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UTILISATION OF MUNICIPAL SOLID WASTE INCINERATION ASH AS A RAW INGREDIENT IN CEMENT MANUFACTURING

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ABSTRACT

This article discusses about the use of MSWI ash (bottom ash and fly ash) as a raw ingredient for cement production. Municipal Solid Waste incinerators (MSWI) are facilities specifically constructed to reduce the mass and volume of the MSW and utilize the generated heat for power or heating. But these facilities generate bottom ash (typically 20-30 per cent of the original waste feed by weight) and hazardous Air Pollution Control (APC) residues (typically 2-6 per cent of the original waste feed by weight). When MSWI ash residues are co-processed in cement kiln, the ash is partly replacing one or more of the feedstock raw materials. However, high alkali, chlorine, trace elements, and organics in untreated ash limit addition to below 10%. Pre-treatment such as washing is proven to effectively reduce the limiting constituents and increase utilisation rate to around 30-50%, with some exceptions. CO2 emissions are mitigated by the introduction of MSWI ash, and life cycle assessments point to MSWI ash kiln feed as an environmentally favourable and cost-effective management strategy.

BRIEF INTRODUCTION TO THE USE OF ALTERNATIVE FUELS AND RAW MATERIALS (AFRS) IN CEMENT MANUFACTURING

The cement industry has many opportunities to replace a portion of the virgin natural resources it uses with waste and by-products from other processes. These may be used as fuels, raw materials, or as constituents of cement, depending on their properties. This is called co-processing which is defined as use of a waste in an industrial process as an input material, additionally or in substitution of standard (primary, natural) input materials.

Co-processing in cement kilns started in the mid-seventies when the petroleum crisis had increased drastically the cost of the fuel oil and when, in different countries, new regulation was issued on waste disposal. As a large amount of energy-rich waste (mainly solvents) was available, the co-processing of waste in cement kilns was the most logical answer to the situation on both environmental and economic fronts. Then, to increase energy saving, more and more sophisticated pre-treatment processes were developed, first to produce liquid substitution fuel and more recently, in the Nineties, to produce solid substitution fuel.

Cement kilns have several features that make them particularly appropriate and efficient for the recovery of minerals and energy from waste fuels and raw materials, for example, high temperature profile in pre-calciner and kiln, high gas residence time of more than five seconds at a temperature higher than 1,000°C (typical incinerator has only 2 seconds), oxidising conditions, alkaline environment, and no residues from the process.

Given the differences in temperature between different parts of the process, it is important that waste materials are introduced at the correct point in the process to ensure complete combustion or incorporation and to avoid unwanted emissions. For example, raw materials with volatile organic components may be introduced in the cement kiln at the main burner, in mid-kiln, in the riser duct, or at the precalciner. They should not be introduced with other raw materials except where tests demonstrate that this will have no effect on the off gases. Treatment of AFRs must meet strict environmental, health, and safety standards, and must not impair the quality of the final product.

Controlling emissions to the atmosphere from cement manufacture requires precise control of the process, whether using conventional or alternative fuels and raw materials. Particular attention is paid to the specification of the fuel, (specifically its homogeneity, particle size, and flammability) and to the use of best combustion practices, including proper metering, feeding, and burner technology to maintain smooth kiln operating conditions.

Cement production is energy and resource intensive and accountable for approximately 7% of man-made CO_2 emissions. Half of this is a result of the chemical process involved in the transformation of limestone into clinker; 40% is a result of burning the fuel. The remaining 10% is split between electricity use and transport. Cement production needs more than 700 million tonnes of fossil fuels like coal and more than 6 billion tonnes of virgin raw materials.

There are many sources of waste materials and by-products that can be used as alternative fuels, raw materials, and cement constituents. Recycling wastes from one process as raw materials and fuels for another creates a web of relationships between industries that moves society closer to a circular economy. Co-processing is one of the important levers for the cement sector in reducing the CO_2 emissions. The table 1 shows the development of thermal substitution rates in different regions of the world, between 1990 and 2019.

Table 1. Development of the thermal substitution rates in different regions of the world between 1990 and 2019 (data from GNR 2019)

Region	1990	2000	2010	2019	Coverage (%) in 20191
World2	2 %	5 %	12 %	19 %	22 %
Europe	3 %	9 %	31 %	50 %	90 %
North America	4 %	7 %	13 %	15 %	86 %
Central America	0 %	2 %	10 %	17 %	74 %
Brazil	5 %	9 %	19 %	31 %	78 %
South America ex. Brazil	0 %	3 %	5 %	7 %	69 %
CIS3	0 %	0 %	1 %	4 %	21 %
Middle East	0 %	0 %	2 %	13 %	14 %
Africa	0 %	0 %	2 %	13 %	31 %
Asia (n.e.c.)4 + Oceania	0 %	0 %	7 %	11 %	27 %
Northeast Asia	1 %	5 %	5 %	6 %	4 %
India	0 %	0 %	1 %	4 %	55 %

1. Coverage is percent of cement production covered in the GNR database- https://gccassociation.org/gnr/

2. Current TSR of world is 6% but because of only 22% coverage the TSR of world in the above table is 19% in 2019.

3. CIS: Commonwealth of Independent States comprising of Azerbaijan, Armenia, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Uzbekistan and Ukraine.

4. n.e.c : not elsewhere counted:

1.1 Regulatory framework for Co-processing in cement kilns – Examples from India and China

1.1.1 India

The MoEFCC in 2016, amended the existing regulatory framework for environmentally sound management of the waste being generated in the country. MoEFCC has notified 6 sets of waste management rules dealing with different kinds of waste: solid waste, plastic, biomedical, construction and demolition, electronic waste, and hazardous waste. These new rules advocate for adopting more scientific, technology driven, sustainable, regulated, and participative environment management.

As per the new Solid Waste Management (SWM) Rules of 2016, the non-recyclable waste having calorific value of 1500 kcal/kg or more shall not be landfilled and shall only be utilized for generating energy either through RDF or by giving away as feedstock for preparing RDF.

Hazardous and Other Wastes (Management & Transboundary Movement) Rules, 2016 included Co-processing as preferential mechanism over disposal for use of waste as supplementary resource, or for recovery of energy. The approval process for co-processing of hazardous waste to recover energy has been streamlined and put on emission norms basis rather than on trial basis (MoEFCC, 2016).

Table 2. Emissions standards for Indian cement plants co-processing wastes (MoEFCC, 2016)

Parameters	Emission limit	Unit	Remarks
Particulate matter*	30	mg/Nm3	
	0.125	kg/tonne of clinker	Raw mill, kiln and precalciner system put together
SO2*	100	mg/Nm3	Pyritic sulphur in the limestone is less than 0.25%
	700	mg/Nm3	Pyritic sulphur in the limestone is 0.25- 0.5%
	1 000	mg/Nm3	Pyritic sulphur in the limestone is more than 0.5%
NOx*	600	mg/Nm3	For kilns commissioned after 25.08.2014
	800	mg/Nm3	For ILC kilns commissioned before 25.08.2014
	1 000	mg/Nm3	For other kilns commissioned before 25.08.2014
HCl	10	mg/Nm3	
HF	1	mg/Nm3	
Total Organic Carbon (TOC)	10	mg/Nm3	Case to case standard if TOC does not result from the co-processing
Hg and its compounds	0.05	mg/Nm3	
Cd + Tl and their compounds	0.05	mg/Nm3	
Sum of other heavy metals and their compounds	0.5	mg/Nm3	Other heavy metals are Antimony (Sb), Arsenic (As), Lead (Pb), Cobalt (Co), Chromium (Cr), Copper (Cu), Manganese (Mn), Nickel (Ni) and Vanadium (V)
Dioxins and Furans	0.1	ngTEQ/ Nm3	

* *The concentration values and timeline for implementation in respect of PM, SO_2 and NOx shall be governed in accordance with the provisions under notification published vide GSR No. 612 (E), dated the 25th August, 2014 and amended from time to time*

For cement plants co-processing wastes, MoEFCC has notified emission limit values vide G.S.R. 497 (E) dated 10 May 2016. Continuous Emission Monitoring System (CEMS) installation is mandated in cement kiln stack for Particulate Matter, SOx and NOx in the first phase, with data uplinked to State and Central Pollution Control Boards.

The Co-processing guidelines (2017) are a revised version of the 2010 CPCB guidelines. The guidelines have been revised for complying with the conditions as specified in the Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016. No trial runs would be necessary for grant of authorisation for co-processing of wastes since MoEFCC has notified the Emission Standards for co-processing of wastes in cement kiln. However, demonstration trials would be conducted for specific

wastes such as POPs, PCBs, obsolete and date expired pesticides, Ozone Depleting Substances, etc. Kiln specific trial runs may be required for such wastes to study the destruction and removal efficiencies (as per the requirement of Stockholm convention). Trial/ approval from CPCB would also be required if waste is fed through coal or raw material route. In the guidelines, standard operating procedure for pre-processing and co processing are defined.

1.1.2 China

The Ministry of Environmental Protection, the National Development and Reform Commission and the Ministry of Industry and Information Technology have recently issued several documents to raise the level of knowledge and improve the development of cement kiln co-processing technology.

Standards and Guidelines reflecting international best practice have been under development for some years, among others as part of the Sino-Norwegian project on co-processing of wastes in the cement industry. The Ministry of Environmental Protection of China issued its first two standards focusing on co-processing of wastes in the cement industry in December 2013

- "Standard for pollution control on co-processing of solid wastes in Cement kiln", GB30485-2013.
- "Environmental protection technical specification for co-processing of solid wastes in cement kiln", HJ 662-2013.

In May 2014, the Cement Standardization Administration of China co-operated with the MEP to issue two standards focusing on co-processing of wastes in cement industry

- "Technical specification for co-processing of solid waste in cement kiln", GB30760-2014
- "Determination of heavy metals leaching for cement and building materials", GB/T 30810-2014

The new standards only allow co-processing in large cement plants with the best pollution control equipment and with high professional competence. The new co-processing standards are complementary to the existing "Emission standard of air pollutants for cement industry" (GB 4915), which applies to cement plants that do not conduct co-processing; together, they will constitute an advanced and comprehensive standard system for pollution control in the Chinese industry.

Based on careful analysis of potential pollution risks during cement kiln co-processing, the standards specify corresponding pollution control measures and describe appropriate feeding point selection, emissions of air pollutants, requirements for the content of hazardous elements in the wastes (including heavy metals, chlorine, fluorine, and sulphur), and cement quality. The standards also prohibit some waste types including radioactive waste, explosive and reactive wastes, whole batteries, waste electrical and electronic equipment, mercury-containing thermometers, blood-pressure meters, fluorescent lamps and switches, chromium slags and unknown and unidentified wastes.

Table 3 lists the new emission limits for air pollutants. The emission limit value (ELV) for dust particles is identical to the EU standard; the ELV for SO2 is close to the EU standard but the ELV for NOx is stricter than the EU standard; the ELVs for HF, TOC, HCl, Hg and dioxin/furans are the same as the EU standard and the ELV for HCl, Hg, dioxin/furans and TOC, which represents volatile compounds, are stricter than the US standard; the ELV for Tl+Cd+Pb+As is less strict than the US and the EU standards reflecting the poor quality of raw materials in China; other ELVs for heavy metals are the same as the EU standard.

The cement industry produces up to 11 percent of all NOx emissions across China's industrial sectors, approximately 2.7 Mta, and has been targeted in the country's move to address air pollution, particularly after hazardous smog repeatedly blanketed skies at the start of 2013. The newly revised and updated emission standards will sharply cut the amount of NOx emitted by existing plants to below 400 mg/Nm3 from an average emission of 880 mg/Nm3 among cement makers now. For cement production lines located in key regions, the emission standard will be capped below 320 mg/Nm3. NOx can be abated with a combination of measures like low NOx burners, staged combustion, feeding alternative fuel to the calciner, SCR and SNCR.

Cement plants must install Continuous Emission Monitoring systems (CEMs) for on-line monitoring of dusts/particulates; SO2 and NOx. HCl, HF, TOC, heavy metals must be measured at least every four months when co-processing hazardous wastes or every six months when co-processing non-hazardous wastes. Dioxins and furans must be measured annually.

Table 3. Emission limit values for Cement Kilns in China (mg/Nm3)

Pollutants	New ELVs for Co-processing of wastes in China- GB 30485-2013 and HJ 662-2013		ELVs for cement plants not co-processing wastes in China GB 4915- 2013	
	Common Region (1)	Key Region (2)	Common Region	Key Region
Particulate matter	30	20	30	20
SO2	200	100	200	100
NOx (as NO2)	400	320	400	320
NH3	10	8	10	8
Fluoride (as total F)			5	3
HCl	10	10		
HF	1	1		
TOC	10	10		
Hg	0.05	0.05		
Tl+ Cd+ Pb+ As	1.0	1.0		
Be+ Cr+ Sn+ Sb+ Cu+ Co+ Mn+ Ni+ V	0.5	0.5		
Dioxin/furans (ng I-TEQ/ Nm3)	0.1	0.1		

(1) Common region means all other regions outside key regions
(2) Key region means a region where land is developed intensely, the local environment is vulnerable or impacts of air pollutants is great, the ecological environment fragile, and strict air pollution control is needed.

Table 4. Heavy metal leaching limits for cement clinker

Heavy Metals	As	Pb	Cd	Cr	Cu	Ni	Zn	Mn
Leaching Limits in China (mg/litre)*	0.1	0.3	0.03	0.2	1.0	0.2	1.0	1.0

**The clinker should be made into cement sample according to "Portland cement clinker" (GB/T 21372-2008), then the cement sample should be made in to cement mortar sample before the leaching test. The leaching test method for the cement mortar sample is similar to the EU leaching method "NEN 7371" except that the pH value of the leaching liquor has been changed to 3.2 from 4.0. (Environment Agency, 2005)*

In May of 2014, MEP issued newly revised "Standard for pollution control on the municipal solid waste incineration" (GB18485-2014). The limits of dusts/ particles, Hg, dioxin in the co-processing standards is nearly the same as the MSW incineration standards, the limits of NOx, SO_2, Cd, Tl in the co-processing standards are a little looser than the MSW incineration standards, and the limits of HCl and other heavy metals in the co-processing standards are stricter than the MSW incineration standards.

The new co-processing standards also specify Leaching Limits for certain heavy metals from cement clinker produced when co-processing solid wastes; see Table 4. It is the first time China has specified requirements related to the environmental safety of cement products.

MUNICIPAL SOLID WASTE INCINERATION(MSWI)

Municipal Solid Waste incinerators (MSWI) are facilities specifically constructed to reduce the mass and volume of the MSW and utilize the generated heat for power or heating. Different combustion technologies that can be utilized to burn MSW are moving grate, fixed grate, fluidized bed, and rotary kiln. Grate incinerators are the most common, constituting 90 per cent of waste to energy (WtE) incinerators in Europe. Due to high organic fraction and high moisture content in MSW in many developing countries, some pre-treatment is needed to increase the lower heating value. The residue from the incineration process is disposed of in a Landfill.

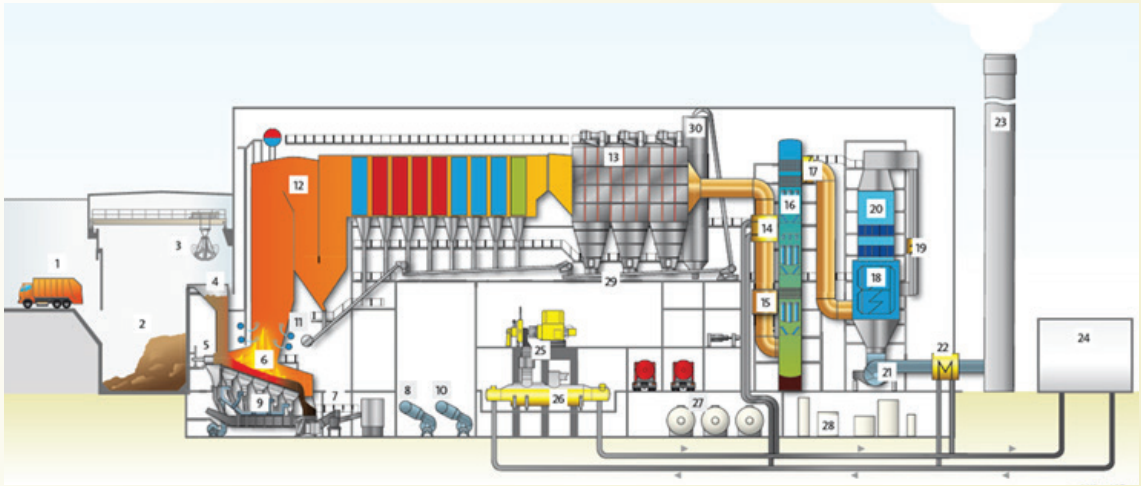
Basic requirement is minimum temperature of 850°C and a two second residence time for processing

MSW. The waste is mostly converted into carbon dioxide and water; non-combustible materials (e.g. metals, glass, stones) remain as solid and ash residues.

The actual plant design and configuration of incineration plant will differ considerably between technology providers. However, an Incinerator with energy recovery will typically comprise of waste reception and handling, combustion chamber, energy recovery plant, flue gas treatment and residual ash handling. Depending on how developed the waste management infrastructure and practices are, incineration of MSW is normally applied to untreated residual MSW (after mechanical biological treatment) and to almost raw MSW in some countries.

Electricity generation from MSWI is only able to contribute with a small fraction of the electricity demand of the region where the waste is generated; efficiency is low, usually 15-25 per cent (best plants in the world achieves 30% efficiency). Combined heat and power incinerators utilize the excess heat for heating applications in addition to the electricity production. This way, the overall energy efficiency of the WtE plant can reach more than 80 per cent. Combined heat and power plants are common in Europe, but hardly used in developing countries. For utilization of excess heat, there must be a heating demand, which is often lower in countries with a warm climate.

In Europe, WtE is considered a reliable method of treatment of waste for which there is no other alternative towards a circular economy. WtE plants in the EU are considered as 'recovery' options only when both electricity and heat are gainfully used. Success of WtE in Europe can majorly be attributed to the regulatory framework to avoid landfilling. WtE plants in Germany and Sweden, for example, receive largely segregated, high-calorific-value waste that is easy to manage. They have also installed highly sophisticated systems to further segregate waste so that a consistent quality of waste is fed to the plant.



Waste receiving and storage	Grate combustion and steam generator		Flue gas treatment		Energy from waste	Consumables and residues
1. Unloading area	*4. Feed hopper*	*7. Bottom ash discharger*	*13. Eletcrostatic Filter*	*18. Gas/gas heat exchanger*	*24. District heating system*	*27. Waste water treatment*
2. Waster pit	*5. Ram feeder*	*8. Primary air fan*	*14. Economiser precipitator 1*	*19. Flue gas reheater 2*	*25. Extraction condensation turbine*	*28. Waster water treatment*
3. Waste crane	*6. Reciprocating incineration grate*	*9. Primary air distribution*	*15. Quench*	*20. SCR-Catalyst*	*26. Hot water condenser*	*29. Ash conveying*
		10. Secondary air fan	*16. Wet scrubber (4 stops)*	*21. ID-Fan*		*30. Ash silo*
		11 . Flue gas recirculation	*17. Flue gas reheater 1*	*22. Econmiser precipitator 2*		
		12. 4-pass steam		*23. Stack*		

Figure 1. Overview of a MSWI plant (Hitachi Zosen INOVA).

2.1 Operating and emissions standards for MSW Incineration in India

MSW Incineration with waste to energy (WtE) is an increasingly popular choice for Indian cities given the increasing waste quantities. WtE normally involves generation of electricity in steam turbines in either mass burn mode or by first producing RDF.

CPCB recommends that before MSW Incineration is installed, a mature and well-functioning waste management system has been in place for a few years. The supply of combustible waste should be stable and amount to at least 500 tonnes/ day. The lower calorific value (LCV) of waste must be at least 1450 kcal/kg (6MJ/kg) throughout all seasons. The annual average LCV must not be less than 1700 kcal/ kg (7 MJ/ kg). Waste to be incinerated shall not be chemically treated with any chlorinated disinfectants. And only low sulphur fuel like LDO, LSHS, Diesel, biomass, coal, LNG, CNG, RDF and biogas shall be used as fuel in the incinerator.

All the facilities in twin chamber incinerators shall be designed to achieve a minimum temperature of 950°C in secondary combustion chamber and with a gas residence time in secondary combustion chamber not less than two seconds. Incineration plants shall be operated (combustion chambers) with such temperature, retention time and turbulence, as to achieve Total Organic Carbon (TOC) content in the slag and bottom ash less than 3%, or the loss on ignition is less than 5% of the dry weight. The CO_2 concentration in tail gas shall not be more than 7%.

If the concentration of toxic metals in incineration ash exceeds the limits specified in the Hazardous Waste Management Rules 2016, the ash shall be sent to the hazardous waste treatment, storage, and disposal facility. Fly ash acts as a catalyst for de-novo synthesis (at 200-450°C) of dioxins and furans. To reduce formation of dioxins and furans, it is imperative that maximum fly ash is removed before gases cool down to 200-450°C. Odour from sites shall be managed as per guidelines of CPCB issued from time to time.

Since the capital investment is very high, the planning framework of the community should be stable enough to allow a planning horizon of 25 years or more. Pre-feasibility study for the technology should point to positive conclusions for the respective community.

Table 5. Emission standard for MSW Incineration Plant (MoEFCC, 2016)

Parameter	Emission standard	
Particulates	50 mg/Nm3	Standard refers to half hourly average value
HCl	50 mg/ Nm3	Standard refers to half hourly average value
SO2	200 mg/ Nm3	Standard refers to half hourly average value
CO	100 mg/ Nm3 50 mg/ Nm3	Standard refers to half hourly average value Standard refers to daily average value
Total Organic Carbon	20 mg/ Nm3	Standard refers to half hourly average value
HF	4 mg/ Nm3	Standard refers to half hourly average value
NOx (NO and NO2 expressed as NO2)	400 mg/ Nm3	Standard refers to half hourly average value
Total dioxins and furans	0.1 ng TEQ/ Nm3	Standard refers to 6-8 hours sampling. Please refer guidelines for 17 concerned congeners for toxic equivalence values to arrive at total toxic eq.
Cd + Th + their compounds	0.05 mg/ Nm3	Standard refers to sampling time anywhere between 30 minutes and 8 hours.
Hg and its compounds	0.05 mg/ Nm3	Standard refers to sampling time anywhere between 30 minutes and 8 hours.
Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V + their compounds	0.5 mg/ Nm^3	Standard refers to sampling time anywhere between 30 minutes and 8 hours.

All values corrected to 11% oxygen on a dry basis.

MSW INCINERATION ASH

3.1 Types and generation volumes

The bottom ash fraction is continually discharged from the combustion chamber and is then cooled (often by water spray). This fraction is classified as non-hazardous waste. The bottom ash typically represents around 20-30 per cent of the original waste feed by weight, only about 10 per cent by volume. The amount of ash will depend on the level of waste pre-treatment prior to entering the incinerator and will also contain metals that can be recovered for recycling. The use of bottom ash in road constructions is a recovery application area for this waste material. However, in some countries, such application is not accepted by the environment authorities (e.g., Norway), for which the remaining option is landfilling.

Flue gas cleaning is often a significant contributor to overall incineration costs (approximately 15% to 35 % of the total capital investment). The emissions limits for specific pollutants that are present in the combustion products (flue gases) are defined by national standards (see table 5). The clean-up of the flue gases will produce solid residues comprising fly-ash, lime/ bicarbonate, and carbon. These residues are usually combined (although several systems may separate fly ash and other components), often referred to as Air Pollution Control (APC) residues, and are classified as hazardous waste; therefore, their disposal must be undertaken in accordance with relevant regulations and guidance. Typically, the weight of APC residues produced will be around 2-6 per cent of the weight of the waste entering the incinerator.

In fluidized bed furnace, the lower (but more even) operational temperatures, nature of the fuel and process in fluidized beds mean that a greater proportion of volatile heavy metals remain in the bottom ash. Consequently, concentrations of heavy metals in the flue-gas residues are reduced. However, sometimes there are problems with Cr (VI) levels in the soluble part of the bottom ash. Furthermore, the degree of vitrification of the ash may be reduced and the burnout may be improved.

Majority of solid residue from fluidized bed incineration is fly ash, which, according to conditions and applied fluidized bed technology, can form up to 90 % of the total ash residue. The bottom ash is also mixed with fluidized bed material (e.g. sand, additives for desulphurization etc.). When waste or RDF is burnt in a rotating fluidized bed the ratio of bottom ash to fly ash is about 50:50.

3.2 Chemical composition

MSWI ash compositions are expected to be variable based on geographic location and variables such as waste stream characteristics and combustion technologies. Chlorides and alkalis in MSW ash are primarily contributed by food waste, plastic, ceramics and glass, and these constituents tend to form volatile organic and inorganic salts at MSWI combustion temperatures; airborne salts then condense in the cooler portions of the APC equipment and are thus concentrated in the fly ash stream.

Table 6. Concentration range (µg/kg) of organic species in MSWI residues (Vehlow, 2002)

Substance	Bottom ash	Boiler ash	Filter ash
PCDD/F (I-TEQ)	<0.001 to 0.01	0.02 to 0.5	0.2 to 10
PCB	<5 to 50	4 to 50	10 to 250
PCBz	<2 to 20	200 to 1000	100 to 4000
PCPh	<2 to 50	20 to 500	50 to 10000
PAH	<5 to 10	10 to 300	50 to 2000

PCBz: Poly Chlorinated Benzenes; PCPh: Poly Chlorinated Phenyls

Typical concentrations of organic compounds in the various solid residues are compiled in Table 6. The data are collected from ash residues generated in modern facilities. It is evident that volatiles are accumulating in the ash residues at increasing distance from the furnace. This is due to the decreasing temperature which increases desorption of volatile substances onto the surface of the flue gas particles. Typical concentration range of metals for the fly ash collected from a modern Czech MSWI plant is given in Table 7. The concentrations for some of the toxic metals are sometimes significantly higher than the limits for hazardous waste (e.g. Norwegian limits).

Table 7. Concentration ranges of different constituents in MSWI fly ash and threshold values for certain constituents in hazardous waste in Norway

Constituent	Unit	Concentration rangea	Hazardous waste limitsb
As	mg/kg	18 to 960	> 1000
Ba	mg/kg	34 to 14000	-
Cd	mg/kg	10 to 2100	> 1000
Cl	g/kg	18 to 380	-
Cr (total)	mg/kg	10 to 860	-
Cr (III)	mg/kg	-	> 25000
Cr (VI)	mg/kg	-	> 1000
Cu	mg/kg	16 to 4100	> 25000
Mn	mg/kg	200 to 1700	-
Ni	mg/kg	19 to 710	> 2500
Pb	g/kg	0.25 to 27	> 2.5
Sb	mg/kg	58 to 3300	-
S	g/kg	1.4 to 120	-
Zn	g/kg	0.4 to 100	> 25

[a]Data from Šyc et al. (2010); [b]Issued by the Norwegian Climate and Pollution Agency

3.3 Pre treatment (Secondary Treatment)

The measures conducted at the incineration plant, for controlling residue outputs (burn out of carbon and volatilization of heavy metals out of fuel bed), are defined as the primary treatment whereas additional external measures (e.g., metal scrap recycling from bottom ash) is considered as secondary treatment or pre-treatment of the ash residues for final disposal or further processing (e.g., landfill, raw material in new products, etc.).

The secondary treatment involves pre treatment technologies that do not necessarily need to be applied at the incineration plant. To make the ash fraction less harmful to the environment, several studies have been carried out regarding possible treatment processes, to MSWI fly ash (including ESP ash) and APC (air pollution control) residues as reviewed by Quina et al (2008). They compile the methods in the following treatment categories: separation (magnetic separation, washing, acid leaching, etc.), solidification/stabilisation (S/S) (e.g., use of cementitious binder) and thermal treatment methods (sintering and vitrification/melting). Costs will be a crucial factor regarding pre-treatment efforts and this aspect is not necessarily sufficiently dealt with in the studies.

Pre treatment by washing is gaining significant interest and may be applied on the problematic APC residues (e.g., fly ash) for removing chlorine, sulphur, alkalis, heavy metals etc, and make the ash amenable to use in cement industry (destroy POPs and use ash as pozzolana) or brick production. The concentrations of constituents like As, Cd, Cl, K, Na, Pb, Sb and Zn increase in the sequence of bottom ash, boiler pass ash and ESP ash

Table 8. Overview of available washing procedures for MSWI ash fractions.

Ash type	Extraction Agent	Liq to Solid Ratio (L/kg)	Extraction Time (hrs)	Process/mixing device	Reference
Boiler, ESP and catalytic filter ash	Acidified water	-	0.75	Commercial process	Syc et al., 2010
Bottom ash	Water	5	6	Concrete mixer in laboratory	Cossu et al., 2012
APC residues	Distilled water	3	1 to 2	Containers in laboratory	Chimenos et al., 2005
Fly ash (cyclone ash)	Distilled water	> 2	1	Containers in laboratory	Wang et al., 2001
Fly ash (fabric filter)	Distilled water	20	3	Containers in laboratory	Saikia et al., 2007[a]
Fly ash	Distilled water + acid	10 + 20	0.25 + 0.5	Containers in laboratory	Pan et al., 2008[a]
Fly ash (cyclone and fabric filter)	Water	10	1/6	Tested in real scale	Wang et al., 2010[b]

[a]Washed material tested in preparation of cement clinker in laboratory; [b]Washed material tested in full scale in the cement clinker production

Most of the washing procedures with the sole aim to use MSWI ash as a raw material in clinker production are mostly carried out in laboratory, i.e., both the washing procedure and the production of cement clinker. A summary of existing washing methods available are shown in Table 8. The recent full-scale demonstration showed satisfying results with water extraction (Wang et al., 2010). In this study, the washing procedure was carried out at the cement plant along with drying and pulverisation. The material was fed into the kiln from a separate hopper in 1 % by weight of raw meal indicating a treatment capacity of 30 tonnes per day. No detrimental effects were observed during the 3 days trial regarding the plant emissions and the quality on the final cement.

CO-PROCESSING OF MSWI ASH IN CEMENT KILN

This article considers only MSWI ash (bottom ash and fly ash) as a raw ingredient for cement production and does not consider MSWI ash used directly as a cement replacement.

In cement clinker production, the cement raw meal is normally a mixture of the finely ground raw materials; limestone, clay, bauxite, and quarts (feed stock). The raw materials are mixed in a proportion that gives a favorable chemical composition of the raw meal for the cement clinkering process. The final chemical composition of the cement clinker determines the composition of the raw meal. The major oxide composition of cement clinker is typically around 21-23 % SiO_2, 63-66 % CaO, 3-7 % Al_2O_3 and 1-6 % Fe_2O_3.

When MSWI ash residues are co-processed in cement kiln, the ash is partly replacing one or more of the feedstock raw materials. The substitution rate is determined by the chemical composition to comply with the oxide composition of the raw meal to obtain the oxide composition of the clinker. In addition, the concentrations of alkalis, chlorides and heavy metals will affect the final cement and need to be limited. Municipal solid waste incineration (MSWI) ash has an elemental composition suitable for cement production and is thus a potentially feasible substitute for traditional raw ingredients (Kyle et al., 2020; Viczek et al., 2020; Ashraf et al., 2019; Sarmiento et al., 2019).

The incorporation of MSWI bottom or fly ash (or a combination of both) into cement production presents itself as an environmentally favourable management option, an integrated use that may serve to mitigate environmental issues (Clavier et al., 2019b; Serclérat et al., 2000; Wey et al., 2006). This practice reduces the requirement for aggregate mining and shipping and extends the useful life of landfills, among other environmental benefits (Ferraro et al., 2016). In addition, municipal waste incinerators who produce, and are thus required to dispose of, MSWI ash may receive financial benefits from reduced landfill tipping fees while the cement manufacturer may save on the cost of raw materials.

Sarmiento et al. (2019) found that MSWI ash fly ash is favourable for cement manufacture, but that allowable fly ash incorporation is severely limited by chloride and alkali content; up to 67.8% fly ash could create a suitable clinker based on mineralogical composition alone, but the viable percentage drops to just 3.72% when constrained by alkalis, and further drops to 0.33% when constrained by chlorides and alkalis. Studies have reported that lime saturation factor decreases as more MSWI ash is added to a cement raw mix.

RAW MATERIALS CONSIDERATIONS

MSWI fly ash has been reported as having 17% or higher chloride content while bottom ash is generally under 1% chloride; bottom ash and fly ash have similar alkali contents that constitute a considerable portion of their total composition. One study reports clinker created with up to 35% MSWI fly ash contains up to 2% chloride, exceeding the 0.1% permitted in European criteria for cement (Bogush et al., 2020). Some kiln operations utilizing alternative raw materials will install an exhaust gas bypass to “bleed” some of the chloride and alkali-laden gasses to avoid this issue.

Excessive chloride content in concrete structures is commonly known to cause corrosion of steel reinforcement. Cement containing too much alkali is also prone to causing alkali-silica reaction in concrete containing reactive aggregates; this deleterious reaction leads to the premature failure of concrete structures. Researchers have also found that excess alkalis in a concrete system cause a porous microstructure and reductions in mechanical strength.

Multiple studies using MSWI ash as a cement kiln feed have noted a pre treatment requirement to avoid issues with chloride and alkalis (Mao et al., 2020; Diliberto et al., 2018; Yan et al., 2018). It is important to consider that pre-treatment of MSWI ash for an industrial scale cement manufacturing operation would require considerable capital investment and infrastructure, as well to manage large quantities of contaminated wash water.

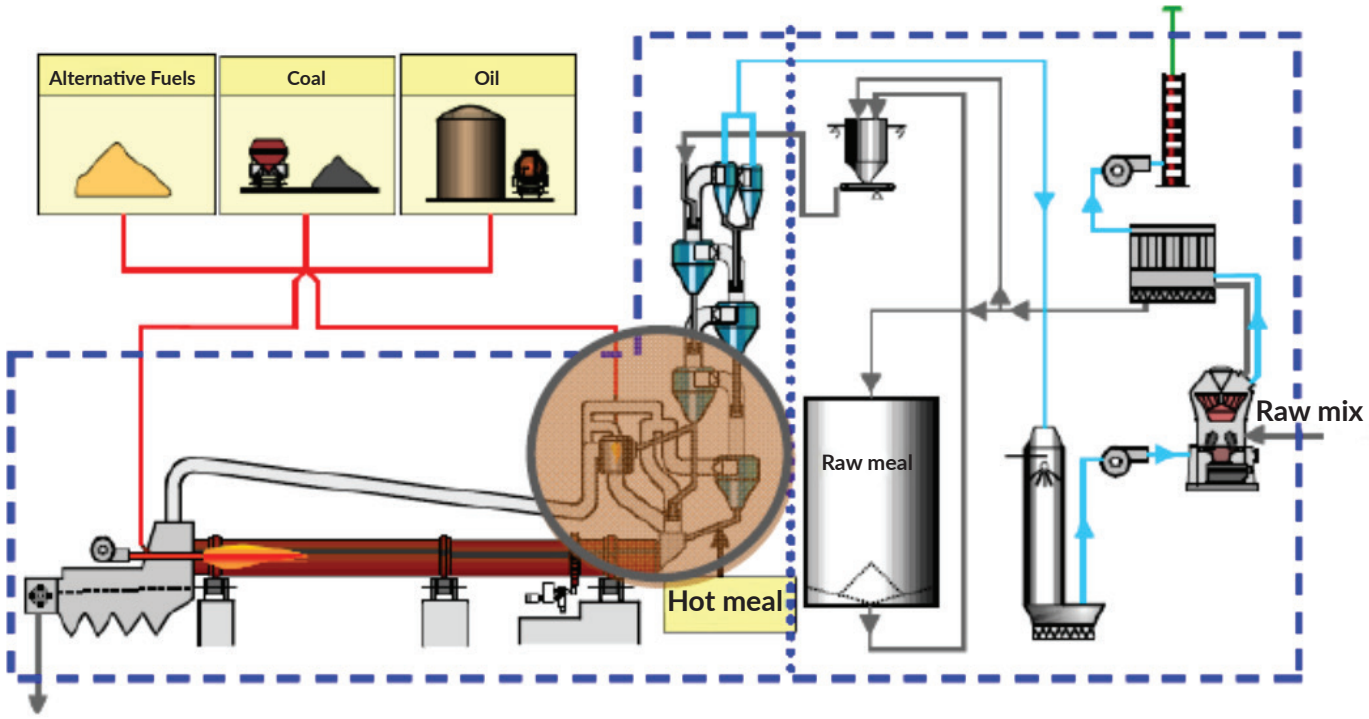


Figure 2. Chlorine circulation in the lower part of the preheater indicated by the circle

Only chloride that is "free" (in the pore solution of concrete) and unbound by clinker minerals can cause corrosion, and thus some researchers have noted that appropriate clinker compositions may fix chloride within the mineralogical composition of the cement to prevent chloride migration. Stable chloride containing minerals that may form during the clinkerization process, such as calcium-chloroaluminate or chlorellastadite, fix chloride within the lattice microstructure, a concept often used to manufacture high chloride containing eco-cements with low chloride leachability (Ashraf et al., 2019).

Similarly, raw materials containing high alkali content may be limited to mix designs that contain lower alkaline traditional raw materials and high sulfur fuels may be required to maintain an equilibrium between the alkalis and SO_3. Sulfur (though not a major input from MSWI ash) and alkali cycling in cement manufacturing operations is a highly complex system, but generally the stoichiometric balance between sulfur (mostly supplied by the fuel source) and alkalis in the raw material is controlled such that the volatility of the resulting alkali sulfates is low and will not accumulate in and circulate between the kiln and preheater tower.

4.2 Clinker composition

Viable compositions for ordinary cement are dominated by the minerals alite (tricalcium silicate, critical for early age strength development) and belite (dicalcium silicate, responsible for late age strength development), among other important phases such as aluminate and ferrite. Higher MSWI replacements in the raw meal created cements with more SiO_2 and belite, but lower CaO and alite. Studies has shown lower alite and higher belite proportions in cement with increasing addition of MSWI fly ash from 5% to 35%, and that clinker containing up to 6% MSWI fly ash might not have sufficient CaO content to form alite; washing the ash resulted in cements with higher alite content which may highlight the influence of trace elements on clinker formation.

2–6% bottom ash clinkers had relatively constant alite content but decreased with 8% addition which is attributed to trace elements present in the ash inhibiting phase formation. Clinkers created with up to 10% MSWI bottom ash and pelletized clinker with up to 15% bottom ash replacement required addition of extra calcium oxide; several studies reported that increasing MSWI ash addition contributed to this issue. Clavier et al. (2019) reported 10% higher alite in ash-amended cements containing 2.8% MSWI bottom ash.

4.3 Cement performance

Pan et al. (2008) found that fly ash (1.75%) and bottom ash (3.50%) additions to cement production were associated with an increase in setting time but no changes in compressive strength of the cement. Bogush et al. (2020) reported that up to

34% MSWI fly ash addition created cement pastes with comparable strength to a control at 28 days, and higher strength than a control at 6 months of curing; 35% replacement of unwashed fly ash created cement paste with poor strength development.

There is some research to suggest that creating eco-cement from 100% waste incineration residues is plausible from a physical performance perspective, if appropriate chemical supplements ($Ca(OH)_2$ and SiO_2) and CO_2 activation are provided to promote reactivity; authors report that these cements had comparable strength to ordinary portland cement (approximately 55 MPa compared to 58 MPa compressive strength at 28 days for ash-amended and control, respectively) (Ashraf et al., 2019).

Researchers have posited that compressive strength issues are a consequence of insufficient alite and calcium oxide formation in MSWI-ash amended clinkers, but higher alite concentrations in MSWI ash-amended cement have also been connected to faster setting times and lower late age compressive strength (Clavier et al., 2019). Higher late-age strength in ash-amended specimens compared to control has been attributed to increased proportions of belite (Bogush et al., 2020). Most studies have noted that performance related issues with MSWI ash-amended products are magnified with increasing addition of MSWI ash.

4.4 Leaching

Generally, available literature indicates that trace elements in MSWI ash are stabilized during cement manufacturing; stabilized refers to the "binding" of concerning elements in the structure of the clinker nodules during the clinkerization or cement product manufacturing process. Stabilization mechanisms may be physical or mineralogical and lead to retention in the clinker and minimal leaching of trace elements (Mao et al., 2020); cement kilns have utilized this phenomenon to act as treatment methods for hazardous MSWI ash and cement-based solidification is a common method for immobilizing heavy metals in waste products.

Wu et al., 2011 manufactured sulfoaluminate cement containing 30.89% MSWI fly ash as a raw ingredient and found that Toxicity Characteristic Leaching Procedure (TCLP) and deionized water extractions showed small amounts of Cu and Zn (deionized water) and Ni and Pb (TCLP) leaching; no heavy metals were detected in monolithic extractions (trace element mass release from a hardened concrete or mortar specimen suspended in deionized water) and Ni, Cu, and Cr were reported as stabilized in the clinkers.

Lam et al. (2011) noted similar TCLP extractions for clinkers containing 8% of MSWI fly ash, washed MSWI fly ash, or MSWI bottom ash; ash-amended clinkers had slightly higher Ba (1.86–3.84 ppm), Cr (2.40 ppm in 8% bottom ash mixes), Pb (3.412 ppm in 8% bottom ash mixes), and Tl (0.872–1.17 ppm) than the control specimen containing no ash (1.327 ppm Ba, 0.263 Cr, non-detect for Pb, 0.056 Tl), but reported values were below regulatory thresholds.

Washed fly ash mixes had lower Ba concentrations and Tl concentrations than unwashed fly ash mixes. Several other studies have noted minimal leaching for TCLP and TCLP-like extractions on MSWI ash-amended specimens (Mao et al., 2020), including in eco-cements made entirely from mixed MSWI ashes (Ashraf et al., 2019).

Clinker retention may reduce leachability, but total trace metal content, especially for elements such as Cd and Pb found in MSWI ash, may jeopardize end of life recycling of MSWI-ash amended concrete products (Lederer et al., 2017; Joseph et al., 2018). Special attention should thus be given to total trace element content in cements manufactured using MSWI ash.

Austrian regulations, for instance, limit heavy metal content of raw materials but allow up to 10% secondary raw material addition if the cement produced has total trace metal contents below regulatory limits. For instance, a MSWI fly ash is allowed if the cement produced from that material has less than 15 mg/kg of As and 200 mg/kg of Pb, with similarly set limits for other elements. Cd, Hg, Pb, and Zn concentrations have been found considerably higher due to MSWI ash incorporation into cement (Lederer et al., 2017). Cd and Pb contents in Austrian cements are expected to increase by 310% and 170% respectively due to widespread MSWI fly ash incorporation.

Jones et al. (2012) reported that As concentrations in coal fly ash, a common raw ingredient for cement, were as high as 58.2 mg/kg, while MSWI bottom ash As concentrations are reported as lower (27.5 mg/kg) (Clavier et al., 2019). This means that even though an intuitive thought may be that MSWI ash will cause elevated As concentrations in clinker, industry standard mix designs may already manufacture clinker with even higher.

Leaching mechanisms for major, minor and trace elements can be assessed by applying thermodynamic modelling to address the long-term behaviour (Engelsen et al., 2009). Furthermore, the sensitivity of the soil, groundwater, and surface water together with the transport pathways (in the vadose and saturated zone) determine the acceptable concentration level in the cement (Engelsen et al., 2012).

4.5 Volatilization

Quantitative data regarding air emissions from cement manufacturing using MSWI ash as a raw ingredient are seldom reported and represent a large gap in the literature. The research indicates that the presence of alkalis and chloride in MSWI ashes may act to volatilize many trace metals that tend to form volatile salts with these compounds.

In a study where MSWI fly ash samples were melted at temperatures of 1300–1500 ^{0}C, it was found that volatile metals such as Cd and Pb were evaporated and less volatile metals such as Cu and Cr were retained in the end product. Wu et al. (2011) noted in lab-synthesized clinkers containing 30% fly ash and heated at temperatures up to 1300 ^{0}C that K, Na, Cd, Zn, Pb, As, and Se all volatilized more than 80% of the original mass present in the fly ash while elements such as Cr, Cu, Ni, and Mn were considerably less volatile (less than 25%).

In a study where MSWI fly ash replaced 5–35% of raw materials and was heated up to 1450 ^{0}C, Al, Si, Ca, Mg, Fe, Ti, and Cr were all fully incorporated into the clinker, while volatilization of S, Cl, and Pb increased with increased addition of MSWI fly ash; washing the ash decreased the amount of volatilized S and Cl (Bogush et al., 2020).

Chloride availability strongly influences volatility, especially for trace metals that form chloride salts with low boiling points, such as Pb, Cd, and Zn. Water washing of MSWI fly ash, for instance, has been reported to decrease Pb volatility in the manufacture of ash-amended cement by up to 50% and eliminate Zn volatility, attributed to the influence of salts on melting behaviour (Bogush et al., 2020). Arsenic volatilization was strongly influenced by chloride content in raw meal, and As and Sb incorporation was enhanced by recirculation of cement kiln dust during the manufacturing process (Wang et al., 2018).

Dioxin and furan compounds are formed during the combustion process of MSWI and may be present in MSWI ash (Karstensen, 2008). These harmful organic compounds have been re-ported to volatilize at clinkerization temperatures; one study reported that 94% of poly-chlorinated dibenzo-p-dioxins and dibenzofurans present in a feedstock were eliminated at cement kiln temperatures (Liu et al., 2015).

Mercury cycling in cement kilns happens because of Hg occurring largely in the coal fly ash used as a raw material for cement production. This process, similar to chloride and alkali cycling in a cement kiln, can cause mercury enrichment and excessively high Hg emissions in cement kiln flue gas. Some cement operations mitigate this issue using “dust shuttling”, whereby mercury enriched dust is removed from the operation and blended in as an inorganic process addition to the cement (Wang et al., 2016).

Though no studies to our knowledge have reported Hg related issues with MSWI ash-amended clinker production, authors have reported total Hg in MSWI fly ashes are higher than coal fly ash, and that stack emissions of Hg associated with MSWI fly ash as a raw material are elevated for as little as 2% replacement of the raw mix (Yan et al., 2018). Furthermore, MSWI fly ash addition to cement production in Austria has been projected to increase Hg content by up to 90% (Lederer et al., 2017). Therefore, to avoid air emissions and enrichment issues associated with Hg when utilizing MSWI fly ash as a raw material, careful consideration should thus be given to the selection of supplementary raw materials and fuels that are low in Hg content.

4.6 Life cycle impacts

The benefits of waste usage in cement manufacture are generally well understood and research points to waste utilization as an effective means of increasing resource productivity and decreasing environmental impact associated with cement production (Viczek et al., 2020), but the use of MSWI ash as a cement kiln feed is an area for which there is comparatively few LCA studies.

The use of alternative raw materials such as MSWI ash may reduce the production of CO_2. The calcium composition in MSWI ashes is in the form of CaO, rather than $CaCO_3$, and thus the contribution of Ca to the clinker formation process does not require the calcination process responsible for CO_2 emissions. Krammart and Tangtermsirikul (2004) found that the use of 5–10% MSWI bottom ash as a raw material for cement production would save 25–49 kg of CO_2 per ton of clinker produced.

Saikia et al. (2007) report that all phases present in ordinary cement can be synthesized at lower temps

(1300 °C) for MSWI fly ash-amended cements. Special cements containing MSWI ash, like eco-cements, alinite cements, and sulfoaluminate cements, can also be created at considerably lower clinker temperatures of 1100–1200 °C (compared to approximately 1450 °C for traditional materials) (Ashraf et al., 2019). Other studies indicate that the trace element composition of MSWI ash (such as high concentrations of Zn) may lower clinkerization temperature (Ghouleh and Shao, 2018).

Huang and Chuieh (2015) found that using washed and chelated fly ash as a cement kiln feed has the lowest environmental impact compared to common disposal options (solidification and landfilling and reuse in bricks and steelmaking) for fly ash. Compared to traditional management methods (solidification and landfilling), beneficially using MSWI bottom ash as a 25% replacement for raw materials in clinker was the preferable recycling scenario with the lowest environmental burden and natural resource consumption; this option was also cheaper than other management options, but transport distances are a key factor in this determination (Margallo et al., 2014).

A separate study comparing different management scenarios found that bottom ash recycling in cement production had lower environmental impacts in all categories (abiotic depletion, acidification potential, eutrophication potential, freshwater aquatic ecotoxicity, global warming potential, human toxicity potential, photochemical ozone creation potential, and terrestrial ecotoxicity potential) except for atmospheric acidification potential and photochemical ozone creation potential (Margallo et al., 2013).

Similarly, Mao et al. (2020) found that solid waste sourced sulphoaluminate cements manufactured with 35% washed MSWI fly ash had lower life cycle impacts than traditional sulphoaluminate cements for all categories except water depletion and natural land transformation; the fly ash washing process was noted to consume a large amount of water.

4.7 Economic and practical feasibility of recycling MSWI residues

The economic feasibility of implementing a practical full-scale recycling practice with MSWI-residues in a cement plant will depend on many factors which has to be evaluated locally. Some important factors that have to be considered in detail, is the following

- Existing and current regulation and cement standards for the area of consideration do it allow adding alternative raw materials and what are the limitations and eventually the testing requirements?
- What are the volumes and the composition of the MSWI-residues produced in the area within a feasible transport distance transportation might constitute a considerable cost?
- What are the current disposal and treatment option practiced in the area, and the associated costs?
- What are the raw material chemistry and the cement manufacturing process (chlorine) in the local cement plant and what are the limiting factors for adding MSWI-residues and how much could be added?
- What is the experience in the cement plants in question, do they practice co-processing/ recycling, do they have logistics, storage and feeding possibilities?
- What kind of process would be most economic and chemical feasible for removing contaminants from the MSWI-residues in question – a broad spectre of technical options needs to be considered.
- How should a complete performance verification test be conducted and what will the cost be?

EXAMPLE OF WATER WASHING PRE TREATMENT OF MUNICIPAL SOLID WASTE INCINERATOR FLY ASH AND CO-PROCESSING IN A CEMENT KILN IN CHINA

Yan et al (2018) conducted full scale experiments with washing of MSWI ash and subsequent co-processing in a cement kiln in China.

In this study, toxic HMs, comprising 3 groups, namely volatile HMs (Hg), semi-volatile HMs (Pb, Cd, Tl, and As) and non-volatile HMs, and PCDD/Fs in the input (untreated MSWI-FA (FA), coal, and raw meal (RM)), intermediate (washed MSWI-FA (WFA), washing water, HM sludge, dried-washed MSWI-FA (DWFA), and salt), and output materials (clinker (CK), cement kiln dust (CKD) and flue gas (Flue)) produced during pre-treatment and co-processing in a cement kiln, were systematically measured. The results obtained in this study might provide important knowledge for the control and reduction of heavy metal and PCDD/Fs in cement kilns co-processing MSWI-FA.

Table 9. Composition of the MSWI Fly ash (FA), washed fly ash (WFA), and dried-washed fly ash (DWFA)- Yan et al, 2018

Compositions	FA	WFA	DWFA	Salt
Moisture (%)	6.63	37.77	0.72	0.66
LOI (%)	23.00	57.63	23.45	5.84
Ash (%)	79.12	42.34	76.99	95.68
Cl (%)	14.47	0.50	1.04	59.91
Na (%)	2.46	0.32	0.82	33.58
K (%)	3.32	0.21	0.5	0.37
SO_3 (%)	4.64	1.80	3.92	0.11
Al_2O_3 (%)	3.64	2.36	3.88	–
Fe_2O_3 (%)	1.19	0.89	1.2	–
MgO (%)	3.06	1.98	3.19	–
CaO (%)	34.87	29.25	48.84	–
SiO_2 (%)	9.82	6.60	11.27	–

'-' means no detectable; LOI and Ash are given in dry-basis, and the other variables are given in wet basis.

MSWI-FA from a municipal solid waste incinerator with grate-based technology and a daily disposal capacity of 1000 tonnes was used in this field study. The major useful components of the original fly ash (FA), which accounted for 49.52% of the total, were CaO, SiO_2, Fe_2O_3, and Al_2O_3, while Cl, Na, and K accounted for 20.32% of the total (see table 9). After water washing and drying process, the major useful components of the dried washed fly ash (DWFA) accounted for 65.19%, and the detrimental components accounted for 2.36% of the total content.

The system consists of a pre-treatment facility and a pre-heating–pre-calcining cement kiln. The plant is equipped with state-of-the-art air pollution control devices, and has a daily clinker production capacity of 2700 t. The pre-treatment is designed to remove the NaCl and KCl dissolved salts without extracting the dissolvable HMs contained in the MSWI-FA.

Table 10. Operating conditions during the pre-treatment and in the cement kiln system

		Test 0	Test 1	Test 2
Input streams	RM consumption (t/h)	178.8	175.5	171
	Coal consumption (t/h)	14.8	14.3	13.6
	FA feeding rate (t/h)	0	4.8	4.8
Intermediate streams	DWFA feeding rate (t/h)	0	3.1	1.7
	CKD production rate (t/h)	10.9	10.9	10.5
Output streams	CK production rate (t/h)	113.5	113.8	110.3
	Salt production rate (t/h)	0	1.3	1.2
	Flue gas volume- at stack after Dryer (NM3/hr)	0	26 000*	66 850**
	Flue gas volume- at Kiln back-end stack (NM3/hr)	270 500	277 500	310 000

**The gas for heating was generated by a furnace burning diesel*
***The gas was introduced from the clinker cooler at kiln inlet*

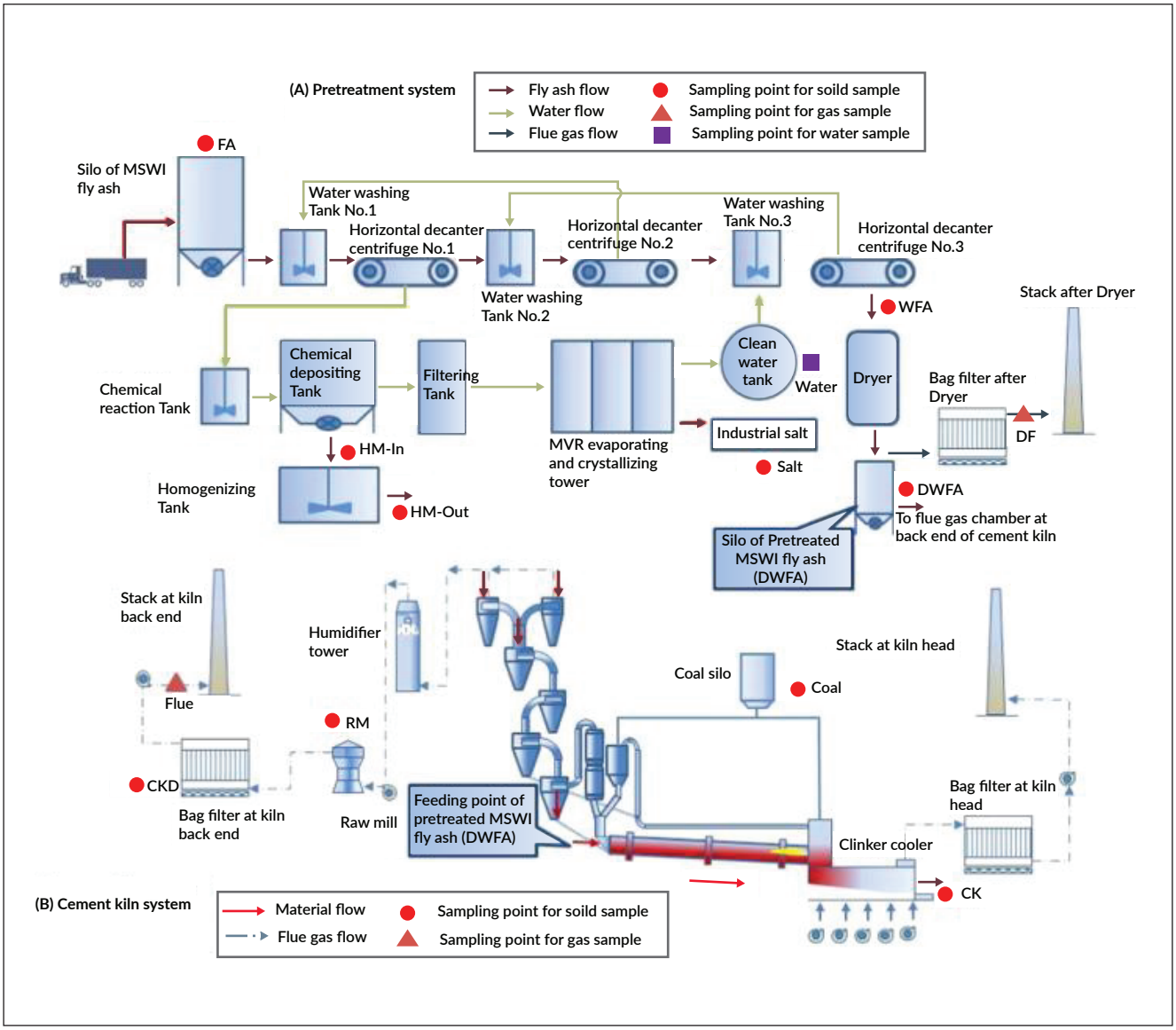


Figure 3. Sampling points in Pre-treatment process and cement kiln system (Yan et al, 2018)

The pre-treatment process involves three rounds of washing-dewatering to maximize the removal of soluble salts from the FA. After the washing process, the HMs dissolved in washing water are precipitated in the chemical depositing tank, and the clean salt solution on the surface goes through the mechanical vapor recompression (MVR) tower, in which the industrial salt is crystalized, and the condensate water is recirculated into the washing tank. The deposited HM sludge is pumped into the 3rd washing tank, and then join with washed FA in the 3rd mechanical drying process to obtain WFA. The WFA is further dried by hot air from the clinker cooler to form DWFA. The DWFA is stored in a silo until it is fed into the flue gas chamber at the inlet of the rotary kiln.

The testing comprised one blank test (test 0) and two tests (tests 1 and 2) under co-processing conditions. Test 0 was conducted on the first day with no DWFA co-processing to determine the baseline conditions. Test 1 was conducted on the second day when the water washing pre-treatment facility was in operation, and DWFA was fed into the flue gas chamber at the kiln inlet at a rate of 3.1 t/h. Test 2 was conducted at a lower DWFA feeding rate of 1.7 t/h. Operating parameters for the pre-treatment and cement kiln line are provided in Table 10.

To measure the transfer of HMs and PCDD/Fs in the pre-treatment process, samples of the FA, WFA, HM sludge in the inlet and outlet of the HM homogenizing tank (HM-in, HM-out), clean water (water), crystallized salt (salt), and drying flue (DF) were analysed for HMs and PCDD/Fs. For all tests, samples of the raw meal (RM), coal, cement clinker (CK), cement kiln dust (CKD), and flue gas from the

stack at the kiln end (flue) were analysed or the PCDD/Fs and HMs as Hg, Tl, Cd, Pb, As, Be, Cr, Sb, Cu, Co, Mn, Ni, V, Zn, Mo, Ba. The sampling points and major test parameters are shown in Figure 3.

Distribution of heavy metals and PCDD/Fs in the water washing and co-processing of MSWI fly ash in cement kiln were studied. Co-processing of DWFA did not influence on the release of PCDD/Fs; baseline and co-processing values ranged from 0.022 to 0.039 ng-TEQ/N m3, and from 0.01 to 0.031 ng-TEQ/N m3, respectively. The destruction efficiency for PCDD/Fs in MSWI fly was 82.6%. Stack emission of Hg seems correlated with feeding rate of MSWI fly ash, further verification study shall be carried out. Co-processing of DWFA had no observable impact on heavy metal content of clinker except for Cd, Pb and Sb (which came from DWFA). This technology seems to be an environmentally sound option for the disposal of MSWI-FA.

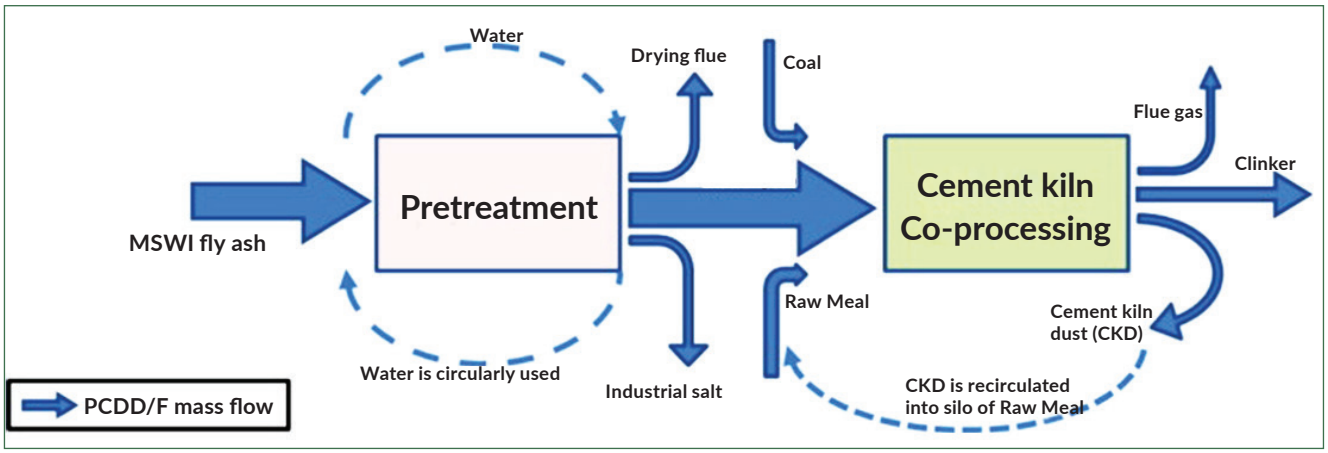


Figure 4. PCDD/F mass balance during pre-treatment and co-processing in the cement kiln (Yan et al, 2018)

CONCLUSION

Ever increasing waste generation coupled with a move towards effective waste management strategies posits MSWI as a preferred technology for waste volume reduction and energy production. The residual ash leftover from the incineration process is a potential substitute for the raw materials traditionally used in cement production.

Several studies have been published on the topic of MSWI ash incorporation into cement production, but a critical gap in the literature is the lack of a comprehensive overview of the published science regarding this practice. Existing studies suggest viable addition of untreated MSWI ash addition is limited to below 10%, but control of harmful substances may increase viable addition to around 30–50%, with some exceptions. The literature points to a variety of implications of this recycling process

- Generally, MSWI ash has the Ca, Si, Fe, and Al necessary for cement production, but may be severely limited as a raw material substitute due to its high chloride and alkali content that leads to deleterious reactions within the production process as well as the final product.
- Pre-treatment of the ash is recommended (or required) before it is used as a cement kiln feed; this is often a water-washing process.
- MSWI ash contains several trace elements that are not found in traditional kiln feed materials, and these trace elements have documented impacts on cement performance.
- Using MSWI ash as a raw material generally creates the necessary clinker mineralogy without issue, with some parameters differing slightly.
- Impacts on cement performance are highly variable, with a negative trend associated with increasing ash addition.
- Trace metals are generally stabilized in clinker, but total trace element content may be an issue for end of life recycling opportunities and could impact clinker phase formation.
- Trace elements have variable volatility dependent on kiln operating conditions and the ability to form volatile salts with low boiling points.
- CO_2 emissions are mitigated by the introduction of MSWI ash, and life cycle assessments point to MSWI ash kiln feed as an environmentally favourable and cost-effective management strategy.

Further research is needed on the long term sustainability and end of life recycling applications for concrete structures made with ash amended cement. Cost effective, industrial scale pre treatment options, coupled with a life cycle assessment, warrant some investigation, as most mentions of ash-washing are performed on a laboratory scale; industrial scale cement manufacturing experiments using MSWI ash are comparatively unavailable. Further research should also be performed on front-end processing techniques, such as combustion additives, to control chloride and trace element concentrations to make MSWI ash more conducive to reuse. In addition to those discussed in this paper, there are practical limitations that should be considered when using MSWI ash as kiln feed, such as physical material conveyance mechanisms, large metallic particles, moisture, and the inherent heterogeneity of the material; a critical literature gap exists in addressing these issues.

Waste recycling continues to evolve, and cement manufacture is one of the most promising waste recycling applications. MSWI ash reuse is a challenging and multifaceted problem for which successful implementation has considerable upside.

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OCEAN PLASTIC TURNED INTO AN OPPORTUNITY IN CIRCULAR ECONOMY

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ABSTRACT

The regional project Ocean Plastic Turned into an Opportunity in Circular Economy – OPTOCE - will investigate how the involvement of private Energy Intensive Industries, like cement manufacturing, can increase the treatment capacity for Non-recyclable Plastic Wastes in China, India, Myanmar, Thailand and Vietnam. The "OPTOCE countries" have currently the highest plastic consumption in the world, producing an estimated 176000 tonnes of plastic waste per day, or around 64 million tonnes annually; large parts are dumped. On the other hand, OPTOCE countries produce around 75% of the world's cement, steel and electric power, in tens of thousands of plants using huge amounts of coal and contribute with much more than 30% of the world's CO2 emissions. Replacing parts of this coal with non-recyclable waste is called Co-processing and represents a win-win concept – saving potentially large amounts coal, reducing the release of plastics to the ocean and indirectly reducing greenhouse gas emissions. Pilot Demonstrations replacing coal with non-recyclable plastic wastes will be carried out in local plants in all the countries in order to investigate and showcase the feasibility, to prove the concept under various local conditions and to uncover limitations of the practice. Lessons learned from all the Pilot demonstrations will be shared in National workshops and in the annual Regional multi-stakeholder forum enabling awareness raising, south-south capacity building and possible replication of success stories.

INTRODUCTION

This project is part of the Norwegian Development Programme to Combat Marine Litter and Microplastics launched in 2018. The programme is intended to contribute to Sustainable Development Goal (SDG) 14.1 which states that by 2025, the world should prevent and significantly reduce marine pollution of all kinds (Regjeringen, 2020).

THE PROBLEM

An estimated amount of 13 million tonnes of plastic leak into our oceans every year, harming biodiversity, economies and, potentially, our own health (The State of Plastics, 2018). If nothing is done, the amount is expected to triple by 2040 (Breaking the Plastic Wave, 2020).

REASONS OF THE PROBLEMS

International action is key to tackle the most significant sources of plastics litter in the oceans, i.e., insufficient waste management in developing countries and emerging economies, especially connected to major world river basins, dumpsites/ landfills, and industrial hotspots.

It is estimated that more than 80% of marine debris comes from land-based sources and Asian countries are among the top contributors to marine litter and microplastics (Jambeck et al., 2015).

OBJECTIVE OF OPTOCE

The regional project Ocean Plastic Turned into an Opportunity in Circular Economy – OPTOCE will investigate how the involvement of Energy Intensive Industries, like cement manufacturing, can increase the treatment capacity for Non Recyclable Plastic Wastes (NRPW) in China, India, Myanmar, Thailand, and Vietnam and thereby contribute to reduce the release of plastics to the Sea.

These countries are producing an estimated 176000 tonnes of plastic waste every day (64 million tonnes/ year) and have some of the highest releases of Plastics to the Sea. Relatively small quantities are handled in an environmentally sound way.

But they also have the highest production of cement, steel, and electric power, using huge amounts of coal and contributing with large amounts of the world's greenhouse gas emissions.

Replacing parts of this coal with Non-Recyclable Plastic Wastes may represent a win-win opportunity preventing the plastic from ending up in the ocean, reducing the need for large amounts of fossil coal and indirectly reducing greenhouse gas emissions by avoiding building new incinerators or landfills.

What is considered waste in one sector becomes a resource in another. This concept represents circular economy in practice and incorporates waste treatment with existing industrial production, which is also preferred to Incineration and Landfilling in the internationally accepted Waste Management Hierarchy.

ADDITIONAL OBJECTIVES

Additional objectives and synergies of the OPTOCE-project will be the following:

- Reduce marine debris from land-based activities.
- Enhance multi stakeholder coordination and partnerships.
- Promote private sector engagement.
- Strengthen research to support science-based policy and decision making.

WHERE DOES ALL THE PLASTIC GO?

An estimated 9.3 billion tons of virgin plastics was produced globally up to 2019.

Out of this, 6.3 billion tonnes have already ended up being plastic waste; of this, only 9% was recycled, 12% incinerated and 79% dumped.

If current production and waste management trends continue, roughly 12 billion tonnes of plastic waste will be in landfills or in the natural environment by 2050 (Geyer et al. 2017).

WHAT ABOUT RECYCLING?

Recycling is the preferred option but not all plastic waste is suitable for recycling. From a technical aspect, it is challenging to recycle plastic that consists of several types of polymers, as you need to separate them.

From an economic perspective, the recycling sector suffers greatly from low oil prices. The main component of plastic is oil; hence the low oil prices lead to low prices of virgin plastic.

Studies from Asia post Covid has shown that the recycling sector has seen a 50 percent drop in demand and a 20 percent drop in prices (Safeguarding the plastic value chain, 2020). Studies has also shown that most of the plastic that ends up in the oceans is low-quality plastic that is hard to recycle (Stemming the Tide, 2015).

INCINERATION IS BECOMING INCREASINGLY POPULAR

Energy recovery from wastes and plastics in Municipal Solid Waste Incinerators with Waste to Energy (WtE) normally involves generation of electricity in steam turbines, but the conversion efficiency to electricity is poor and will not recover the construction costs (Mutz et al., 2017).

WtE-plants are expensive to build and operate, they represent an additional emission source and produce large amounts of residues (fly ash, bottom ash etc.) that need to be treated/landfilled.

Incineration of wet wastes in the rainy season is another challenge, which causes difficult burning conditions and results in elevated emissions.

WHAT ABOUT INTEGRATED OPTIONS?

Countries with cement industry may to a certain degree forego building expensive WtE-incinerators.

Cement kilns are already in operation and may increase the waste treatment capacity significantly if integrated into the waste management strategy. They are usually cost efficient and do not produce any residues that needs disposal.

POSSIBLE TO USE CEMENT KILNS?

Cement kilns have proven to be effective means of recovering value from waste materials and co-processing in cement kilns is now an integral component in the spectrum of viable options for treating several waste categories, practised in developed countries for the last four decades.

The two cement plants we have in Norway, replace today around 75% of its coal with waste, including plastic, and this has been the only treatment option for disposal of organic hazardous wastes in Norway for the last 30 years – a dedicated incinerator for hazardous wastes was never built.

This practice has been cost-effective, resource-efficient, and environmentally sound compared to incineration. The energy utilization efficiency is much better than in an Incinerator with WtE – and no residues are produced, compared to around 30% in a WtE.

A preheater cement kiln possesses many inherent features which makes it ideal for waste treatment; high temperatures, long residence time, surplus oxygen during and after combustion, good turbulence and mixing conditions, thermal inertia, counter currently dry scrubbing of the exit gas by alkaline raw material (neutralises all acid gases like hydrogen chloride), fixation of the traces of heavy metals in the clinker structure, no production of by-products and efficient recovery of energy and raw material components in the waste.

A WIN-WIN OPPORTUNITY?

As not all plastic waste can be recycled, we need to find additional solutions to avoid that the plastic strangles us and our planet!

The OPTOCE project is expected to uncover an untapped potential to remove, treat and beneficially utilise non-recyclable plastic wastes by the private sector.

Cement production in five countries needs huge amounts of coal and emits the bulk of the CO_2.

Research has shown that co-processing mixed plastic waste can potentially save as much as -1200 kg CO_2-equivalents per ton waste treated, when accounting for avoided emissions from provision and usage of coal (Astrup, Fruergaard and Christensen, 2009).

The world likely needs to halve greenhouse gas emissions within 2030 to prevent dangerous levels of global warming.

Global carbon dioxide emissions from fossil fuels will rise for the third straight year in 2019, ticking up an estimated 0.6% to a record 37 billion metric tons, according to the closely watched annual report from the Global Carbon Project.

Slight declines in the US and European Union were offset by projected increases in China, India, and other parts of the world, where economic growth is fuelling rising energy demands.

WE WANT TO SHOWCASE THE PLASTIC REMOVAL POTENTIAL THROUGH LOCAL PROOF OF CONCEPT

OPTOCE will carry out Pilot Demonstrations in local cement plants to investigate and document the feasibility, to prove the concept under various local conditions and to uncover potential limitations of the practice.

We have entered into agreements with central and local authorities, and with leading Waste management companies and Cement industry in all the OPTOCE-countries; we have agreements with universities and NGOs and will cooperate with international organisations like the Asian Development Bank, UNDP, UNEP, UNIDO etc.

The Pilot Demonstrations will document the performance, i.e., describe the co-processing capacity for Non-Recyclable Plastic Wastes, the environmental performance, cost and energy efficiency, and the need for pre treatment and preparation of the Non-Recyclable Plastic Wastes prior to co-processing, limitations in types and volumes of Plastic Wastes that can be co-processed etc.

The overall aim is to provide a quantitative and qualitative assessment of how the involvement of private industry can improve plastic waste management and prevent marine litter reaching the ocean in each country.

PILOTS IN THAILAND

Some Waste landfills and dumpsites in Thailand contain up to 42% plastic. There are about 2500 of these scattered around the country, which together will contain up to 190 million tonnes of accumulated plastic waste if representative (Sharma et al., 2020).

We have entered into an agreement with the second largest cement producer in the country, which extract plastic waste from dumpsites and use it as a coal substitute.

There is a great interest in utilizing resources and cleaning up landfills and dumpsites in Asia they occupy large areas of valuable land and contributes with local and global pollution. We also intend to investigate and document the environmental implications and benefits of landfill mining together with the Asian Institute of Technology. The pilot demonstrations will be conducted in 2022.

PILOTS IN CHINA

The Yangtze River in China is draining waste materials from hundreds of millions of people which leads to turbine problems in a large hydropower dam located in Hubei Province.

We entered into an agreement with Huaxin cement in the town of Zigui, located upstream of the dam, to document the possibility of collecting and co-processing floating materials from the river, including large quantities of plastic.

A Pilot Demonstration was conducted in Yangtze River with Huaxin Cement in December 2020. The result – as much as 20 000 tons of plastic waste can yearly be prevented from potentially reaching our oceans.

PILOTS IN VIETNAM

Asian paper mills use mostly used paper and cardboard imported from Europe and the Middle East in their production of new paper. Used paper with laminated plastic is a major waste problem throughout Asia.

We entered into an agreement with Vietnam's largest Paper producer, which is located at the Mekong River and produces large quantities of Non-Recyclable Plastic Waste, such as pieces of tape, laminated plastic pieces and stickers

In December 2021 we conducted a pilot demonstration in the INSEE cement plant located in Hon Chong, Kien Giang province, to assess the suitability and feasibility of co-processing such wastes.

In Vietnam we will also cooperate with UNDP in their project "Scaling Up a Socialised Model of Domestic Waste and Plastics Management in Five Cities". The OPTOCE project will collect the non-recyclable fraction of plastic waste and use it as fuel in the INSEE cement plant in Hon Chong.

PILOTS IN MYANMAR

Myanmar has currently no treatment options for non-recyclable plastic wastes. Together with environmental authorities MONREC-ECD and Myanmar's largest waste management company, we will initiate demonstration experiments in cement factories outside Mandalay and Yangon and assess whether plastic waste can be handled in an environmentally sound manner by involving the industry.

Due to the military coup in February 2021, the project activities in Myanmar have been put on hold. SINTEF is, however, discussing with the private companies operating in Myanmar, on possible collaboration on building capacity of the Myanmar cement industry and conducting a pilot demonstration in a suitable cement plant, without active involvement of the government authorities.

PILOTS IN INDIA

OPTOCE activities in India is part of the India-Norway Marine Pollution Initiative, which has four other projects, managed by Indian and Norwegian partners, and coordinated by UN Environment. The programme steering committee of the initiative comprises of members from Ministry of Environment, Forests and Climate Change, Central Pollution Control Board, NITI Ayog, Ministry of Earth Sciences, Ministry of Housing and Urban Affairs, UN Environment, TERI, and the Royal Norwegian Embassy. SINTEF regularly presents on the progress of the OPTOCE project in the steering committee meetings.

Ghazipur pilot project which was principally approved by Principal Scientific Advisor's (PSA) Office of GOI was cancelled in Q2 2021 because of Covid-19 related & other delays. The pilot project aimed to

remove and segregate 75 000 tons of landfilled waste and showcase integrated waste management solutions. SINTEF was expected to carry out a scientific evaluation/ comparison of three different treatment options for the non-recyclable plastic fraction: 1) Cement kiln, 2) WtE and 3) Thermal power plant.

For additional pilots, SINTEF has signed contracts with major cement companies, consultants, and multilateral organisations, to demonstrate the feasibility of handling post- consumer plastic wastes and other NRPW from major cities in Uttar Pradesh and Goa. There have been considerable delays in finalising pilots because of Covid-19 related travel and other restrictions, resulting in reduced activity locally. With easing of travel restrictions, activities will gather pace in 2022-23.

Two Master Theses were completed and submitted in July 2021 as a deliverable under the OPTOCE project's academic collaboration with leading universities in the country. Three Master theses will be funded by the project in academic year 2021-22.

SINTEF has co-authored the book "Sustainable Management of Wastes through Co-processing" together with two Indian colleagues. The book was published in November 2021 by Springer, Singapore. This is the world's first comprehensive book that deals with different aspects of co-processing.

SINTEF has been sponsoring and conducting several awareness workshops and specials sessions where topics such as NRPW management options, EU's green deal and the OPTOCE project, are presented.

ACADEMIC COLLABORATION

The OPTOCE project, a part of the Norwegian Development Programme to Combat Marine Litter and Microplastics, has launched an Academic Collaboration in our partner countries.

The objective of the Academic Collaboration is to build competence on treatment options for Non-Recyclable Plastic Wastes (NRPW) and provide better knowledge about the NRPW situation in the country and the possibility to involve local energy intensive industry to solve waste problems. Parallel MSc-thesis research will be carried out in our partner countries.

The OPTOCE project will generally contribute to support all the objectives of the Bangkok Declaration, while this Academic collaboration aims to build capacity, to strengthen research capacity and to support science-based policy and decision making.

Some of the topics of the finished and on going studies are

- Non recyclable plastic waste (NRPW) generated in cities and municipalities: how much NRPW is generated, how does the informal waste collectors assess recyclable versus non-recyclable and how is the NRPW disposed of.
- NRPW in dumpsites/landfills: how much NRPW and which kinds of NRPW are accumulated in dumpsites, and how much/how is it released to nearby waterways/groundwater.
- NRPW in landfill/dumpsite mining: how can landfill mining contribute to mitigate the leakage of plastic waste to the ocean, how can quality fuel be produced from the landfill NRPW, and what can be done with the rejects.NRPW in rivers: how can floating materials in rivers, including NRPW, be removed from the rivers and treated in an environmentally sound way.

MARINE PLASTIC ABATEMENT

The Asian Institute of Technology in Thailand has launched the first postgraduate program on marine plastic litter in the Asia, called Marine Plastic Abatement (MPA)[1].
This programme is supported by the Japanese Government and aims to fund one year MSc-scholarships for many students.

OPTOCE is involved in the development of the course curriculum, in teaching and in relevant research and student follow up[2].

CAPACITY BUILDING

Lessons learned from OPTOCE pilot demonstrations and from the academic collaboration will be shared through a regional multi-stakeholder forum, enabling awareness raising, capacity building and replication across the continent. The first forum is planned organised in Bangkok 27-28 October 2022.

The aim is to share and discuss experiences, practical applications, research and recent findings and information about current treatment practice for non-recyclable plastic wastes.

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CONCLUSION

Opportunities and challenges linked to plastic waste are increasingly global and addressing them will significantly contribute to achieving the 2030 Sustainable Development Goals. Establishing sound plastic waste management systems in these emerging economies in Asia, is essential to keep plastics out of the sea. There is currently a low rate of recycling and reuse of plastics waste with most going to open dumps, landfills or incinerators. The non-recyclable plastic waste represents the largest share of marine litter which could be cost-efficiently used as alternative fuels in the local energy intensive industries, such as the cement industry. Pilot Demonstrations, under the OPTOCE project, will investigate and showcase the feasibility, to prove the concept under various local conditions and to uncover limitations of the practice.

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