Environmental regulations in European countries and Canada are based on leaching criteria set by standard test procedures [10] for beneficial utilization of MSW IBA and disposal of MSW IFA after treatments. In the U.S., on the contrary, MSW IBA and MSW IFA are combined to be disposed as combined ash. Environmental regulations of MSWI ashes in European countries and U.S. are summarized below. The development of a legal frame-work comprises two regulatory actions: the enactment of a formal legal instrument e.g., an act, ordinance, or decree, and the development of regulations, rules, and orders by the authority designated in the formal legal instrument (World Health Organization, 1987 [133]). Current environmental legislation in different countries is guided by their own set of principles [134]. Table 8 summarizes the key features of some current guiding principles for setting environmental standards [135] while

Table 9 lists formal legal instruments and subsidiary regulations for lists formal legal instruments and subsidiary regulations for environmental protection for some major countries.

Principle	Features
"Safe" Levels	• Pollutant levels are set to levels deemed to be safe. • Definition of "safe" not defined. • Aspires to maximum safety benefit without regard to cost.
Prudent Reduction	• A particular pollutant level is set at some "worthwhile" reduction from present levels. • There is recognition that a "safe" level may not be identifiable.
Precautionary Principle	• Broadly applied general principle. • Recommendation to consider action to avoid possible harm even if it is not certain to occur (WHO). • High level of protection taking into account the diversity of situations in the various regions of the Community (under the context that the principle is formally a part of EU law). • Take action to avoid potentially damaging impacts of substances that are persistent, toxic and liable to bioaccumulate even where there is no scientific evidence to prove a causal link between emission and effects (definition given at the third North Sea Conference in 1990).
Best Available Technology Not Entailing Excessive Cost (BATNEEC)	• Recognizes that if a "safe" level exists it is likely to be too costly to achieve. • The cost of standard is clear and reasonable. • Technology should be "best" at preventing pollution and "available" to operator of activity concerned ("The effectiveness of policy instruments for energy-efficiency improvement").
As Low As Reasonably Achievable (ALARA)	• Broadly applied general principle. • Any procedures for controlling pollutant levels should employ the latest and best technological aids to achieve outcomes that are ALARA. • ALARA levels are implied to ensure safe or prudent levels and that more than this cannot be expected from the pollutant. • Major application in radiation risk and protection

Table 8 Principles of setting environmental standards [135]

Country	Significant formal legal instruments	Selected Regulations	Reference
United States	Resource Conservation and Recovery Act (1976	40 CFR Part 256: Guidelines for Development and Implementation of State Solid Waste Management Plans 40 CFR Part 258: Criteria for Municipal Solid Waste Landfills 40 CFR Part 260: Hazardous Waste Management System 40 CFR Part 268: Land Disposal Restrictions.	US EPA US Government Publishing Office
China	Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Wastes (1996)	GB 5085.3-2007: Identification Standards for Hazardous Wastes – Identification for Extraction Toxicity GB 16889-2008: Standard for Pollution Control on the Landfill Site of Municipal Solid Waste GB 18485-2014: Standard for Pollution Control on the Municipal Solid Waste Incineration	Ministry of Environmental Protection, People's Republic of China
Netherlands	Soil Protection Act (1987, revised 2008)	Decree No. 39 of 1995 concerning the discharge of water for purposes of soil protection Decree No. 649 of 1997 relative to the discharge of liquid substances into the soil Decree No. 469 of 2007 containing rules relative to quality of soi	Food and Agriculture Organization of the United Nations
Singapore	Environmental Protection and Management Act (enactment in 1999, revised 2002)	Hazardous Substances Regulations Trade Effluent Regulations	Food and Agriculture Organization of the United Nations
Germany	Basic Law (Grundgesetz) Article 74 Number 24 (promulgation in 1949)	Federal Waste Prevention and Disposal Act Packaging Ordinance Hazardous Substances Control Act Federal Nature Conservation Act	The Environmental Law System of the Federal Republic of Germany. Annual Survey of International & Comparative Law 3 (1, Article 6). [136]

Table 9 Regulations - solid waste management in different countries [147].

4.2. Compilation of MSW Environmental Standards

4.2.1. European Union waste acceptance criteria

The European Union (EU) has a clear and defined objective in regards to its waste management. Its long-term goal is to become a recycling society, avoiding waste, and using unavoidable waste as a resource wherever possible (European Commission, 2010) while contributing to a circular economy [136]. Through a combination of member state politics, regulatory politics, and international market competitiveness, the EU attempts at legitimizing the precautionary principle, and establishing international credibility, which contributes to its progression in environmental protection policies [137].

In 1989, international outrage as a result of uncontrolled shipping of hazardous waste to developing countries and to Eastern Europe led to the adoption of the Basel Convention [138]. The Basel Convention aims to, among other objectives, reduce hazardous waste generation and restrict transboundary movements of hazardous wastes. In 2001, the Landfill Directive was adopted to address problems of pollution from incinerators, landfills, and recycling plants [138]. Today, the Waste Framework Directive, the Hazardous Waste Directive, and the Waste Shipment Regulation (adopted in 2006) form the basis of the regulatory structure on waste in the EU (European Commission, 2005).

Since EU legislative power derives from the European Economic Community treaty, and as a supranational organization to which member states have ceded special administrative and legislative powers, the waste regulatory structure basis applies to Member States. This has helped protect the environment and human health across the European Community [138]. As for the reuse of solid waste in construction applications, the waste acceptance criteria (WAC) have been established in Europe, but there are no European limits especially for construction products. While the recycling of MSW incineration ash is widely practiced, management practices for incinerator residues vary in different jurisdictions, and there is still need for legislation on recycling of waste incineration residues at the EU level [139].

4.2.2 European Union waste acceptance criteria (WAC) Standard

The Landfill Directive of 1999 defines the different categories of waste, among other matters. It is a minimum directive, and EU member states can set stricter criteria nationally. The European Council Decision 2003/33/EC (published in January 2003 and taking effect in July 2004), on the other hand, lists the WAC for the different categories of waste pursuant to the Directive of 1999:

- Inert wastes,
- Non-hazardous wastes,
- Hazardous wastes acceptable in non-hazardous landfills, and
- Hazardous wastes acceptable in hazardous waste landfills.

These criteria are listed in Table 10. The concept behind the WAC is that leaching should not result in an unacceptable increase in key pollutant concentrations in the groundwater downstream the landfill. The procedure for setting the WAC consisted of several consecutive steps. First, the point of compliance (POC) was set to be the groundwater quality 20 meters downstream the landfill [140]. Quality criteria were then set for the peak concentrations of contaminants in the groundwater based on existing European groundwater or drinking water legislation.

The release of contaminants from the source can be expressed as a function of liquid-to-solid ratio (L/S), and the transport of contaminants from the landfill through soil and into the groundwater can be modeled based on contaminant-subsoil sorption. Using the contaminant release and transport models, forward calculations could be done for the concentration at the POC for each contaminant. An attenuation ratio, source peak concentration divided by forward calculated peak POC concentration, was used to back calculate permissible values at the source from the groundwater quality criteria at the POC for each contaminant. The source term criteria could then be transformed into limit values for a specific leaching test and L/S value [141].

Table 6, shows the implementation of EU requirements related to acceptance criteria area is achieved in the majority of EU-15 Member States. In the Netherlands, Portugal, and the England and Wales parts of the UK, the inorganic leaching criteria are identical to the EU WAC, while in the Flanders part of Belgium, France, Germany, and the Northern Ireland part of the UK the inorganic leaching criteria are identical to or even more stringent than the EU WAC.

Leaching limits as set out in Council Decision 2003/33/EC

	Inert wastes			Non-hazardous wastes			Hazardous waste acceptable at non-hazardous waste landfills			Hazardous waste acceptable at hazardous waste landfills		
Element or substance	L/S = 2 L/kg mg/kg	L/S = 10 L/kg mg/kg	C_0 percolation test mg/L	L/S = 2 L/kg mg/kg	L/S = 10 L/kg mg/kg	C_0 percolation test mg/L	L/S = 2 L/kg mg/kg	L/S = 10 L/kg mg/kg	C_0 percolation test mg/L	L/S = 2 L/kg mg/kg	L/S = 10 L/kg mg/kg	C_0 percolation test mg/L
As	0.1	0.5	0.06	0.4	2	0.3	0.4	2	0.3	6	25	3
Ba	7	20	4	30	100	20	30	100	20	100	300	60
Cd	0.03	0.04	0.02	0.6	1	0.3	0.6	1	0.3	3	5	1.7
Cr (total)	–	–	–	4	10	2.5	4	10	2.5	25	70	15
Cu	0.9	2	0.6	25	50	30	25	50	30	50	100	60
Hg	0.003	0.01	0.002	0.05	0.2	0.03	0.05	0.2	0.03	0.5	2	0.3
Mo	0.3	0.5	0.2	5	10	3.5	5	10	3.5	20	30	10
Ni	0.2	0.4	0.12	5	10	3	5	10	3	20	40	12
Pb	0.2	0.5	0.15	5	10	3	5	10	3	25	50	15
Sb	0.02	0.06	0.1	0.2	0.7	0.15	0.2	0.7	0.15	2	5	1
Se	0.06	0.1	0.04	0.3	0.5	0.2	0.3	0.5	0.2	4	7	3
Sn	–	–	–	–	–	–	–	50	–	–	–	–
Zn	2	4	1.2	25	50	15	25	50	15	90	200	60
Cl^-	550	880	450	10000	15,000	8500	10,000	15,000	8500	17,000	25,000	15,000
F^-	4	10	2.5	60	150	40	60	150	40	200	500	120
SO_4^{2-}	560	1000	1500	10,000	20,000	7000	10,000	20,000	7000	25,000	50,000	17,000
Phenol index	0.5	1	0.3	–	–	–	–	–	–	–	–	

Table 10 Leaching limits as set out in Council Decision 2003/33/EC [152]

	Austria	Belgium Brussels	Belgium Flanders	Belgium Wallopia	Denmark	Finland	France	Germany	Greece	Ireland	Italy	Luxembourg	Netherlands	Portugal	Spain	Sweden	UK England/Wales	UK Northern Ireland	UK Scotland
Inert waste landfill leaching limit values	Black	White	Gray	White	Black	Gray	Gray	Gray	White	White	Gray	White	Gray	Gray	White	Gray	Gray	Gray	Gray
Non-hazardous waste landfill leaching limit values	White	White	Gray	White	White	White	Black	Black	White	White	White	White	Gray	Gray	White	White	Gray	Black	White
Non-hazardous waste landfill for hazardous waste leaching limit values	Gray	White	Black	White	White	White	Black	Gray	White	White	White	White	Gray	Gray	White	White	Gray	Gray	Gray
Hazardous waste landfill leaching limit values	Gray	White	Black	White	White	White	Gray	Gray	White	White	White	White	Gray	Gray	White	White	Gray	Black	Gray

Table 11 Implementation of Decision 2003/33/EC [155]

Black = more stringent, Gray = identical, White = slight differences

4.2.3 United States

Despite of having many studies regarding successful demonstration projects of MSWI ash utilization in transportation applications [10] [133] [134], acceptance of ash is still under debate. Absence of proper Federal regulation and guidance and their variable applicability in different states hinder the implementation of the beneficial use of MSWI ash.

An important purpose of environmental regulations is to regulate the use of resources to ensure minimal impact on the environment and human health. As the economy grows and income rises, the increased demand for natural resources and manufactured consumer goods has put strains on the environment [135]. Thus, the amount of solid waste generated increases in parallel to economic development, due to excessive consumerism.

4.2.3.1 Waste characterization and landfill requirements.

In the United States there is no relevant or equivalent standard for cumulative release from diffusion testing to be used for the reuse of construction materials [145]. Perhaps this is one reason why little incineration ash is reused in the US. Another reason against reuse could be legal liabilities: if mixtures of fly and bottom ashes are determined to be hazardous by EPA standards, anyone connected with the distribution of those products may be held legally responsible (ASTM, 1989). Currently, mixed waste-to-energy ash is mostly disposed of in landfills [29]. The US EPA SW-846 Method 1311 Toxicity Characteristic Leaching Procedure (TCLP) test applies to ash from municipal waste incinerators that manage hazardous solid wastes [146]. Nevertheless, there are regulatory levels for identifying hazardous waste. According to the TCLP test Method 1311, if any of the contaminant level from an extract of a representative solid waste is at or exceeds the regulatory level Table 12, the solid waste is considered to exhibit toxicity characteristics, and is classified as a hazardous waste. The approach for the derivation of the TCLP regulatory level takes into account three key determinations:

- Acceptable level at the groundwater consumption point based on risk,
- The dilution/attenuation factor between the disposal unit and the receptor, and
- The leachate concentration from the waste that would be permitted.

In addition, explicit determination of allowed concentration from risks of exposure to the leached constituents is needed. Particularly, the risks are based on risk-specific doses for carcinogenic compounds that result in an incidence of cancer equal to or less than 10^{-5}, reference doses for non-carcinogenic constituents based on an estimate of the daily dose of a substance that will result in no adverse effect even after a lifetime of such exposure, and the proposed maximum contaminant levels in drinking water [147]. Criteria for wastes from different industries are listed in 40 CFR 268.40. A restricted waste, as identified in 40 CFR 268.40, cannot be land disposed if a TCLP extract of the waste or a TCLP extract of the treated residue of the waste exceeds the value in 40 CFR 268.40 as it is shown in Table 13. In the latter case, the treatment standard has not been met, and further treatment is required prior to land disposal.

USA Maximum concentration of contaminants for toxicity characteristics

Contaminant	Regulatory level (mg/L)
Ag	5.0
As	5.0
Ba	100.0
Cd	1.0
Cr	5.0
Hg	0.2
Pb	5.0
Se	1.0
Testing method	TCLP Method 1311

Table 12 USA Regulatory level [158]

Inorganic hazardous constituents in hazardous waste leachates from 40 CRF 268.40

Contaminant	Regulatory level (mg/L)
As	5
Ba	21
Cd	0.11
Cr (total)	0.60
Pb	0.75
Hg	0.25
Se	5.7
Ag	0.14
Ni	11
Sb	1.15
CN^-	590
Testing method	TCLP Method 1311

Table 13 Inorganic hazardous constituents in hazardous waste leachates

4.2.4 China

In China there are no government-mandated standard criteria for the use of incinerated waste materials. According to the Standard for Pollution Control on the Municipal Solid Waste Incineration (GB16485 2014), IBA can be landfilled directly. In addition, IBA that has lower leachability of heavy metals than China's leaching standard and TCLP can be treated as non-hazardous waste for use as building materials. Also, according to GB16485 (2014) IFA is to be managed as hazardous waste, but if it needs to be landfilled it must meet the requirements of GB16889 (2008). On the other hand, if IFA is to be treated in a cement kiln, it must meet the requirements of GB 30485 (2013) [149].

4.2.4.1 Hazardous waste identification and landfill waste requirements.

The leaching limit criteria for the purpose of identifying hazardous waste in China can be seen in Table 14, similar to the function of TCLP regulatory limits in the US. The criteria are identical for the elements that the two countries share in common (i.e., Ag, As, Ba, Cd, Cr, Hg, Pb, Se). In China, if wastes meet the criteria as listed in Table 15, they can be landfilled. Unlike the EU waste acceptance criteria, the GB 16889 criteria do not distinguish between inert, non-hazardous, and hazardous waste landfills.

Hazardous waste identification in China

Contaminant	Regulatory level (mg/L)
Ag	5
As	5
Ba	100
Be	0.02
Cd	1
Cr (total)	15
Cr (VI)	5
Cu	100
Hg	0.1
Ni	5
Pb	5
Zn	100
Testing method	HJ/T 299-2007

Table 14 China Hazardous waste identification [160]

Landfill waste requirement in China

Contaminant	Regulatory level (mg/L)
As	0.3
Ba	25
Be	0.02
Cd	0.15
Cr (total)	4.5
Cr (VI)	1.5
Cu	40
Hg	0.05
Ni	0.5
Pb	0.25
Se	0.1
Zn	100
Testing method	HJ/T 300-2007

Table 15 China Landfill waste requirement [161]

4.2.5 The Netherlands

The Dutch waste management system is well respected around the world. To some degree, Dutch national waste management policy has even influenced some European policies in recent years [150].

The Netherlands's standing in waste management can be attributed to nation-wide efforts to establish a well-defined national waste management policy with quantitative targets, as well as comprehensive waste processing infrastructure. The first piece of Dutch legislation that dealt explicitly with waste was the Waste Substances Act 1977, which covered discrete sectors of the environment separately, such as surface water, air, chemical waste, and noise. However, regulators found this sector-wise approach to be inadequate, and an integrated approach was required.

The integrated approach was realized in the Environmental Management Act 1993. The Act covers a wide range of aspects such as waste collection, hazardous waste disposal, air quality, noise nuisance, environmental permits, and setting of environmental management strategies. At present, the Environmental Management Act is the central piece of legislation that governs the planning framework for environmental authorities, integrated permitting, compliance monitoring activities, and harmonization with other environmental laws (OECD, 2009) [149].

Emission limits from the Dutch regulation as part of the Soil Quality Decree; limit values are specified for monolithic products (in mg/m2), granular construction materials in ‘‘open” applications (infiltration rate of 300 mm/year), and in applications with isolating measures (infiltration rate of 6 mm/year) [151].

Element	Monolithic (mg/m^2)	Granular, open (300 mm, mg/kg)	Granular, isolated (6 mm, mg/kg)
As	260	0.9	2
Ba	1,500	22	100
Cd	3.8	0.04	0.06
Cr	120	0.63	7
Co	60	0.54	2.4
Cu	98	0.9	10
Hg	1.4	0.02	0.08
Mo	144	1	15
Ni	81	0.44	2.1
Pb	400	2.3	8.3
Sb	8.7	0.16	0.7
Se	4.8	0.15	3
Sn	50	0.4	2.3
V	320	1.8	20
Zn	800	4.5	14
Br^-	670	20	34
Cl^-	110,000	616	8,800
F^-	2,500	55	1,500
SO_4^{2-}	165,000	1,730	20,000
Testing method	NEN 7375	CEN/TS 14405	

Table 16 Emission limits from the Dutch regulation [163]

The Dutch approach to waste management, also known as the ‘‘Lansink’s Ladder,” is to: avoid as much waste as possible in the first place, recover reusable resources from wastes, generate energy through waste incineration, and then dispose the remaining waste into landfills [152]. In keeping with the practice of recovering reusable resources from wastes, stony wastes can be reused in construction applications.

Solid Waste can be reused as construction material but the solid waste must meet the criteria as stipulated in the Dutch Building Materials Decree. From 1995 to 2008, the Dutch Building Materials Decree regulated the potential impact of construction materials on the environment.

It specified the environmental quality criteria for the use of stony materials in construction, and did not distinguish between primary, secondary, and waste materials. The regulations were updated in 2007 into the Soil Quality Decree (came into force in July 2008). The reason for the revised decree was to develop a simplified and more transparent regulation containing a consistent set of emission limit values [146].

There are limit values for monolithic and granular construction products in the Soil Quality Decree shown in Table 16. In general, these values are derived from impact modeling of groundwater and soil quality, which are determined by ecotoxicological criteria [153]. The emission limit values for granular construction products were calculated in six steps, using leaching results from tank leaching test carried out over 64 days [151]. A generic average release pattern (in mg/m2) for each inorganic substance based on a large collection of quality control data for construction products was determined using the percolation test NEN 7343. Geochemical modeling was then used to calculate how the substance concentrations varied with time and depth of the soil. These substance concentrations were compared with established compliance values at the POC. The source release was then adjusted to match Table 17 Waste acceptance criteria for non-hazardous mineral waste in Denmark (exactly the compliance values in the soil and groundwater at the POC. The adjusted substance releases from the source were then transformed into emission limit values (in mg/kg). The more stringent emission limit value of the soil or the groundwater was selected, for being protective of both the soil and groundwater.

4.2.6 Denmark

The Danish EPA decided to use a similar modeling methodology employed for the EU landfill directive, but adjusted for Danish conditions [108]. Denmark relies heavily on groundwater as a source for drinking water, and therefore has a strong incentive to strictly protect groundwater quality. Because of this, the Danish acceptance criteria should be more stringent than those set by the EU. In addition, the Danish POC is located 100 meters downstream of the landfill, and the Kd values, used to describe the contaminant-subsoil interaction in the transport modeling, have been adjusted for Denmark [154].

Also, three subcategories of landfills for non-hazardous waste are defined: landfills for mineral waste, mixed waste, and non-reactive hazardous waste. Furthermore, mineral waste landfills are divided into three types: inland mineral waste landfills (MA0), seacoast mineral waste landfills with higher dilution potential by the nearby sea (MA1), and seacoast mineral waste landfills with lower dilution potential by the nearby sea (MA2) [154]). Table 17 lists the leaching limit values for non-hazardous mineral waste.

The European Committee for Standardization (CEN) sets three categories, 1 to 3, based on the leaching criteria using the compliance standard batch leaching test (CEN EN 12457, L/S = 2,) [133]. Categories 1 and 2 have the strict leaching criteria, while category 3 has lenient criteria. MSW ash is categorized as soil and inorganic residue; IBA mostly falls under category 3 and never falls under category 1 due to the high inorganic constituent. Some of the details of the regulations are as follow [10] [77]:

- Category 2 IBA can be utilized in roads, paths, cable graves, floors and foundations, parking lots, noise banks, and ramps.
- Category 3 IBA is not allowed to utilize in parking lots, noise banks, and ramps.
- Ash residue can be applied to dikes, dams, and embankments with the approval from Danish Environmental Protection Act [77].
- All MSWI ash application should be covered with liner.
- Utilization site has to be remote from drinking water well over 30 m.
- IBA should be placed above the ground water table.
- The average thickness of the IBA layer should be 1 m, while thickness requirements for the specific applications are: 0.3 m for path, 4 m for ramps, and 5 m for noise bank. Danish Highway Department also set some performance criteria for IBA use as subbase in road construction:
- Maximum particle size should be 50 mm.
- Fine contents should be less than 9% below 0.075 mm and less than 8% below 0.063 mm.24
- Water content range should be between 17 and 25 %. However, according to Danish Soil Pollution Act [77], it is recognized that IBA utilization area was determined as contaminated land that pose obstacle for BA beneficial use.

The criteria are listed in Table 18. Soil and residues to be utilized are classified into three different categories, based on the determination of trace element content after partial digestion with 7 M nitric acid [151], with different applications.

Denmark Waste acceptance criteria for non-hazardous mineral waste

Waste category	MA0: Mineral waste landfills located inland			MA1: Mineral waste landfills located near the seacoast			MA2: Mineral waste landfills located near the seacoast with lower dilution factor		
Contaminant	L/S = 2 L/kg mg/kg	L/S = 10 L/kg mg/kg	C_0 mg/L	L/S = 2 L/kg mg/kg	L/S = 10 L/kg mg/kg	C_0 mg/L	L/S = 2 L/kg mg/kg	L/S = 10 L/kg mg/kg	C_0 mg/L
As	0.082	0.37	0.040	0.40	2.0	0.30	0.40	2.0	0.30
Ba	9.5	28	5.5	30	100	20	10	30	6.0
Cd	0.072	0.11	0.060	0.60	1.0	0.30	0.60	1.0	0.30
Cr (total)	0.36	1.0	0.20	4	10	2.5	1.5	4.0	1.0
Cu	5.9	13	4.0	25	50	30	15	35	10
Hg	0.012	0.050	0.0063	0.050	0.20	0.030	0.050	0.20	0.030
Mo	0.44	0.90	0.31	5.0	10	3.5	5.0	10	3.5
Ni	0.22	0.50	0.14	5.0	10	3.0	5.0	10	3.0
Pb	0.28	0.60	0.18	5.0	10	3.0	5.0	10	3.0
Sb	0.022	0.080	0.012	0.20	0.70	0.15	0.20	0.70	0.15
Se	0.17	0.31	0.12	0.30	0.50	0.20	0.30	0.50	0.20
Zn	2.1	5.0	1.4	25	50	15	25	50	15
Cl^-	2,000	2,900	1,700	10,000	15,000	8,500	10,000	15,000	8,500
F^-	13	33	8	60	150	40	60	150	40
SO_4^{2-}	2,600	5,200	1,800	10,000	20,000	7,000	10,000	20,000	7,000
Testing method	EN 12457-1	EN 12457-2 or CEN/TS 14405	CEN/TS 14405	EN 12457-1	EN 12457-2 or CEN/TS 14405	CEN/TS 14405	EN 12457-1	EN 12457-2 or CEN/TS 14405	CEN/TS 14405

Table 17 Denmark Waste acceptance criteria non-hazardous waste [167]

Limit values for content and leached amounts in Statutory Order 1662/2010

Substance	Category 1 (mg/kg)	Category 2 (mg/kg)	Category 3 (mg/kg)
	Total element content in dry matter[a]		
As	⩽20	>20	>20
Cd	⩽0.5	>0.5	>0.5
Cr (total)	⩽500	>500	>500
Cr (VI)[b]	⩽20	>20	>20
Cu	⩽500	>500	>500
Hg	⩽1	>1	>1
Ni	⩽30	>30	>30
Pb	⩽40	>40	>40
Zn	⩽500	>500	>500
	Leached amount at L/S = 2 L/kg		
Chloride	⩽300	⩽300	300–6,000
Sulfate	⩽500	⩽500	500–8,000
Na	⩽200	⩽200	200–3,000
As	⩽0.016	⩽0.016	0.016–0.1
Ba	⩽0.6	⩽0.6	0.60–8.0
Cd	⩽0.004	⩽0.004	0.004–0.080
Cr	⩽0.02	⩽0.02	0.020–1.0
Cu	⩽0.09	⩽0.09	0.090–4.0
Hg	⩽0.0002	⩽0.0002	0.0002–0.002
Mn[b]	⩽0.30	⩽0.30	0.30–2.0
Ni	⩽0.02	⩽0.02	0.020–0.14
Pb	⩽0.02	⩽0.02	0.02–0.20
Se	⩽0.02	⩽0.02	0.020–0.060
Zn	⩽0.2	⩽0.2	0.20–3.0
Testing method	EN 12457-1, L/S = 2 L/kg		

Table 18 Denmark Limit values Statutory Order 1662/2010 [151]

4.2.7 Summary

Environmental standards and regulations are integral to protecting and improving environmental quality. A set of these standards deals with Municipal Solid Waste and Incinerated MSW. Through closely examining the environmental regulation history of various countries and their MSW leaching criteria, one can make the following generalizations:

- Countries with limited natural resources should have an interest in resource reuse.
- A country's uniqueness, for example historical, social, and/or economic aspects, plays a role in setting environmental policies.

- Between developed and developing economies, more developed ones tend to have greater environmental concerns, and waste management focus priorities in developing economies generally follow similar paths as those in developed ones.

- Standard setting is a science that takes into account the natural environment setting that needs protection, the transport phenomena of contaminants through different media, and the contamination source. For some countries, it may be practical to follow standards established in other countries, especially if those countries face similar challenges. These generalizations may serve as implications that will help decision makers in governments that are looking to begin to set MSW leaching criteria standards initiate proposals. It is hoped that, with more standards in place, there is a greater degree of resource reuse and preservation.

Setting environmental standards have the benefits of setting legally enforceable regulations, enjoying the strong infrastructures already in place for their ease of implementation, and being understandable for the public to comply. However, as environmental technologies become more sophisticated the cost for compliance and initial investment costs may increase, much scientific work and deliberation by policymakers are needed to finalize standards, and tracing the origins of limit values in standards may not be possible.

Future research studies in MSW standards should look into opportunities and threats. Increasing popular support for standards in general propagated by social media and open innovation, increasing demand for sustainable technology brought on by the dwindling and rising cost of resources, and aligning business interests with waste and energy cost reduction goals may increase standards' importance and availability. Meanwhile, perceived economic priority over environmental concerns, partisan political paralysis from gridlock in governments, judicial reinterpretation of past environmental statutes, and business groups' lobbying efforts may hamper standards promulgation. For future research studies, analyzing the relationship between these new trends and MSW environmental standards would be worthwhile.

CHAPTER 5 MSWI ASH BENEFICIAL USES, TREATMENT AND LEACHING

CHAPTER 5 MSWI ASH BENEFICIAL USES, TREATMENT AND LEACHING

5.1 Introduction

The Beneficial utilization of MSWI ash (IBA, IFA) are growing interest due to limited space for landfills, ash monofills reaching full capacity, cost associated with landfill disposal, natural resource recovery, and environmental pollution perspective. Common utilization of the MSWI ashes has included PCC, HMA, road base and subbase layer, embankment and landfill cover. Chemically reactive MSWI ashes are required to be pretreated prior the utilization in order to reduce the vulnerability of toxic release. However, utilization of MSWI ashes such cement and asphalt stabilization can render further encapsulation of toxic elements so that environmental exposure can be minimized. Due to the high soluble salt and heavy metals contained in MSWI ashes, the risk of toxic leaching associated with ash beneficial utilization can be a concern. Therefore, assessment of leaching potential using proper leaching tests is required prior to the utilization in the field so that environmental safety is confirmed.

5.2. Pre-treatment techniques

MSWI ash is not an industrial product it is the by-product of the incineration of municipal solid wastes. Therefore, controlling its properties it is difficult, and beneficiation of ash is mandatory for recycling. Metal recovery is the most important treatment step, as it is advantageous both for the economy of the plant and for enabling further use of the ash as a cementitious material [156]. Some of the pre-treatment techniques are currently employed at an industrial scale, and others are still in the research stage.

5.2.1 Pre-Treatment Techniques Used at the Industrial Scale

5.2.1.1 Magnetic Separation

This is the most popular technique to separate materials based on their magnetic properties, ferromagnetic, paramagnetic or diamagnetic, and also their degree of magnetism. There are different types of magnetic separation techniques involving cross-belt magnetic separators, drum magnetic separators or magnetic pulley separators [157]. The magnetic density separation (MDS) technique can be used to separate the aluminum from other non-ferrous heavy metals based on their difference in apparent density in a gradient magnetic field. It is presently used to separate larger fractions, but not employed in the treatment of other finer residues from the incinerator. It is reported that the efficiency of ferrous metal recovery by magnetic separation is as high as 57–83% [158].

5.2.1.2 Eddy Current Separation

Eddy current separation (ECS) is the preferred method used in incineration plants and waste sorting facilities to separate the non-ferrous metals like aluminum from waste and ash. It has limited efficiency when applied to wet ash, thus its efficiency depends on the size of the particles and ranges from up to 100% efficiency for particle sizes greater than 20 mm, down to 0% for those less than 5 mm. The efficiency can be improved by increasing the number of screening steps. On average, the efficiency of aluminum removal from MSWI ash by ECS is around 30% [159].

5.2.1.3 Washing

Washing is the simplest beneficiation technique used to remove many of the deleterious compounds in MSWI ash preventing its utilization. Washing in alkaline conditions hydrates elemental aluminum and removes certain heavy metals and in acidic conditions removes certain other heavy metals and chlorides and sulfates. Since the washing process carries with itself the huge disadvantage of secondary water pollution, some waste water streams have also been tested for this purpose, providing some additional advantages including binding of heavy metals. The presence of soluble leachate salts cuts the utilization potential of MSWI ashes. Water washing techniques have been tested for their effectiveness to remove excess chlorides and sulfates and also heavy metals present especially in the fine fractions. Many have reported that the chloride content in ashes can only be reduced to 0.5% by washing due to the presence of insoluble chlorides [160]

5.2.1.4. Shaking Table

Shaking tables/wet tables such as Wilfley tables are density separation technologies that separate heavy metal particles from other lightweight particles [161]. They have a sloping plank with ribs on the surface. Water/slurry flows perpendicular to the ribs, and the table oscillates parallel to the ribs. The technique is used at the industrial scale, and it successfully separates precious metal particles such as tin, copper, gold, lead, zinc, tungsten, etc., of a size of 50 µm–2 mm [162].

5.2.1.5. Jig Head Separation

These devices are designed to separate materials in wet condition that works on the principle for density separation. The particles are pushed upwards by pulsating motion, and when the pulse in water drops, the particles settle in order of their densities and thus can be separated. A tank filled with the slurry to be separated is pulsated up and down, and this results in settling of denser particles of gold, chromium, lead, etc., of a size of 75 µm–6 mm, which are collected and separated [162].

5.2.1.6. Ageing

Ageing is an effective and widely-used technique to reduce the leaching of heavy metals. It is a combined process of hydration, carbonation and oxidation. It is an exothermic process and raises the temperature of bottom ash from 70–80 ◦C. During ageing, more minerals such as ettringite, hydrocalumite, C-S-H, carbonates, sulfates, etc., are formed, which bind and encapsulate heavy metals, thus reducing leaching.

5.2.2 Pre-Treatment Techniques in the Research Stage

5.2.2.1. Washing with Alkali

Higher alkalinity accelerates the oxidation of aluminum to form hydrogen and also increases the solubility of sulfates [163]. The disadvantages of alkaline washing include the dissolution of fine reactive particles, leading to some loss of cementitious properties during the washing process, and also the high cost of alkali.

5.2.2.2 Sulfide Rich Effluent

Effluent from waste water treatment contains sulfides generated by sulfate-reducing bacteria. When ash is treated with this sulfide-containing water, the heavy metals are precipitated as insoluble sulfides and are thus stabilized. The stabilization effect of anaerobic effluent also acts through carbonation, by CO2 dissolved in the effluent. It is reported that the treatment can stabilize Ca, Cu, Pb, S and Zn, whereas it increased leaching of P and had no effect on As, Cr and Mo [164].

5.2.2.3. Wet Grinding

For utilization of ash as supplementary cementitious material, grinding of bottom ash is required to break it down to particle sizes comparable to that of cement. If the grinding process is done in wet condition, it provides enough water, turbulence and dissolution of alkaline phases like Ca (OH)2, which gives enough pH for the aluminum reaction to occur. The 180-day compressive strength of concrete increased by four-fold compared to that of dry ground ash and was 25% higher than that of 100% ordinary Portland cement (OPC) mix. This was mainly because of the removal of expansive Al [165]. Further, wet milling is identified as an effective technique to stabilize certain heavy metals such as Pb, Cr, Cu, Zn and Pb for ash from grate furnaces and of Cr and Zn for ash from fluidized bed incinerators without a water extraction procedure [166] .

5.2.2.4. Carbonation

Carbonation is an effective technique to immobilize the heavy metals, if the ash needs to be disposed safely, or when used as an aggregate when it is not milled. Stack gas from the incinerator was also used as a source of CO2. However, for applications that involve milling, carbonation does not prove to be very effective in immobilizing heavy metals [67]. In addition, chlorides existing as insoluble Ca-salts can be disintegrated by carbonation and then can be removed by washing.

6.2.5. Phosphation

Phosphation is the process of converting heavy metals into their insoluble phosphate form to prevent leaching into ground water. As a result of Phosphation treatment, apatite group minerals are formed. They encapsulate the heavy metals present in the ash and thus stabilize them. Carbon dioxide gas evolves during phosphate reaction. The reaction also results in a reduction of pH, even though fly ash with high calcium hydroxide content is reported to maintain high pH [167].

5.2.3 Beneficial uses of MSWI Ashes

5.2.3.1 Asphalt and Road Paving Application

MSWI ashes can be used beneficially as a substitute of crushed rock and gravel in many civil engineering applications, such as road base course and sub-base. These are widely used in European countries in road construction as compacted road base, structural fill in wind barrier, highway ramps, sound barriers, and in asphalt application [130]. In France, three-year study has been conducted for the utilization of MSWI BA in road pavement where leachate concentrations of heavy metals were below the authorized limit of potable water, indicating environmentally safe utilization of MSWI BA. Approximately half of MSWI ashes produced in Germany have been utilized beneficially in road construction. The Netherland, having many years of experience in handling of MSWI FA, has implemented the use of FA in asphalt application as a substitute of natural aggregate without imposing environmental impact by toxic leaching. In the U.S., MSWI ashes was investigated showing satisfactory performance in demonstration projects for more than 20 years. Unbound ashes by asphalt or cement were used as gravel and aggregate substitute in road base layer. In asphalt concrete, substitution of rock aggregate by MSWI ashes with reduced particle size smaller than ¾ inches demonstrated potential utilization option for MSWI ashes in several projects in the U.S. without any environmental effect [10]. MSWI ashes are desirably applicable as base and filler material due to having high stability and low density with some consideration of low durability. FHWA provides an extensive set of guidelines for using MSWI BA and combined ashes in pavement construction [168]. According to FHWA, after removal of metal, ash passing ¾ inch screen can be used as a replacement of 10% to 25% of natural aggregate in bituminous surface courses and up to 50% in base and binder course. Addition of hydrated lime by 2% by weight with MSWI ash has also been suggested in order to prevent striping problem of asphalt binder from the ash. Ash storing for maturation for 30 days are required until 20% of replacement of pavement material in order to stabilize potentially reaction ingredients. In granular base application, use of the ash passing ½ inch screening after 1 to 3 months of maturation has been suggested [12].

5.2.3.2 Concrete Application

MSWI ashes are assumed to cause pozzolanic reactivity when Ca component is retained from APC devices in the ash and then the ash can act as a partial replacement of Portland cement and also MSWI BA can substitute as rock aggregate in PCC [5]. In European countries, several studies used the MSWI BA and FA as partial replacement of cement in order to investigate their effect on the cement paste and PCC. MSWI ashes has been also utilized as substitute of rock aggregate in concrete blocks in several states in the U.S. [10].

MSWI ashes in PCC appeared to be promising, however, metals, glass, and soluble salts removal prior utilization is necessary which comprise the strength of the final product [3]. However, some of side effects in PCC applications have been reported. Although sometimes MSWI FA is considered to have similar properties with cement experimental observation reveals that both ashes contain considerable amount of metallic Al that can generate hydrogen gas , resulting in volume expansion, cracks and voids in cement paste specimens [169]. In addition, the FA contains significant amount of Cl, which may increase corrosion probability of reinforcing steel in reinforced concrete structure. Due to the swelling originated from hydrogen gas evolution, cement pastes containing MSWI BA exhibit inferior mechanical properties compared to those of control specimen of cement paste. On the other hand, the compressive strength of the cement paste containing the FA is sometimes similar or higher than those of control specimens.

CHAPTER 6
MATERIAL CHARACTERIZATION OF MSWI ASHES

CHAPTER 6 MATERIAL CHARACTERIZATION OF MSWI ASHES

6.1 Introduction

According to a recent research work by the UN International Environmental Technology Centre (IETC) [170], the number of Thermal Waste to Energy Plants in the world exceed 1700, although these plants reduce the amount of garbage the incineration process generates great amounts of residues (ash) which ranges from 15-25 percent (by weight) and from 5-15 percent (by volume) of the MSW processed [30]. In regards to the utilization of the ash, in Canada all the ash generated is landfilled, In the USA all the ash generated in the 75 Thermal Waste to Energy Plants is landfilled [30], in Singapore all the ash generated is landfilled [133], China reuses almost all its bottom ash in concrete products (blocks), and Europe uses beneficially a great percentage of is ash beneficially as a road subbase [54].

Global trends for the Thermal Waste to Energy technology are increasing as many countries are looking into this technology as the best technology to cope with the huge amounts of MSW generated. Therefore, the amount of waste incineration residues in the world will increase around the globe [170].

Owing to the large quantity consumptions and relatively low-quality requirements, the use of MSWI ashes as construction materials would be a very attractive option. In fact, many research works have addressed the utilization of MSWI ashes as a gravel material in road base layers as well as aggregate for reinforced concrete structures [10]. One of the important factors hindering the accepted use of the ashes as construction materials, however, is their uncertain physical and chemical properties due to their heterogeneous characteristics. Thereby, in order to expand the utilization of MSWI ashes in construction, understanding of the physical and chemical properties is critical.

A typical waste treatment process involves a thermal treatment, in which waste materials are combusted at a temperature of approximately 1,000 ºC. During the thermal treatment, the quantity of the waste is reduced by 65-80% in mass and 85-90% in volume. As a result of this incineration, two types of ashes are produced: fly ash, which is typically considered a more hazardous material due to the presence of heavy metals and dioxins and bottom ash, large agglomerated residue [30].

In this chapter, efforts were made to physically and chemically characterize MSWI fly ash and bottom ash in order to assess the feasibility of the reuse of the ashes in Portland Cement Concrete Structures. Basic physical properties of the bottom ash were studied in accordance with American Standard Testing Methods (ASTM). Petrographic examinations, including scanning electron microscopy (SEM), energy dispersive x-ray (EDX), and x-ray diffraction (XRD) were carried out in order to identify the chemical and microstructural properties of the ashes.

6.2. Materials and Experiments

Figure 19 Photographs of MSWI Fly Ash (left) and Bottom Ash (right)

Basic physical properties of the ashes, including specific gravity, absorption capacity, unit weight, void content, and L.A. abrasion mass loss were evaluated in accordance with ASTM guidelines. Microstructural morphology and chemical element compositions of both ashes were determined by SEM and EDX analyses, respectively, using the Zeiss Ultra-55 SEM equipped with UltraDry silicon drift x-ray detector. Phase compositions of the ashes were examined by XRD analysis using the Rigaku D/MAX-II XRD with copper K-α radiation.

6.2.1. Instrumental Techniques

The microscopic analysis tools utilized were SEM and EDS. The SEM analysis employed the Zeiss Ultra-55 SEM Spectrometer with acceleration voltage of 5 to 20 kV, equipped with Ultra-Dry silicon drift EDS detector. Two different modes of detection utilized in this study are secondary electrons (SE) and back-scattered electron (BSE). In the secondary electron imaging, a primary electron beam collides with electrons from the sample atom and results in low energy electrons that gives near surface images of the sample. In the back-scattered imaging, high energy beam electrons are scattered by the sample. Heavier elements with higher atomic number produce stronger BSE than lighter elements having lower atomic number; thus, they appear brighter in the image. Therefore, the BSE are commonly used to identify the prominent contrast between areas with different phase and chemical compositions.

The EDS provides chemical compositions of the sample at a particular spot either point or area. In EDS, a high electron beam is bombarded with sample and produces X-ray spectrums that are detected by an energy dispersive detector. This technique produces a set of peaks on a continuous background where every peak is the chemical information of particular elements, and thus the position of peaks and corresponding relative intensity enables the identification of different elements within the sample. The mineralogical analysis was performed using Rigaku X-ray diffractometer which is equipped with 40KV Copper X-ray tube, 2 Theta Goniometer.

The mineralogical analysis is facilitated with Datascan 4 Acquisition Software and, Jade 7 Analysis Software with JCPDS (Joint Committee on Powder Diffraction Standards) Database. X-Ray diffraction is a technique that measures the characteristic intensity of Xrays, diffracted by a sample specimen which corresponds to crystallographic information from that particular material. XRD analysis offers the determination of the crystal structure and lattice parameters of crystalline materials using the JCPDS database for phase identification of unknown samples.

6.2.1.1 Microstructure Analysis by SEM

Surface morphology and texture of the ash samples were investigated using Zeiss Ultra-55 SEM Spectrometer with acceleration voltage of 5 to 20 kV. Thin sections of sample were coated with Gold-Palladium using a sputter coater. The below figures show the SEM images of IBA and IFA at different magnifications from 500X to 8000X. IBA exhibits poor crystalline structure, IFA exhibits more angular shape. IBA particles are mostly rounded after crushing, with no distinguishable crystal structures due to having amorphous phase, while IFA exhibits planar, cylindrical, and spherical particles on sintered clusters with highly crystalline phase. IFA particle size of is a lot smaller than the crushed IBA particle size, in the concrete mix design the IFA small particle size is likely to render an intense filling effect.

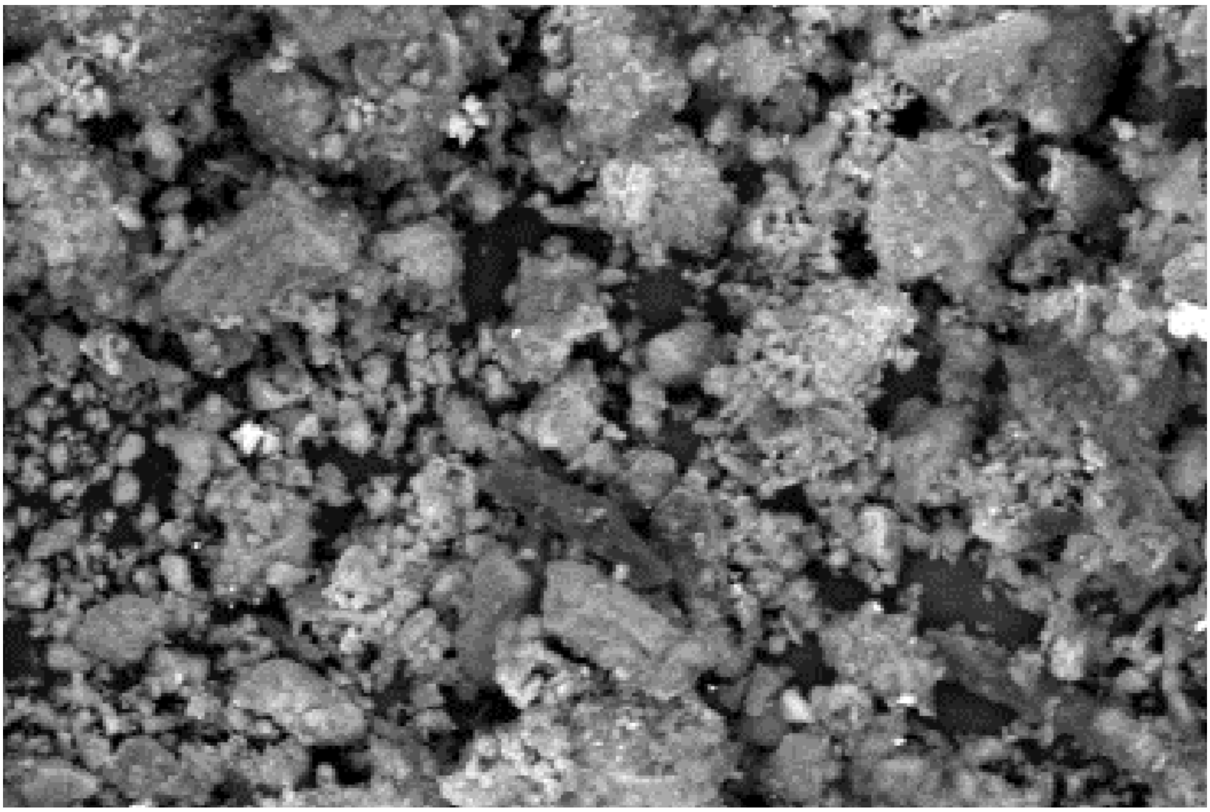


Figure 20 SEM images of bottom ash 500X

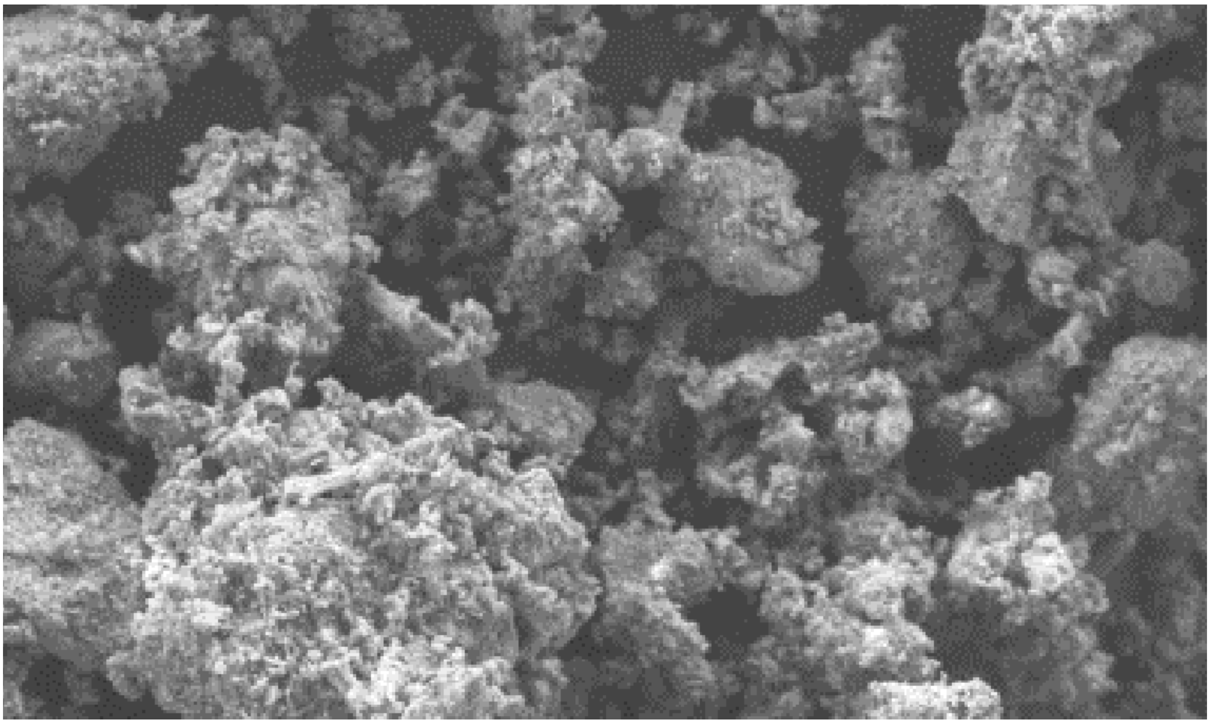


Figure 21 SEM images of bottom ash 1000X

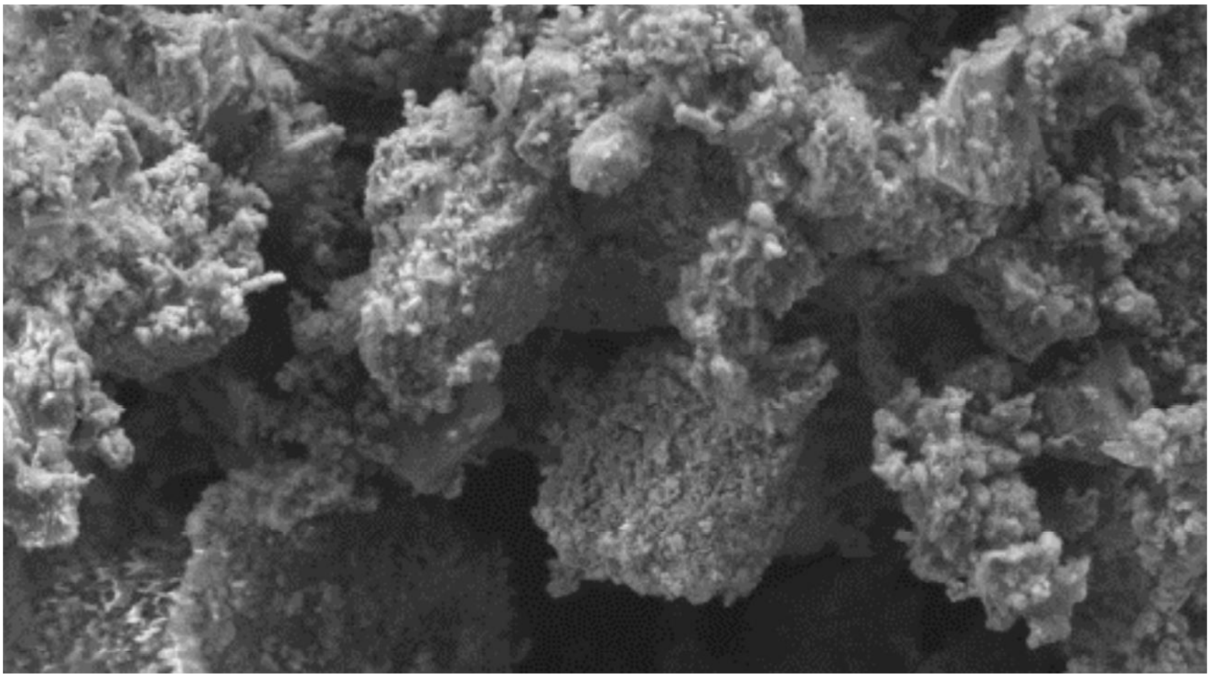


Figure 22 SEM images of bottom ash 2000X

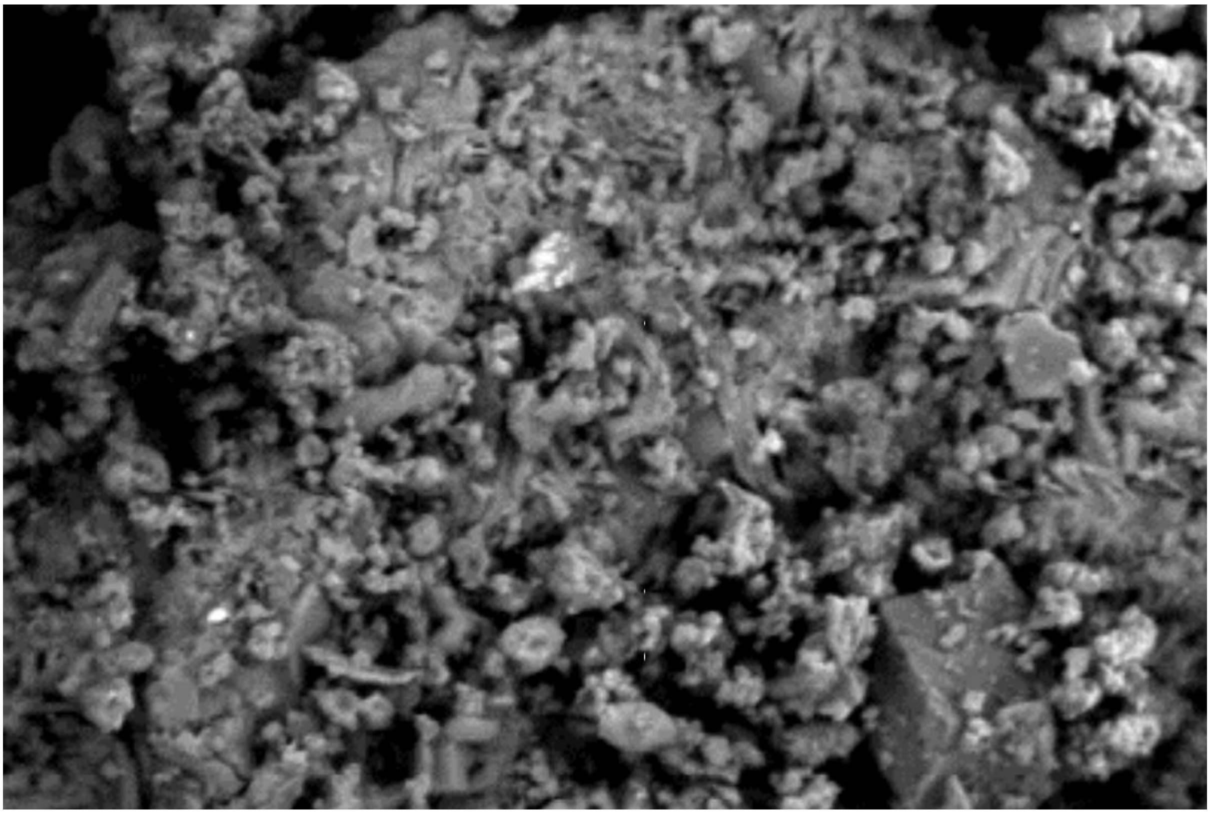


Figure 23 SEM images of bottom ash 4000X

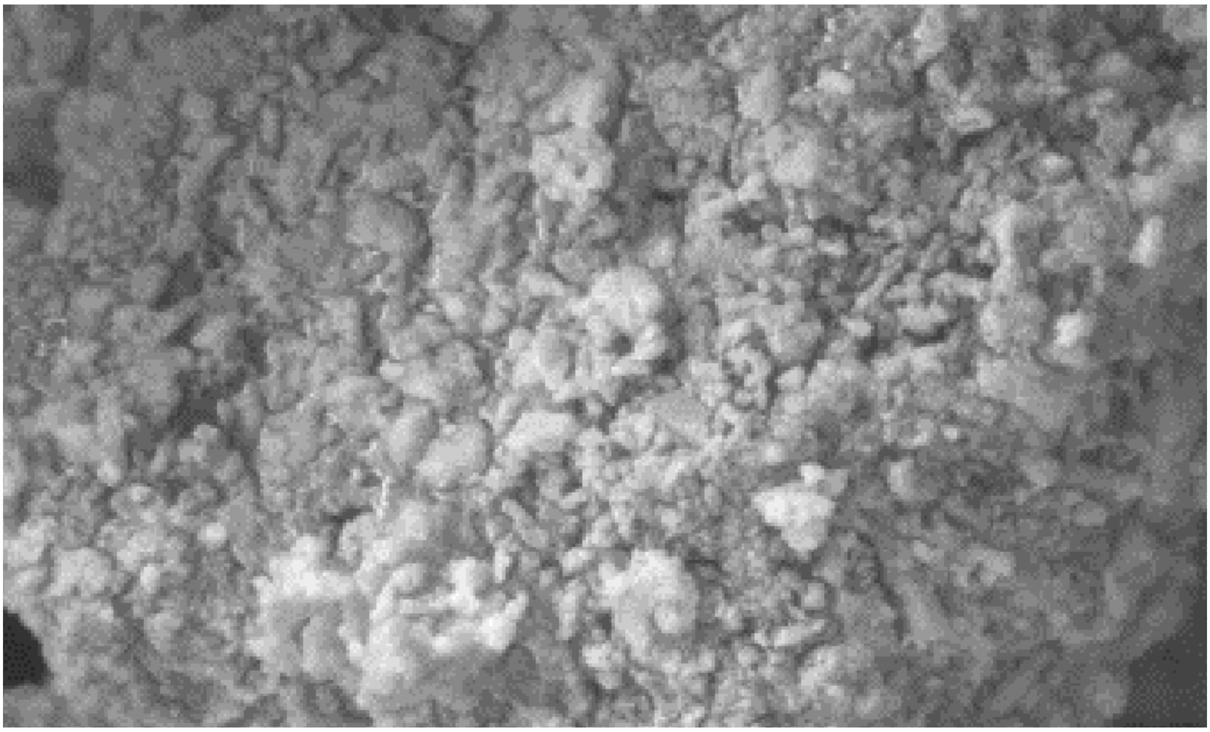


Figure 24 SEM images of bottom ash 8000X

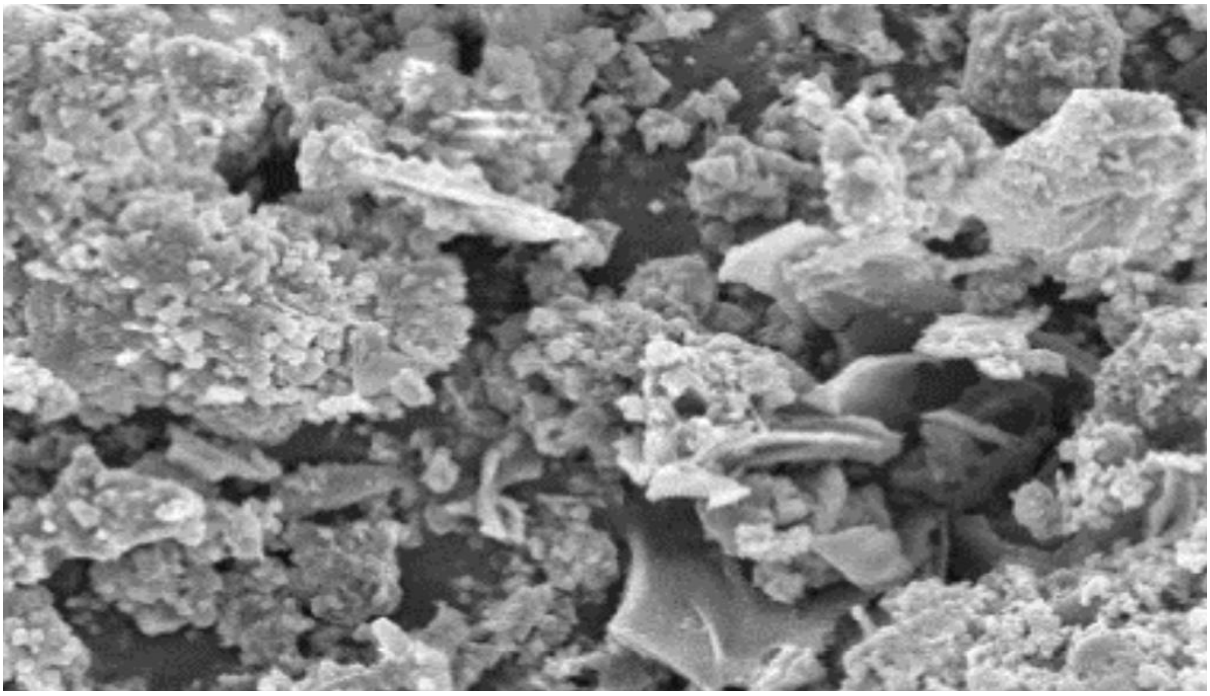


Figure 25 SEM images of MSW IFA 1000X

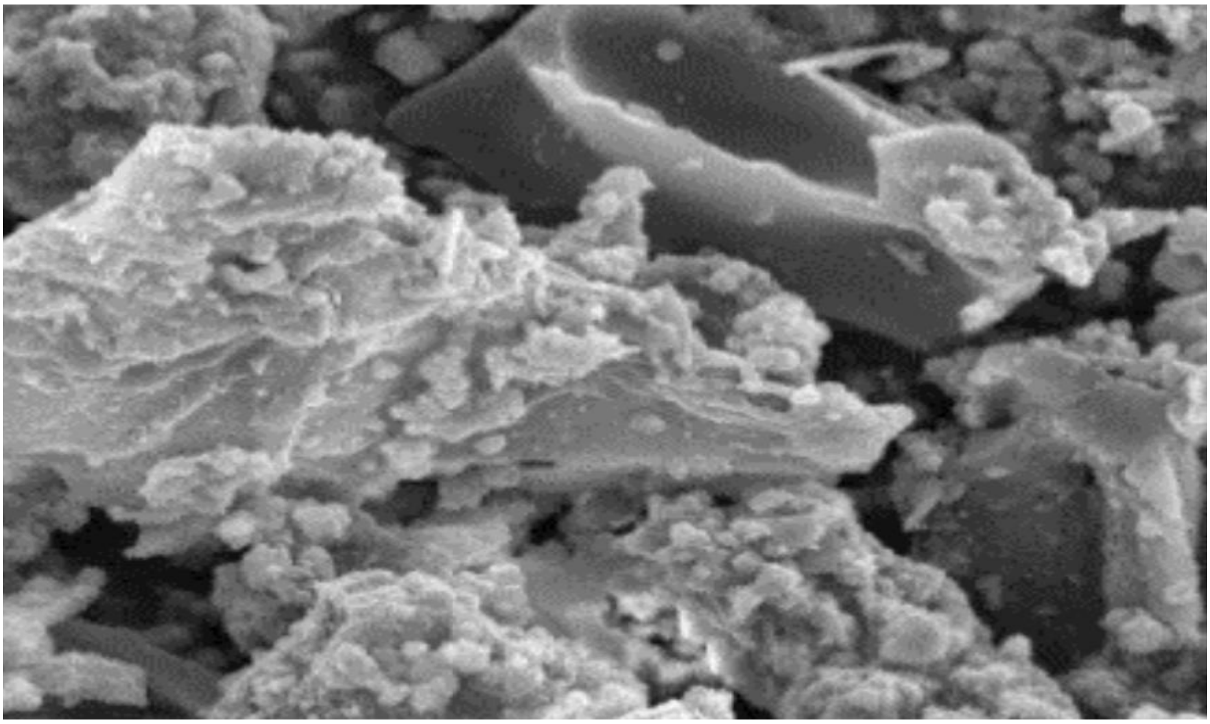


Figure 26 SEM images of MSW IFA 2000X

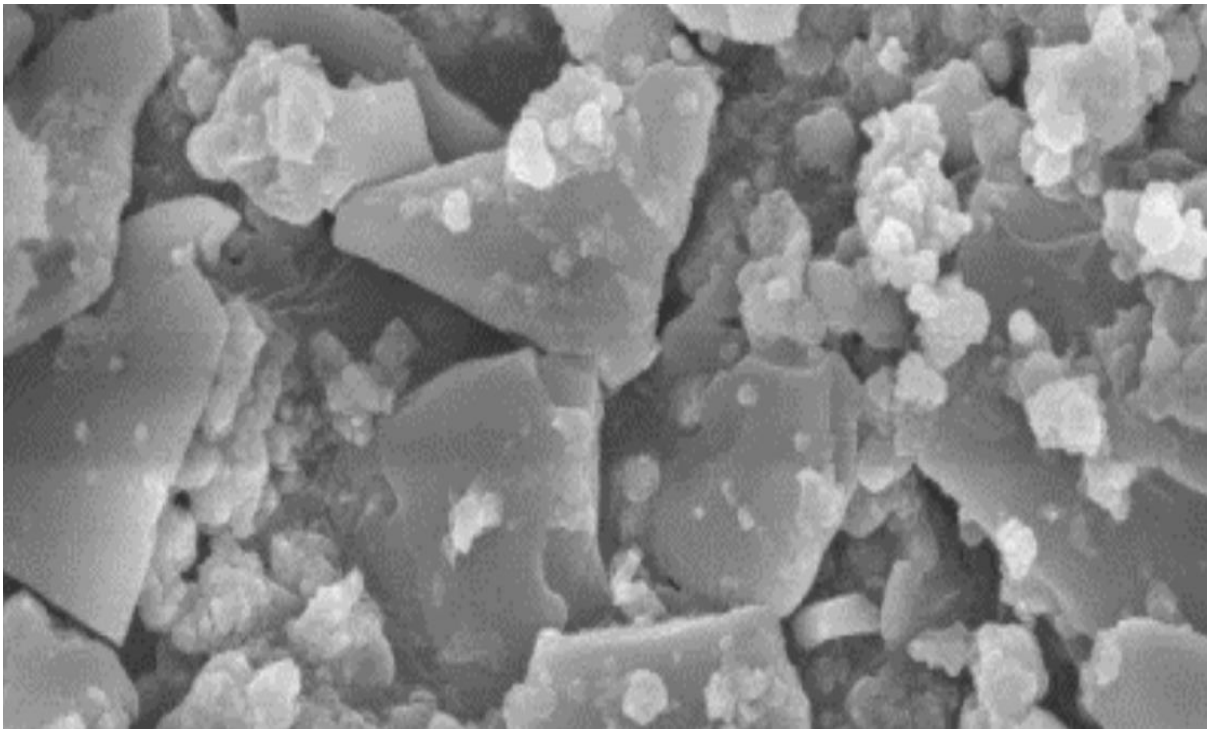


Figure 27 SEM images of MSW IFA 3000X

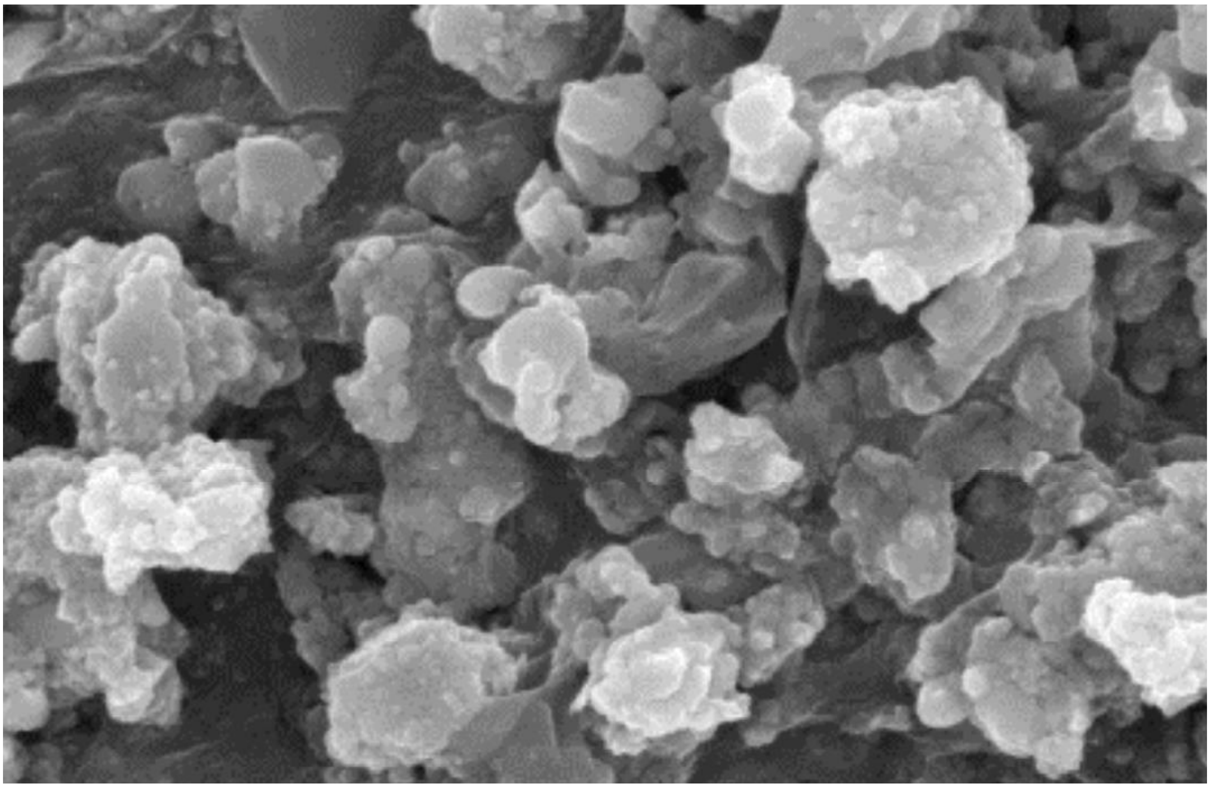


Figure 28 SEM images of MSW IFA 4000X

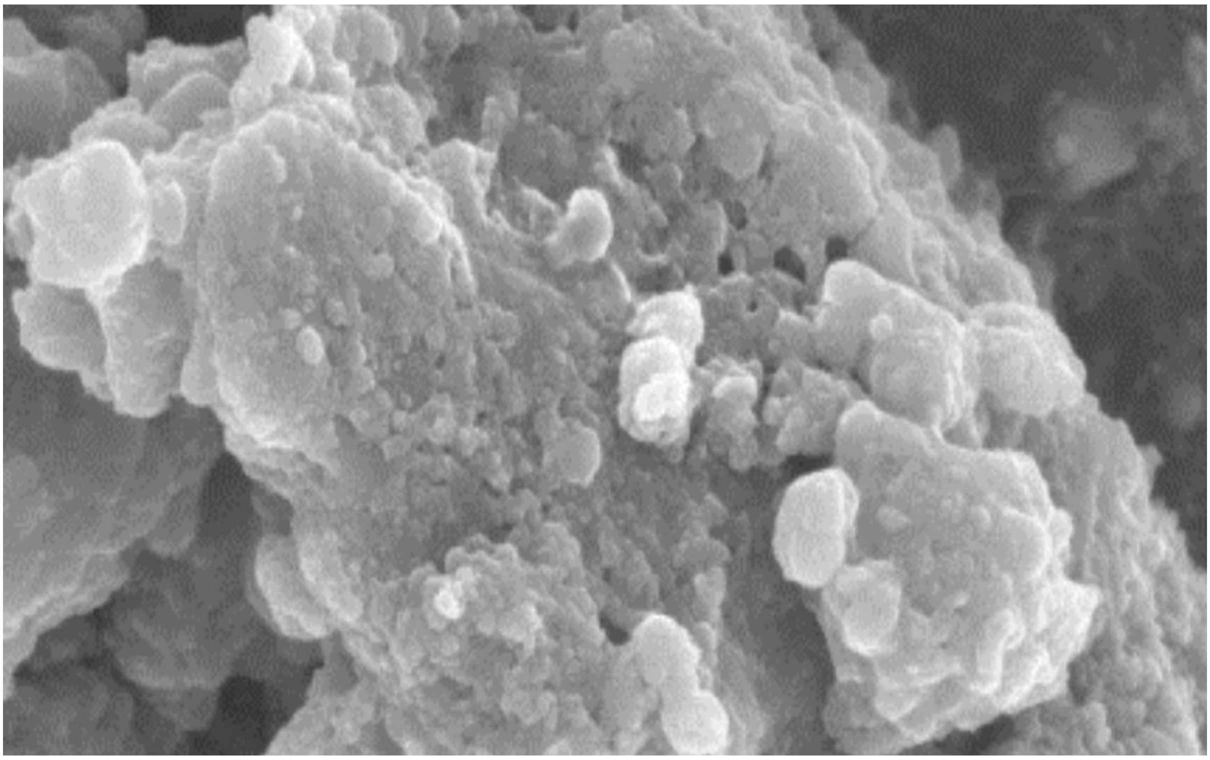


Figure 29 SEM images of MSW IFA 8000X

6.2.1.2 Compositional Analysis by EDS

IBA and IFA Chemical elemental analysis was performed out using the EDS. Average chemical compositions (elemental and oxide form) are listed in Tables 19 and 20. The EDS results show that the major elements of the IBA are Ca, Si, and Al and the minor elements are Na, Mg, Fe, and Ti with small amount of K, Cl, and Zn.

Oxygen is the predominant element; therefore, it can be assumed that most chemical elements exist in oxide form. Higher amounts of Cl and Hg are observed in the IFA. Major elements of the IFA are Cl, Ca, K, Na, and Hg and minor elements are Si, Al, Cu, and Co.

Due to the lime scrubber treatment that absorbs acid gases generates different salts, higher amount of Ca than what expected is observed in the IFA.

IBA – IFA Elemental Composition

Element	BA	FA
O	43.79	6.43
Na	3.70	3.19
Mg	1.90	0.25
Al	4.66	1.12
Si	8.04	1.07
P	1.00	-
S	3.85	0.39
Cl	2.05	32.45
K	0.81	10.92
Ca	26.61	25.63
Ti	1.37	-
Cr	-	0.28
Mn	-	0.12
Fe	1.01	1.66
Co	-	0.28
Ni	-	1.48
Cu	0.65	0.90
Zn	0.56	6.76
Hg	-	7.07
Total	100	100.00

Table 19 IBA-IFA Elemental Composition

IBA – IFA Elemental Composition Oxides

Oxide form	BA	FA
Na_2O	5.64	4.29
MgO	3.08	0.6
Al_2O_3	9.6	1.66
SiO_2	18.68	2.09
P_2O_5	2.49	-
SO_3	10.03	1.18
Cl	2.28	34.2
K_2O	1.19	13.29
CaO	39.05	19.27
TiO_2	2.42	-
Cr_2O_3	-	0.13
MnO	-	0.14
Fe_2O_3	3.67	2.61
CoO	-	0.35
NiO		2.16
CuO	1.1	1.26
ZnO	0.77	8.78
HgO		7.99
Total	100	100

Table 20 IBA-IFA Elemental Composition Oxides

6.2.1.3 Mineralogy Analysis by XRD

Rigaku X-ray diffractometer with CuKα radiation, 2θ scanning from 5 to 80º with 0.02º step size and 1 second per step was employed for the mineralogical analysis of the IBA and IFA and IBA concrete samples. The XRD results are presented in Figures 30, 31 and 32, respectively. The XRD result for the IBA appears to have relatively fewer crystal peaks compared to those of IFA due to poor crystallinity in IBA. This is in agreement with the observation from the SEM images 20 to 24 that IBA has amorphous phase without distinguishable crystal structures. On the contrary, the IFA exhibits highly crystalline phase as seen in Figures 20 to 25 that is in good agreement with the X-ray diffraction results with numerous peaks of crystals.

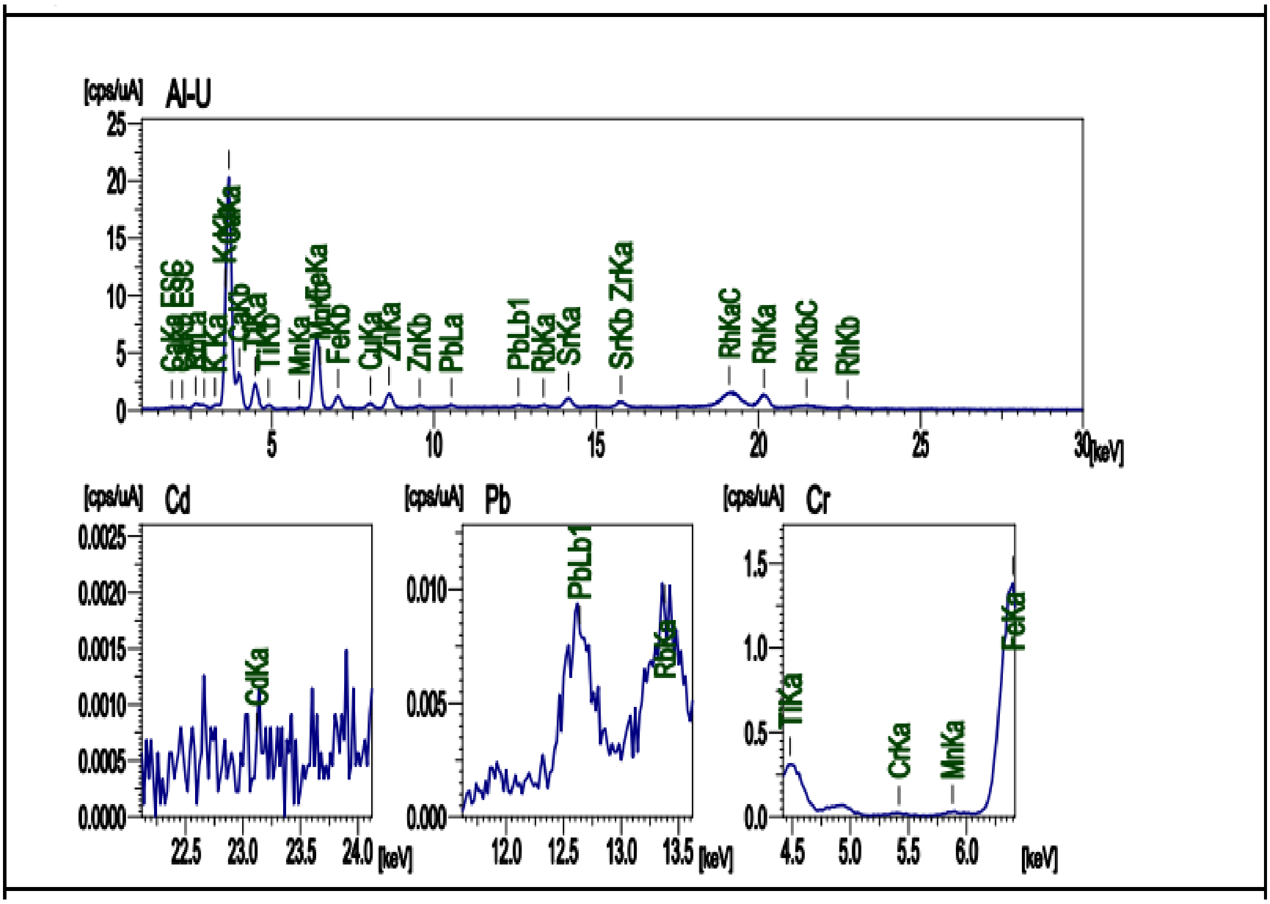


Figure 30 MSW IBA Concrete X-ray diffraction pattern

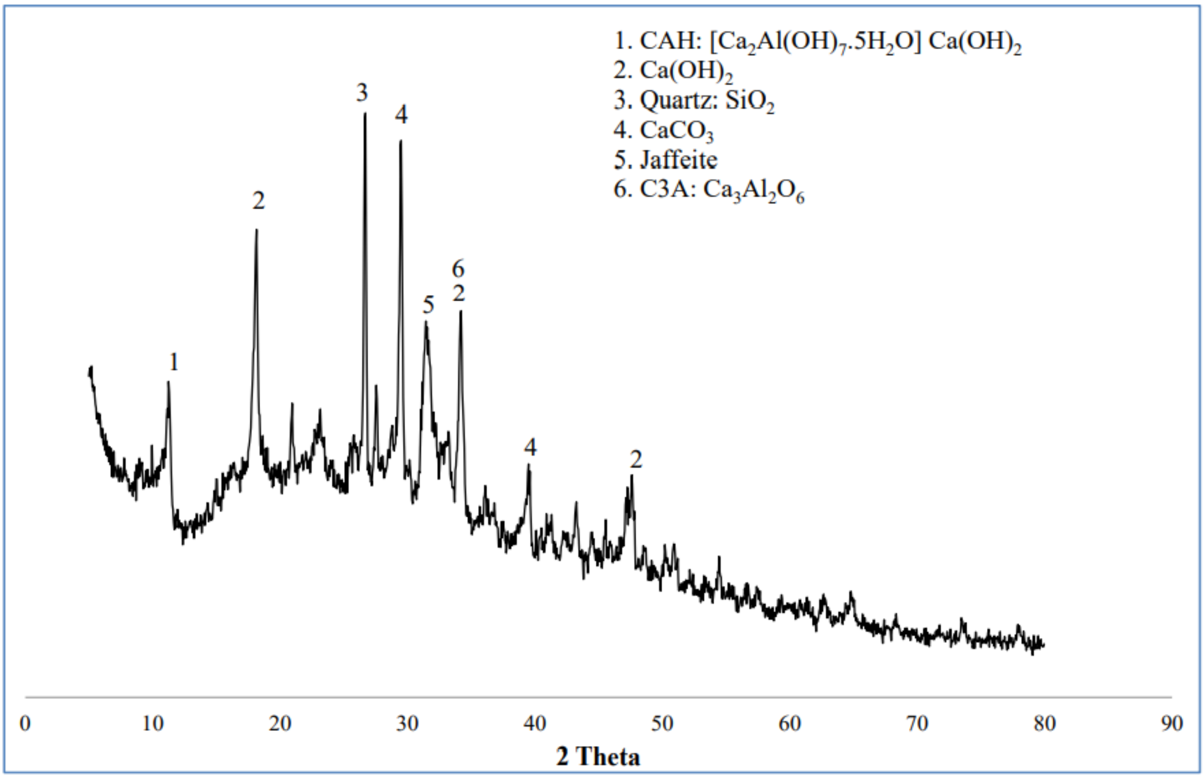


Figure 32 X-ray diffraction pattern for MSW IBA

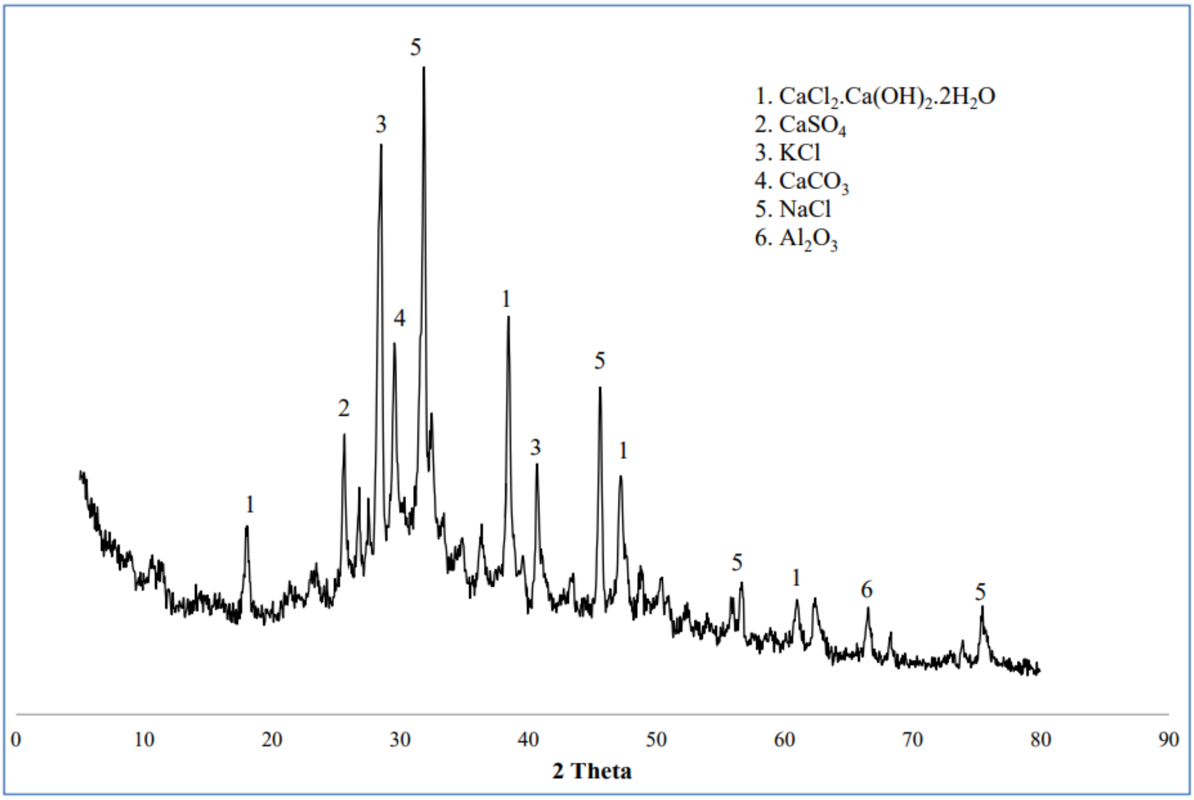


Figure 31 X-ray diffraction pattern for MSW IFA

XRD patterns shows major mineral phases in the IBA, such as portlandite ($Ca(OH)_2$), quartz (SiO_2), and calcite ($CaCO_3$) and minor compounds are calcium aluminum hydrate ($Ca_2Al(OH)_7 \cdot 5H_2O$), jaffeite ($Ca_6(Si_2O_7)(OH)_6$), and tricalcium aluminate ($Ca_3Al_2O_6$). Very minor peak appears to be xonotlite ($Ca_6Si_6O_{17}(OH)_2$). In the IBA, oxide and hydrated phases are present: jaffeite, poorly crystalline calcium silicate hydrate in high temperature which is relevant to the high temperature incineration of MSW; $Ca_3Al_2O_6$, an integrated component of cement grain, and xonotlite, a natural equivalent to tricalcium silicate hydrate that happened to be cement constituent.

Bottom ashes cover a wide range of compositions that are closest to that of iron blast furnace slags and of coal combustion fly ashes. The chemical composition of MSWI fly ashes depends on their separation temperature from the flue gas line. The content of soluble salts (Cl^- and SO_3^{2-}) and most heavy metals (As, Cd, Pb, Sb) increases with decreasing separation temperature.

6.2.1.4 Summary

In order to investigate the potential beneficial uses of MSWI ashes as aggregate for construction material, extensive material and chemical characterization have been conducted. According to the microstructural analyses, the IFA particles exhibit more irregular, angular morphology and internal porosity compared to the IBA; thus, it may cause the reduced workability on the other hand there a high leaching potential of heavy metals from the IFA. Based on the chemical composition and phase analyses using EDS and XRD, respectively, beneficial components are present in both MSW IBA and IFA.

CHAPTER 7 EVALUATION OF MSWI BOTTOM ASH AND COMBINED ASH WHEN USED AS AGGREGATE IN CONCRETE

EVALUATION OF MSWI BOTTOM ASH AND COMBINED ASH WHEN USED AS AGGREGATE IN CONCRETE

7.1 Introduction

The prospects for MSWI bottom ash and MSWI fly ash lie within the realm of substitution aggregate in the place of natural aggregates due to the environmental perspective as well as its cost effectiveness, IBA has been considered as a potential ingredient for use as a recycled construction material in concrete, however, if the IBA is used beneficially, the utilization of IBA will create a high WtE operation costs in countries like the USA were IBA and IFA are combined and disposed of in landfills. Numerous research studies have been conducted globally in order to increase the recyclability of MSW and a number of studies were focused on the use of IBA in concrete: as sub-bases for pavement structures, embankment, Portland cement replacement material, aggregate replacement material [10]. However, there are no established ASTM standards for the utilization of MSW IBA nor Combined Ash as a potential construction material. This is mainly because unfamiliarity with the concrete properties when IBA is used as replacement of fine aggregate. In this chapter, a new type of concrete was designed replacing natural aggregate by IBA and IFA in accordance with existing ASTM standards and the feasibility of the use of IBA and IFA in concrete was evaluated. IBA and Combined concrete was subjected to mechanical property and durability tests according to ASTM standards.

7.2. Evaluation of MSWI Bottom Ash when used as aggregate in concrete.

7.2.1 Experimental Procedure

7.2.1.1. Materials

Ordinary Portland cement (OPC) Type-I conforming to ASTM C 150 was used to make concrete with IBA and Combined Ash as the primary binding material. Certified fine sand passing 4.75 mm was obtained and used as a fine aggregate. The gradation curve of the sand met the ASTM requirement (ASTM C33) as shown in Figure 33. Fineness modulus of fine aggregate was 2.36, which also complies with the ACI requirement.

Gradation curve for fine aggregate - sand (ASTM C33)

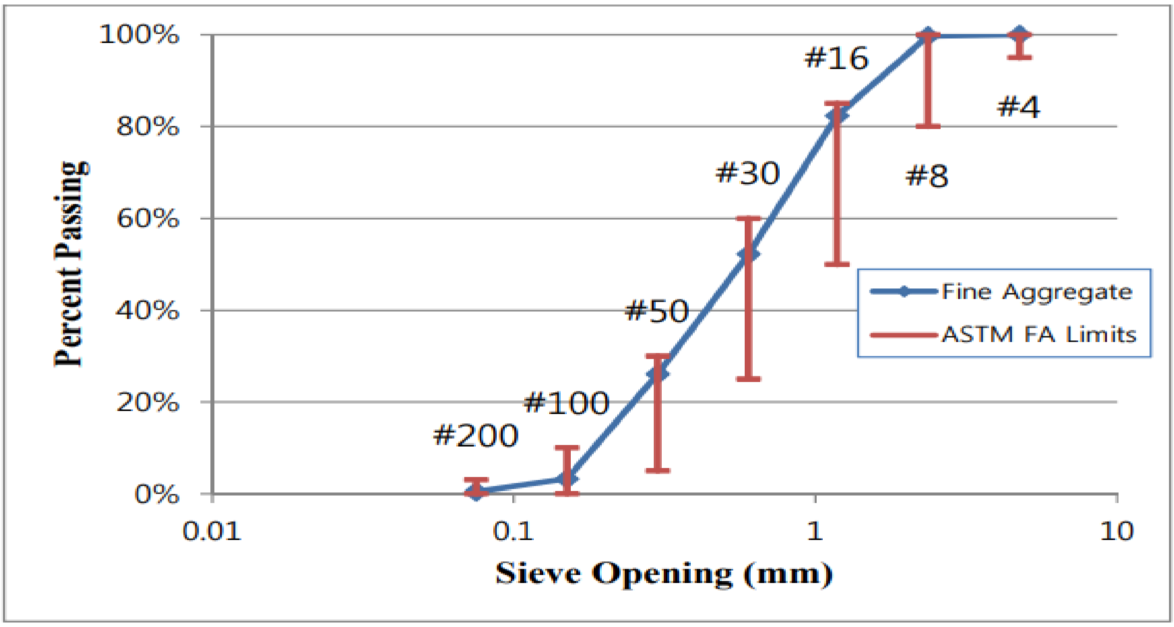


Figure 33 Gradation curve for fine aggregate

Gradation curve for fine aggregate - IBA (ASTM C33)

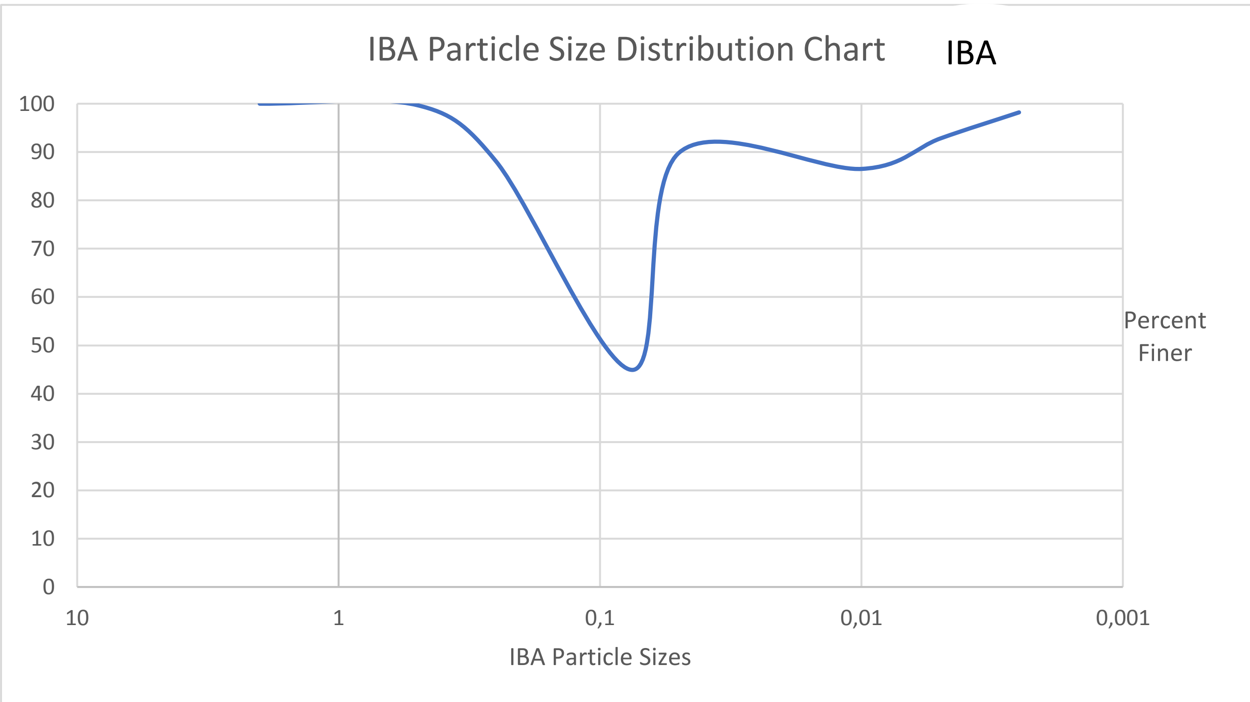


Figure 34 Gradation curve for fine aggregate IBA

MSW IBA obtained from a Thermal Waste to Energy Plant in Ningbo China, was sun dried for 24 hours and ground, the gradation curve of the IBA is shown in Figure 34.

7.2.2. Physical properties of materials

Bulk specific gravity of materials was obtained according to ASTM C127 and C128 and their results are summaries in Table 35. According to the results, specific gravity of IBA is approximately 20% lower than that of fine aggregate; therefore, density of concrete specimen is expected to decrease with increasing amount of ash addition.

Property	Value	
	Fine aggregate	MSWI BA Ground
Bulk specific gravity	2.7	1.70-2.22
Fineness modulus	2.36	2.02
Bulk density (kg/m3)	1703	--
Absorption (%)	2	13.0-17.0
Void content (%)	--	--
Loss on ignition (%)	--	6.4
Maximum Density kg/m (lb/ft)	--	1267
Proctor Compacted Permeability (cm/s)	--	Approx. 10^{-3}

Figure 35 Selected Physical Properties of Materials

7.2.3 Specimen Preparation

7.2.3.1 Concrete Made with Bottom Ash

Twelve samples of concrete specimens were casted using 65% Fine MSW IBA, 10% Fine Sand and 24.5% OPC and 0.5% a Multi Stage Nanocomposite treatment and water reducer. The compressive strengths of the 12 samples can be seen in Table 36. The actual mixing was carried out according to ASTM C1437 mixed in a Conele Planetary Concrete Mixer. Bottom Ash being the largest percentage of aggregate was poured into the Mixer first followed by the sand, then Cement was mixed with the Nanocomposites and poured into the mixer, followed by the water reducer and water.

7.2.3.2. Visual Observation

The hardened specimens at 65% IBA replacement ratios in the mix design are shown in Figure 36 and 37. It is observed that the number and size of surface pores is comparable with UHPC blocks which are generated during deairing. Although there is a small percentage of surface pores that could had been caused by hydrogen gas evolution, there is no significant deterioration to the overall structure, in addition, it is observed that blocks have an impermeable structure due to the Ultra High Tortuous Paths generated by the filling of small spaces due to small particles.

Figure 36 Photos of MSWI bottom ash concrete at 65%

Block top notice air bobbles and smooth surface

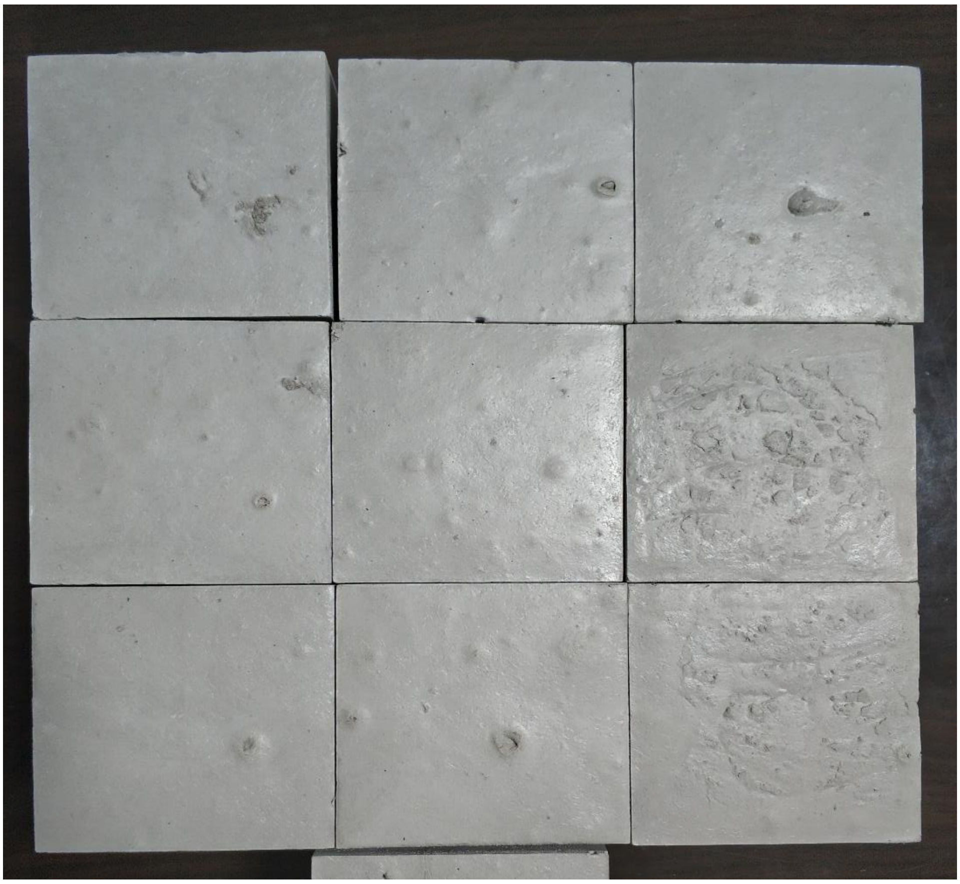


Figure 37 Harden Specimen 65% IBA replacement ratio TOP

7.2.4. Compressive Strength

The compressive strengths shown in Figure 38 validate the conclusion drawn from the visual evidence. The compressive strength of concrete made with 65% IBA as the only aggregate ranges from 29.8 Mpa to 31.2 Mpa as seen in Figure 38.

It is established that the compressive strength depends on the strength of the cement matrix, the aggregates, and the matrix-aggregate interfacial bond. The high compressive strength in this study can be attributed to the use of small particles as aggregate and the nanocomposites that excelled the bonding strength of OPC. The standard deviation of the strengths shows a very similar high compressive strength at 65% IBA content.

Utilizing this mix design there is no difference in workability a 65% - 70% or 75% IBA in the mix design.

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65% IBA Concrete Compressive Strength

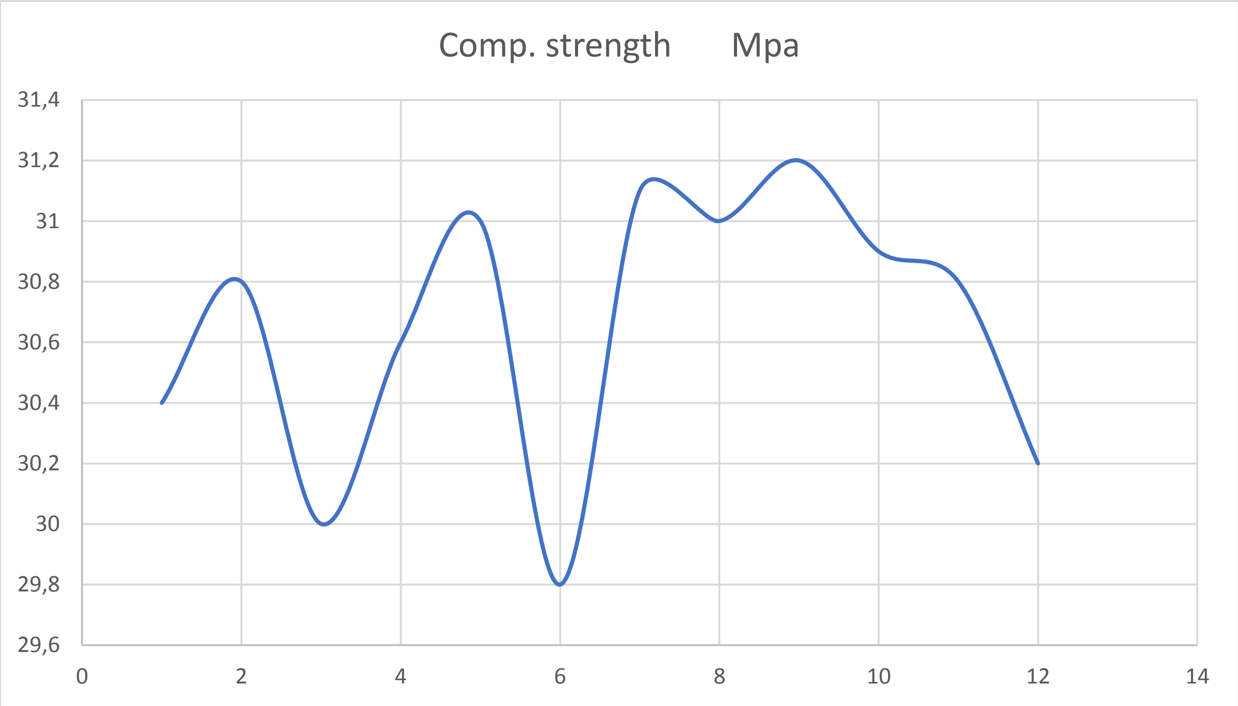

Figure 38 IBA Concrete compressive strength

7.2.5. Leaching Characteristics of IBA Ash in PCC

The leaching behavior of the concrete mix design containing 65% IBA has been investigated. Leaching concentrations were obtained for the inorganic constituents originated from IBA incorporated in concrete specimen with a different range of particle size.

MSW IBA obtained from a mass incineration plant in China, was sun dried for 24 hours, subsequently, ash was ground and ferrous and non-ferrous metals were removed. IBA sand at 65% proportion in the mix design was mixed with 10% fine sand, cement and nanocomposites, water and water reducer. 12 blocks 10cmx10cmx10cm were made and 24 hours later were taken out of the mold. Hardened concrete specimens were air cured for 28 days and compressive strength test was performed Figure 38, all specimens surpassed 4,000 psi compressive strength. One of the blocks was selected randomly and sent to a laboratory in order to investigate leaching potential of major and minor constituents, the below pictures show a comparatives of leaching tests vs Leaching limits criteria in USA, Taiwan, China and the European Community.

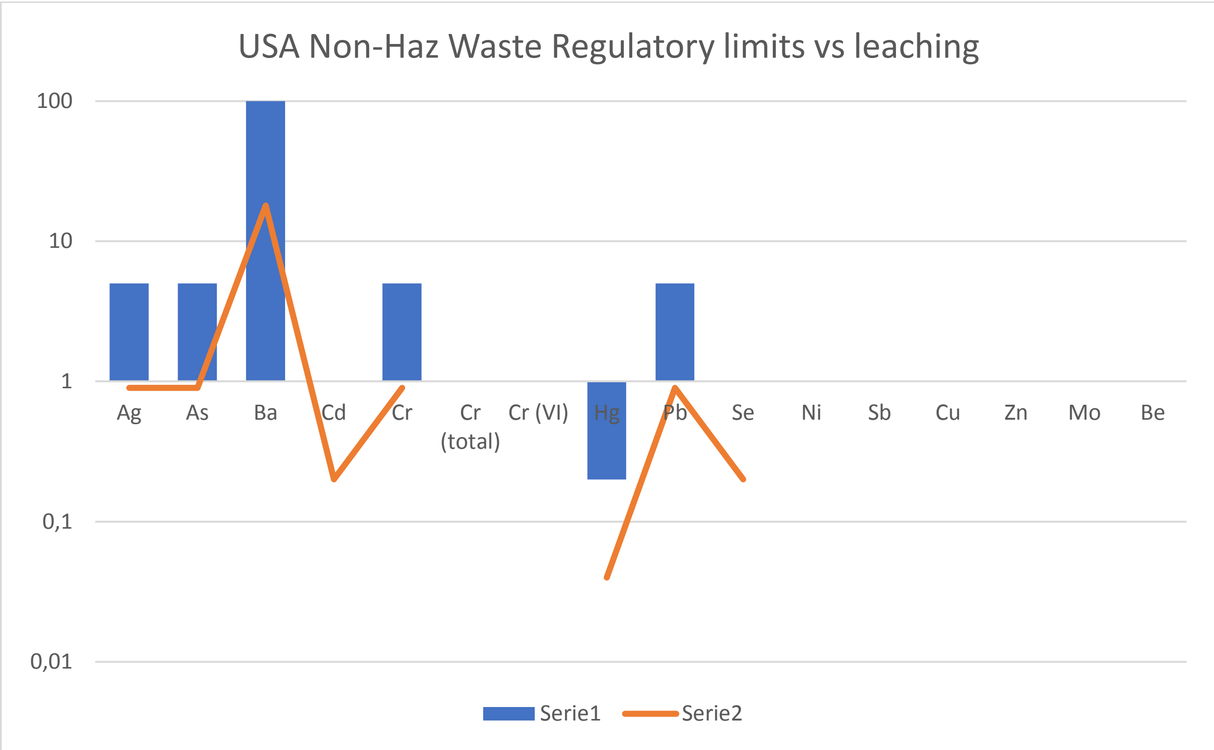

Figure 39 USA TCLP Regulatory Limits

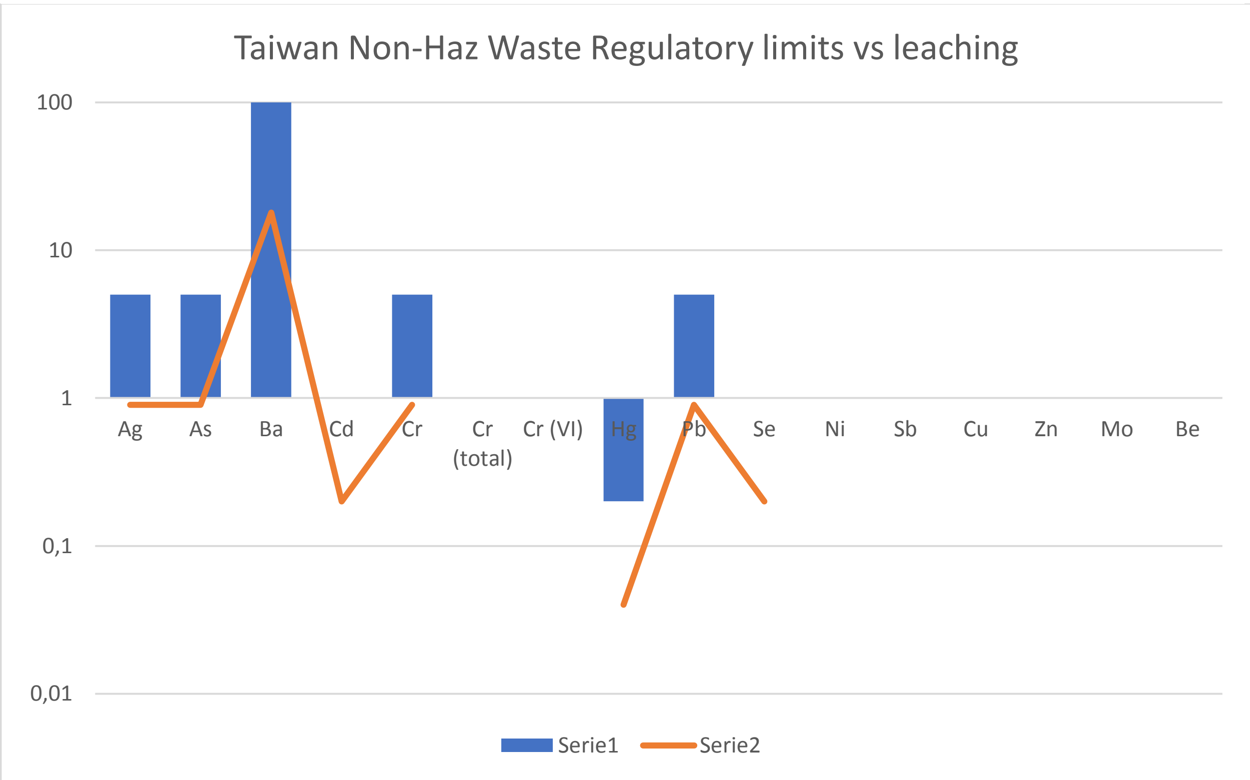

Figure 40 Taiwan TCLP Regulatory Limits

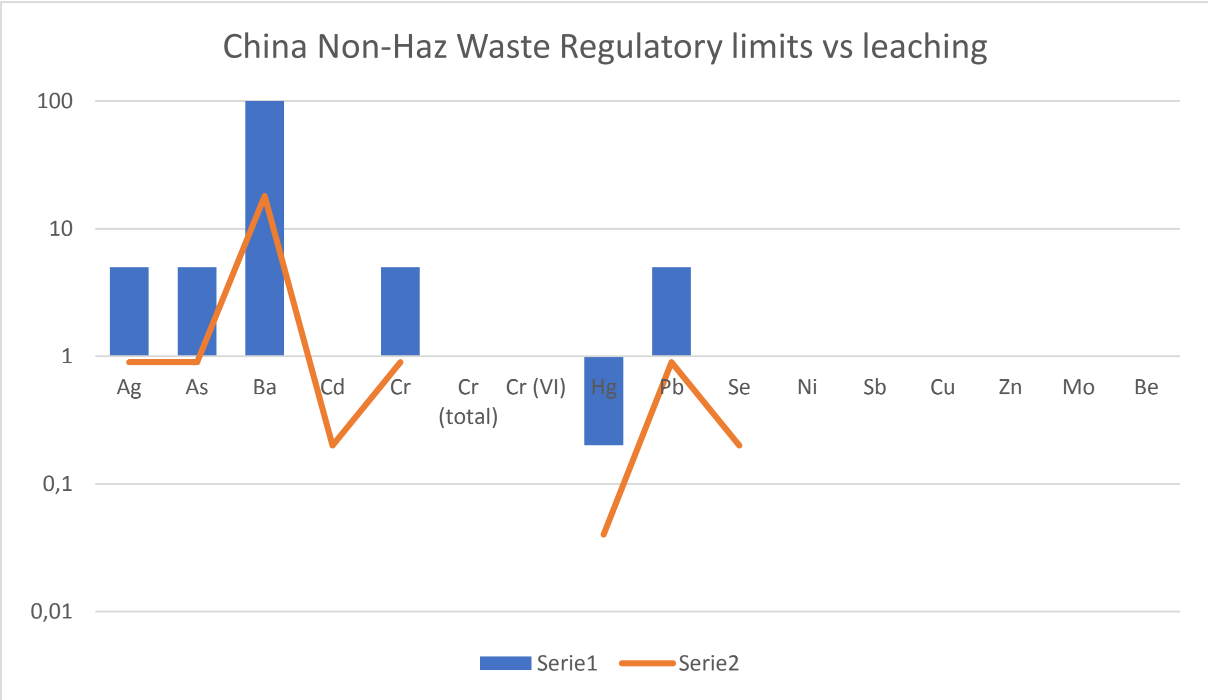

Figure 41 China Leaching Regulatory Limits

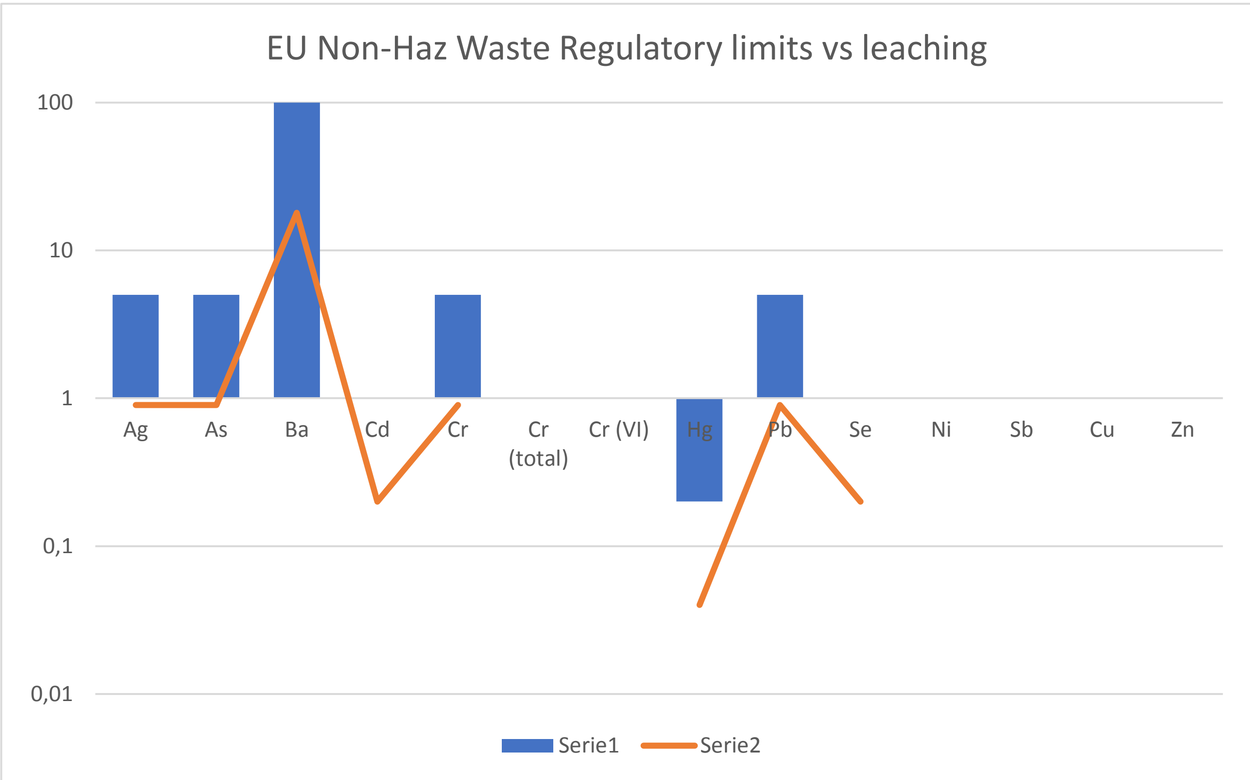

Figure 42 EU Leaching Limits Decision 2003/33/EC

The figures 39,40,41 and 42 show a comparative of the regulatory levels in USA, Taiwan, China and the EU and concrete made 65% IBA, the bars in blue represent the regulatory level and the line shows the actual leaching test results, demonstrating that leachate is below the regulatory limits, complying with US EPA, China, Taiwan and the EU environmental standards.

7.3. Evaluation of MSWI Combined Ash when used as aggregate in concrete.

7.3.1 Experimental Procedure

7.3.1.1. Materials

Municipal Solid Waste Incineration Ash is classified as a hazardous waste due to the presence of high percentages of heavy metals and salts, thus, it has to be treated before its use. MSW IFA was treated with Phosphoric acid. During the Phosphation process heavy metals are converted into their insoluble phosphate form to prevent leaching into ground water. As a result of Phosphation treatment, apatite group minerals are formed. They encapsulate the heavy metals present in the ash and stabilize them.

After Fly Ash Phosphation it was mixed with ground IBA as shown in Figure 34, Ordinary Portland cement (OPC) Type-I conforming to ASTM C 150 as the primary binding material and certified fine sand passing 4.75 mm. The gradation curve of the sand met the ASTM requirement (ASTM C33) as shown in Figure 33. Fineness modulus of fine aggregate was 2.36, which also complies with the ACI requirement.

7.3.2. Physical properties of materials

Bulk specific gravity of materials was obtained according to ASTM C127 and C128 and their results are summaries in Table 35. According to the results, specific gravity of IBA is approximately 20% lower than that of fine aggregate and combined ash is 26.5% lower than that of fine aggregate; therefore, density of concrete specimen is expected to decrease with increasing amount of ash addition.

7.3.3 Specimen Preparation

7.3.3.1 Concrete Made with Combined Ash

Sixteen samples of concrete specimens were casted, two mix designs were tested the first mix design was 15% treated Fly Ash, 55% Fine IBA, 10% Fine Sand and 19.5% OPC and 0.5% a Multi Stage Nanocomposite treatment, and water reducer, the second mix design had 20% treated Fly Ash, 50% Fine IBA, 10% Fine Sand and 19.5% OPC and 0.5% a Multi Stage Nanocomposite treatment and water reducer. The compressive strengths of the 14 samples can be seen in Table 44. The actual mixing was carried out according to ASTM C1437 mixed in a Conele Planetary Concrete Mixer. Bottom Ash being the largest percentage of aggregate was poured into the Mixer first followed by the treated fly ash, sand, then Cement was mixed with the Nanocomposites and poured into the mixer, followed by the water reducer and water.

7.3.3.2. Visual Observation

The hardened specimens of combined ash (fly ash+ bottom ash) replacement ratios in the mix design are shown in Figure 43. It is observed that the number and size of surface pores is comparable with UHPC blocks which are generated during deairing. Although there is a small percentage of surface pores that could had been caused by hydrogen gas evolution, there is no significant deterioration to the overall structure, in addition, it is observed that blocks have an impermeable structure due to the Ultra High Tortuous Paths generated by the filling of small spaces due to small particles.

Figure 43 Combined Ash concrete

7.3.4. Compressive Strength

The compressive strengths shown in Figure 44 validate the conclusion drawn from the visual evidence. The compressive strength of concrete made with Combined Ash as the only aggregate ranges from 28.8 Mpa to 30.8 Mpa.

It is established that the compressive strength depends on the strength of the cement matrix, the aggregates, and the matrix-aggregate interfacial bond. The high compressive strength in this study can be attributed to the use of small particles as aggregate and the nanocomposites that excelled the bonding strength of OPC. The standard deviation of the strengths shows a very similar high compressive strength when using combined ash.

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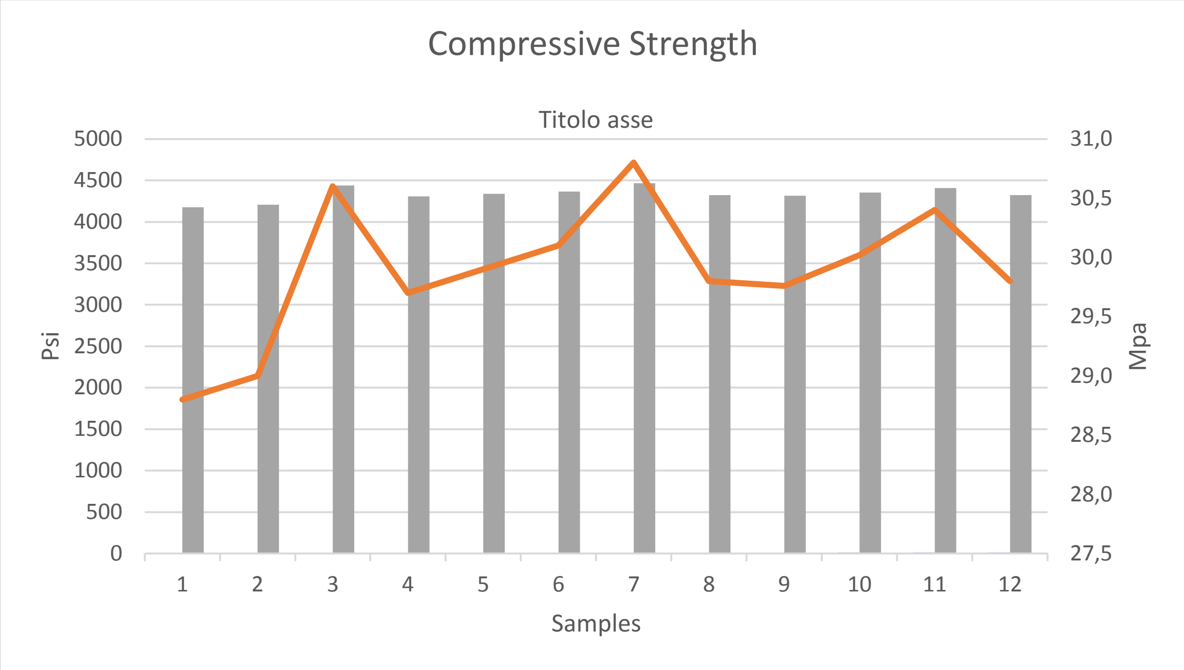

Figure 44 Combined Ash Concrete Compressive Strength

7.2.5. Leaching Characteristics of Combined Ash in PCC

The leaching behavior of the concrete mix design containing a combination of fly ash and bottom ash in the mix design has been investigated. Leaching concentrations were obtained for the inorganic constituents originated from the combined Ash incorporated in concrete specimen with a different range of particle size.

MSW Ash was obtained from a mass incineration plant in China, an elemental analysis for three elements was performed on the Fly Ash (Pb, Cd, and, Zn) to determine the contaminants ranges in the Fly Ash, afterward, a leaching test was conducted on the sample and subsequently it was treated using phosphoric acid and a leaching test was done on a sample of the treated ash, the results can be seen in the Figure 45 and Table 21. The leaching test on the treated fly ash demonstrated a 97.76% reduction in Pb leaching, in regards to Cd a 26.35% leaching reduction was found, and a 53.77% leaching reduction was detected on Zn.

After the Fly Ash was treated it was mixed with ground bottom ash, fine sand, cement and nanocomposites, water and water reducer. 16 blocks 10cmx10cmx10cm were made and 24 hours later were taken out of the mold. Hardened concrete specimens were air cured for 28 days and compressive strength test was performed Figure 43, from the 16 cured blocks 12 blocks were picked and a compressive strength test was performed, all specimens surpassed

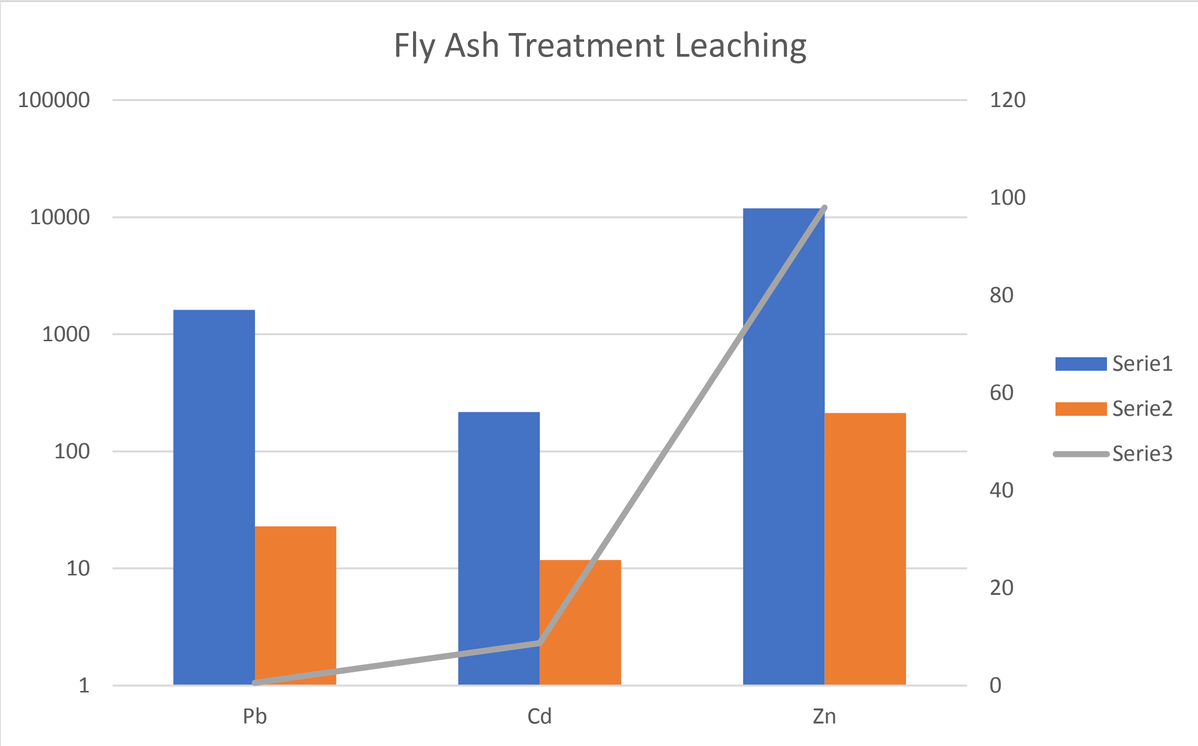

Figure 45 Fly Ash Treatment Results

Contaminant	FLY ASH		
	Elemental Composition mg/Kg	Leaching on raw mg/Kg	Leaching on treated mg/kg
Pb	1620	22.8	0.51
Cd	217	11.8	8.69
Zn	11900	212	98

Table 21 Fly Ash Elemental Analysis and Treatment

4,000 psi compressive strength as it can be seen in Figure 44.

Two blocks were selected randomly and sent to a laboratory in order to investigate the leaching potential of major and minor constituents, the Figures 22 to 29 and Table 30 show comparatives leaching tests vs Leaching limits criteria in USA, Taiwan, China and the European Community, as it can be seen concretes made with combined ash comply with the environmental regulations as USA, China, Taiwan, and the EU.

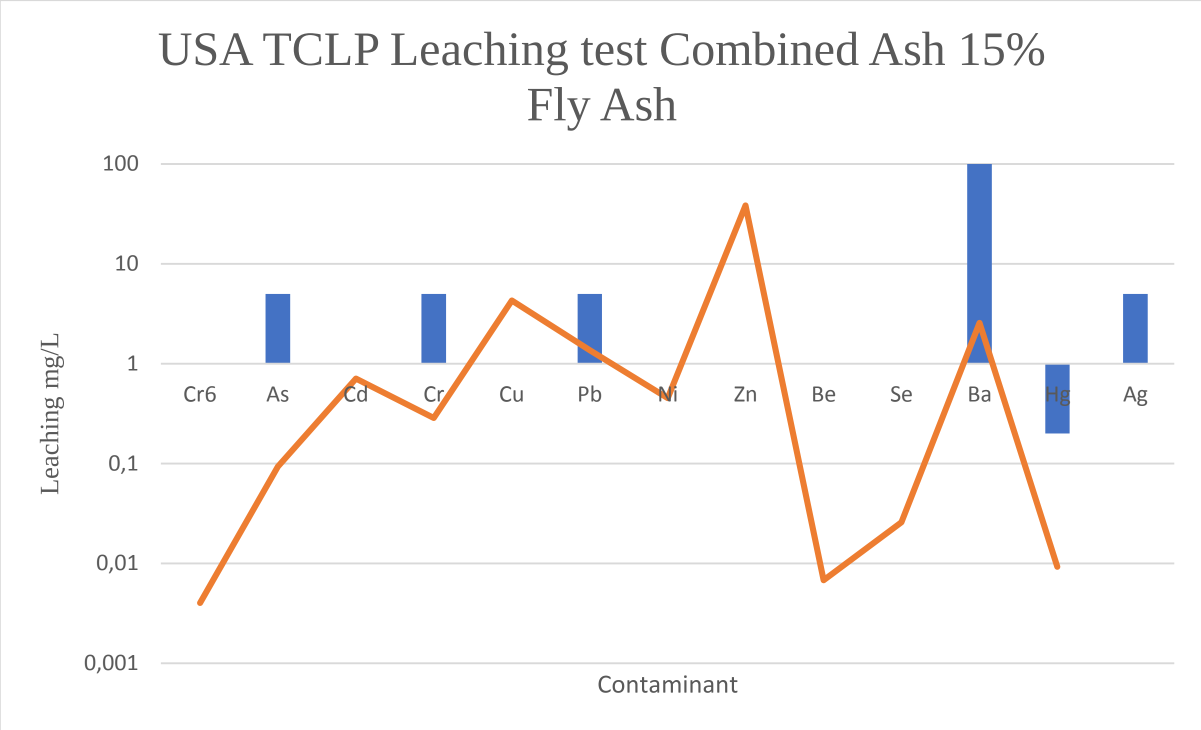

Table 22 USA Leaching test combined ash 15% fly ash

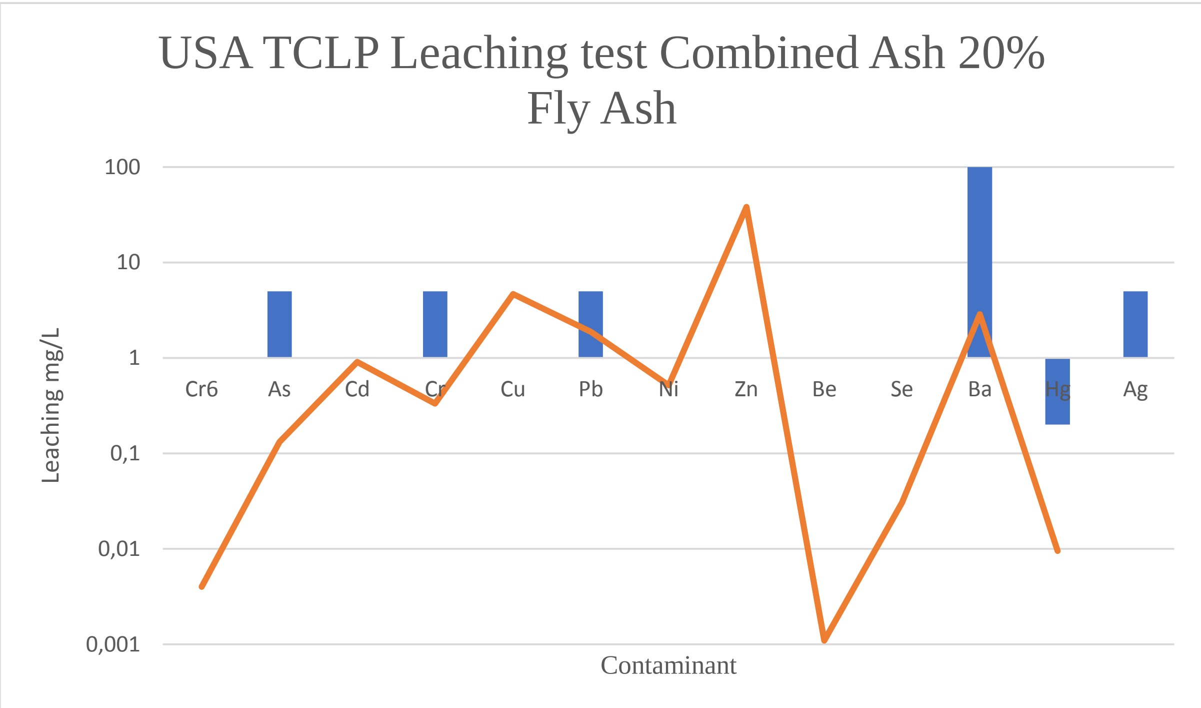

Table 23 USA Leaching test combined ash 20% fly ash

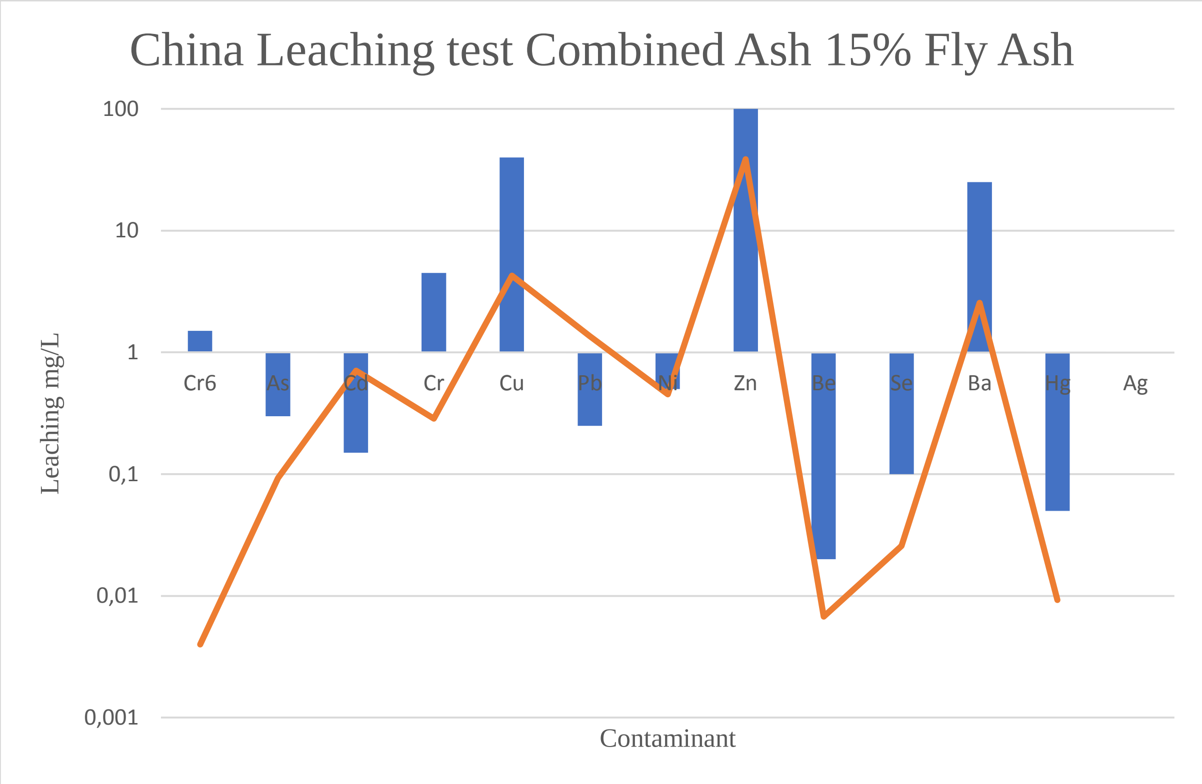

Table 24 China leaching test combined ash 15% fly ash

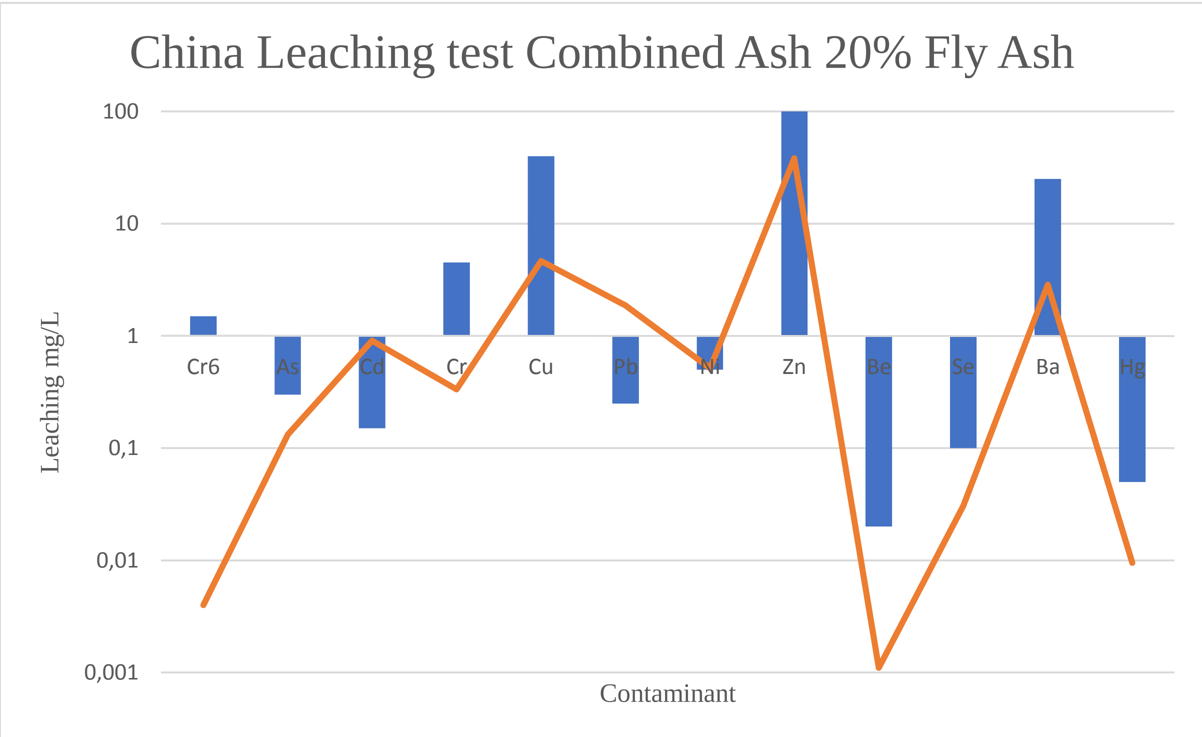

Table 25 China leaching test combined ash 20% fly ash

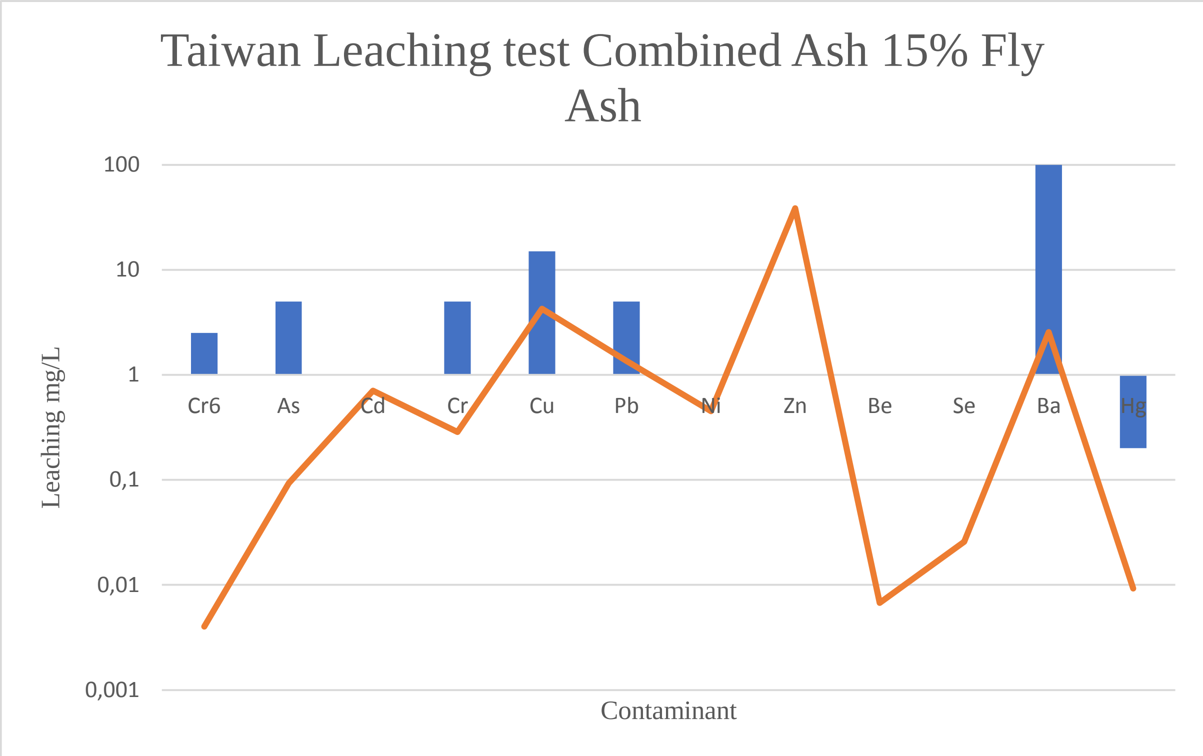

Table 26 Taiwan leaching test combined ash 15% fly ash

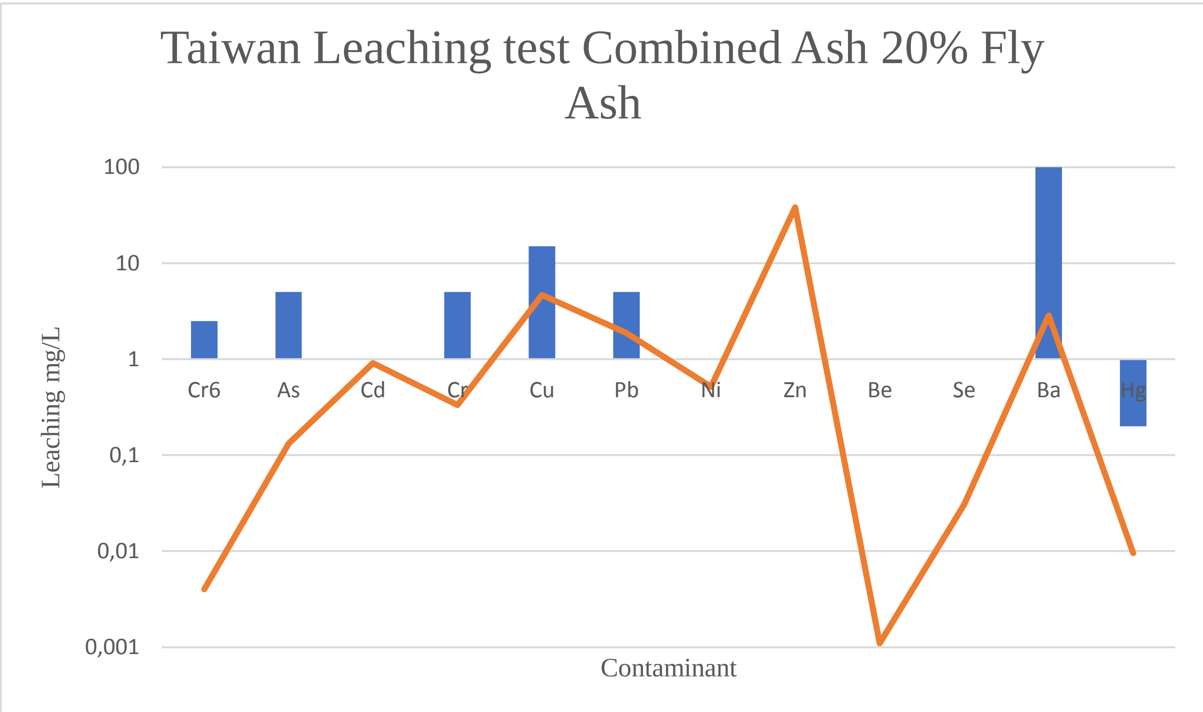

Table 27 Taiwan leaching test combined ash 20% fly ash

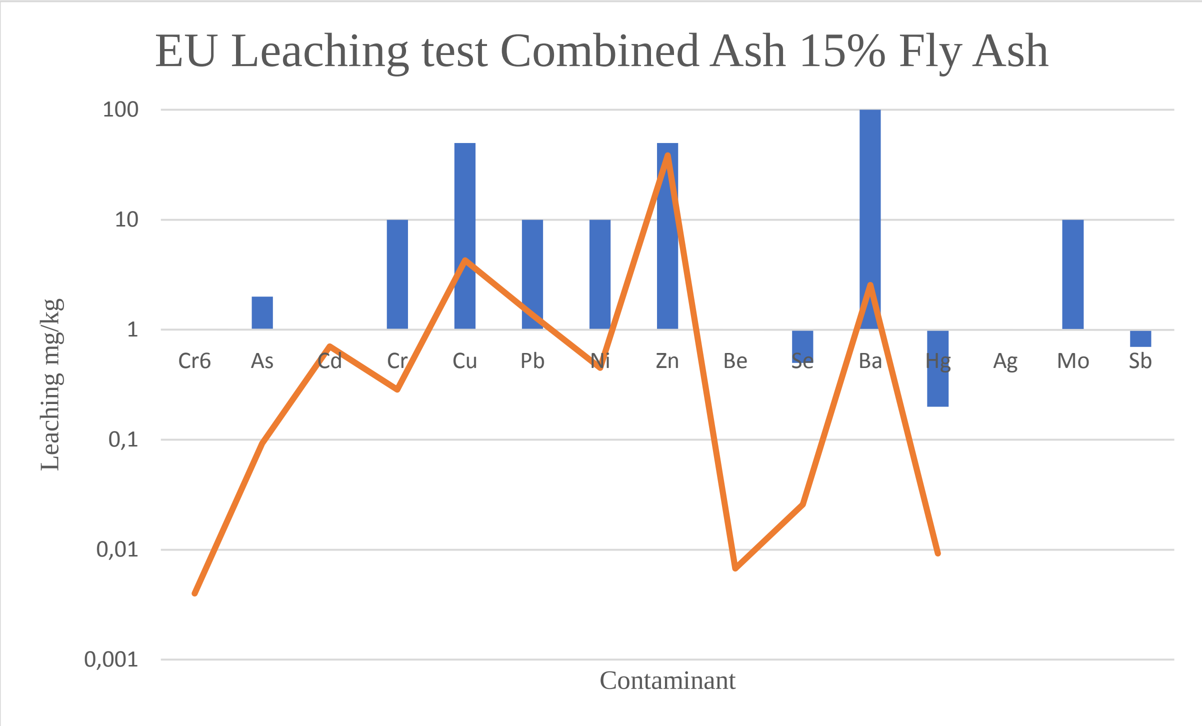

Table 28 EU leaching test combined ash 15% fly ash

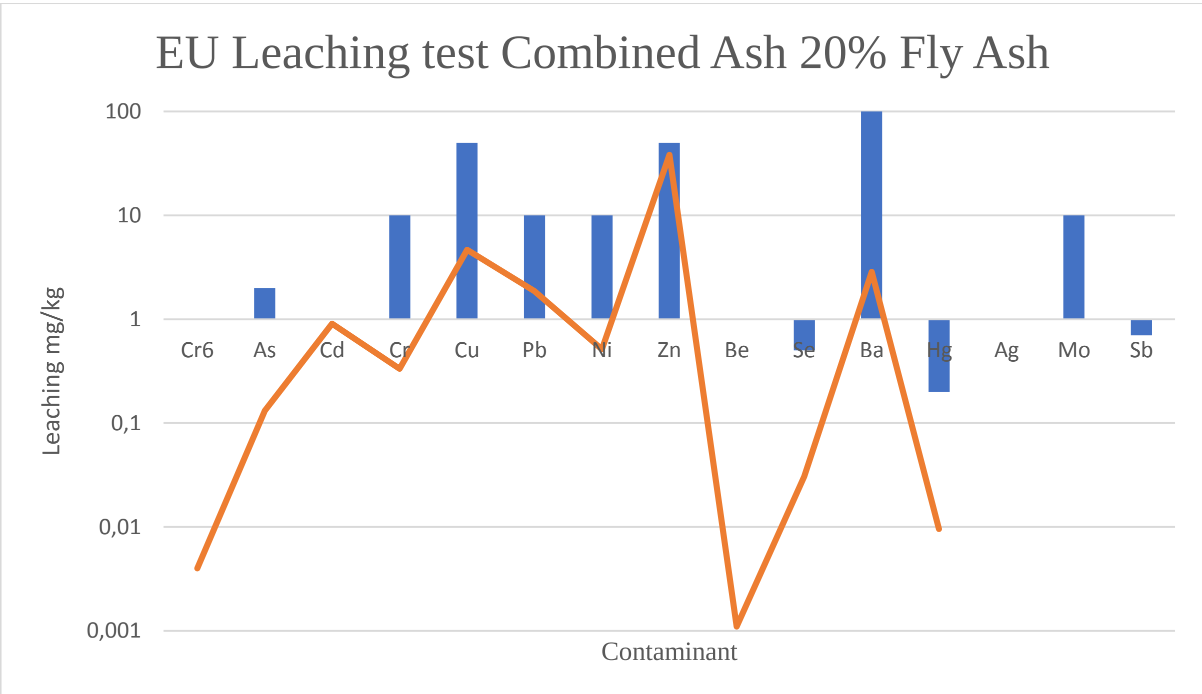

Table 29 EU leaching test combined ash 20% fly ash

Contaminant	USA	CHINA	TAIWAN	EU	Fly Ash	Fly Ash
	Regulatory level mg/l	Regulatory level mg/l	Regulatory level mg/l	Regulatory level mg/l	15%	20%
Ph					5.36	5.30
Cr6		1.5	2.5		0.004	0.004
As	5	0.3	5	2	0.0929	0.132
Cd	1	0.15	1	1	0.708	0.907
Cr	5	4.5	5	10	0.286	0.333
Cu		40	15	50	4.27	4.65
Pb	5	0.25	5	10	1.36	1.87
Ni		0.5		10	0.452	0.515
Zn		100		50	38.5	38.2
Be		0.02			0.00675	0.0011
Se	1	0.1	1	0.5	0.0257	0.0306
Ba	100	25	100	100	2.55	2.86
Hg	0.2	0.05	0.2	0.2	0.00926	0.00953
Ag	5					
Mo				10		
Sb				0.7		

Table 30 Regulatory levels vs leaching test

CHAPTER 8
SUMMARY AND CONCLUSION

8.1 Summary

World governments have established challenging recycling goals to be achieved by 2025. Thermal Waste to Energy technology reduces Municipal Solid Waste mass up to 80% reason why the existence of over 1700 Thermal Waste to Energy plants around the world, a number that is increasing exponentially as the Middle East and Russia are developing the technology and China will increase the number of plants to 800, however, the incineration process generates great amounts of residual wastes which are presented in form of ash and non-incinerables.

Recovery and recycling of waste-to-energy (WTE) fly ash and bottom ash offer significant potential contribution to meet governments zero landfill goals while contributing to a circular economy. The objectives of this study were to evaluate the benefits of using WTE ashes as the main aggregate, and to reduce the amount of cement used in Portland cement concrete (PCC).

Chapter 3 provides the background and literature review regarding current management practices of Municipal Solid Waste Combustor Ash around the world, Chapter 4 presents the existing regulations, and environmental consequences of MSWI ashes utilization, worldwide.

In Chapter 5, fundamental properties of MSWI bottom ash pretreatment ash techniques and beneficial uses of fly ash and bottom ash were studied. In Chapter 6, efforts were made to characterize ash, look closely to the ash particles microstructure, and the chemical components. Petrographic examinations, such as scanning electron microscopy (SEM), energy dispersive x-ray (EDX), and x-ray diffraction (XRD) were performed in order to identify chemical composition of the ashes and to determine their contents, In Chapter 7, fine and coarse aggregate were replaced with MSWI bottom ash, and combined ash, the feasibility of the use of the ash in concrete was evaluated as well as the potential contamination due to heavy metals leaching. In addition, the main side effect of ashes when used in concrete were evaluated as well as the influence ashes have on engineering properties and performance of cement paste specimens when a high percentage of aggregates (sand and gravel) were replaced with ground and sieved MSWI ashes. Bottom ash and Combined ash concrete were subjected to mechanical property and durability tests according to ASTM standards.

8.2. Conclusions

Based on the results of this study, the following conclusions and recommendations are made and summarized below.

8.2.1. Concrete Application

- Many countries, especially European and Asian have already successfully implemented systematic approach towards the beneficial utilization of MSWI Bottom Ash. Although research and demonstration projects ensure the beneficial utilization of MSWI ashes as a feasible option, currently there is no recycling of ash in the U.S. where 8 million tons a year of combined ash are disposed of in landfills, the same fate has the ash in Canada and Singapore. This is due to the nationwide inconsistency in ash management, regulations, and standard leaching test procedures. In addition, debates regarding highly soluble salt content and heavy metal concentration in MSWI ashes further discourage their utilization.

- The incorporation of MSWI ash in concrete significantly reduces the release of toxic elements, so many researchers recognize that this treatment is an encouraging option for ash utilization.

- Compared with typical natural aggregates, the specific gravity and unit weight of MSWI fly ash and bottom ash are slightly lower. For bottom ash, Los Angeles abrasion mass loss meets ASTM requirements, but a fairly high absorption capacity is obtained.

- According to the microstructural evaluation using SEM, the fly ash particles exhibit irregular and angular morphology and a high internal porosity compared with the bottom ash. This can cause reduced workability when mixed with cement as well as a high absorption rate and leaching for the fly ash.

- Based on the chemical components analyses by EDX and XRD, the presence of high concentration of aluminum was observed from both ashes. This can reduce the strength and durability of a concrete structure due to the development of hydrogen gas. In addition, high content of Cl found from the fly ash has a high potential for corrosion of embedded reinforcement.

- It was demonstrated that the use of nanocomposites at a very low percentage hindered the development of hydrogen gas, enhanced the bonding properties of the particles while increasing the compressive strength of the specimens.

- Phosphoric acid was effective as fly ash treatment in this process the acid converted heavy metals into their insoluble phosphate form preventing heavy metals leaching complying with environmental guidelines.

- The specimens incorporating ground bottom ash, and combined ash, mechanical and durability characteristics were comparable or superior to those of the ordinary cement paste. This is mainly attributed to the tight particle packing within the cement paste.

- The density of bottom ash concrete and combined ash concrete decreased due to the lower specific gravity of the ash while maintaining a high compressive strength, which can be beneficially in many applications like bridge decks.

- The 28-day compressive strength of concrete with 65% aggregate replacement by IBA, and the concrete made with combined ash was comparable to the control concrete and complied with environmental regulations.

8.2.2. Recommendations

Concrete Application

- Bottom Ash weathering is not necessary to make concrete, but ash should be dried before use. If combined ash is going to be used, fly ash should be treated with phosphoric acid prior application as a proper pretreatment method, to avoid heavy metals leaching.

- For the cement replacement, the cement paste with 20% cement replacement, exhibited approximately equal compressive strength, compared to that of the control specimen.

- Up to 65% of the aggregate can be replaced in the mix design by fine bottom ash depending on the application. According to the experimental investigations, concrete with 65% ash replacement did not exhibit compression mode of failure and comply with environmental regulations.

Following detailed specifications are proposed when replacing cement or aggregate in concrete:

- Replacing coarse aggregate with bottom ash the same size of coarse aggregate may not be recommended. Some of the reasons are:

  (1) The strength of bottom ash particles is significantly lower than that of typical coarse aggregate used in concrete,

  (2) Many large particles of Al might remain in bottom ash causing hydrogen gas evolution, specimen cracks and ASR.

  (3) ASR might develop in the specimen due to the swelling reaction that occurs between highly alkaline cement and the reactive amorphous silica found in the bottom Ash when given sufficient moisture.

  (4) The high porosity of Bottom Ash would make the concrete design absorb more water; thus, the overall compressive strength of the specimen will get reduced.

  (5) Although, ASTM International has work a lot with bottom ash, there are no existing standards for the use of ash in concrete and it is difficult to comply the ASTM coarse aggregate gradation with bottom ash.

  (6) Up to 20% Portland Cement can be replaced by ground bottom ash, ash must be dry and ground, the grinding must take place in a impact grinder.

When replacing coarse aggregate by bottom ash in order to comply with ASTM, the particle size of the ash should be comparable and compatible with the material to be replaced. For example, bottom ash is recommended to be ground and sieved through particles size less than 75 μg for the cement replacement application, not only to have similar particle size compared to the cement, but also to ensure the micro-filling effect. For the fine aggregate replacement, the ashes would be ground (if necessary) and sieved to comply with the ASTM specification of fine aggregate gradation.

Generally, the chemical elements and their concentration in the ashes are highly variable with waste source, location of incineration facility, and quality of incineration process. Therefore, it is recommended to chemically characterize the ashes prior to utilize them in concrete. For example, to measure the number of heavy metals in the ash to determine a possible pretreatment before use (phosphoric acid).

Lower water to cementitious materials ratio is likely to reduce the hydrogen gas evolution effect, due to the less reactivity, thus, the use of plasticizer is recommended. Low consistency of concrete and the large pores created on the surface may be avoided by the use of plasticizer when mixing concrete.

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