Ministry of Environment and Forestry
Republic of Indonesia

Ministry of Environment
of Denmark
Environmental
Protection Agency

Management of FABA from waste incineration

DanWS-ID	2021-126
Client:	Miljøstyrelsen (v. Jan Møller Hansen)
Author(s):	Jiri Hyks
QA:	Ole Hjelmar
Version:	Final 1.0
Date:	10-12-2021

- This page is intentionally blank -

List of contents

List of annexes:

Executive summary

Background

Indonesia, the world's fourth-largest country with a population of 268 million people, has in recent years experienced a fast-growing economy of 5-6% annually. As a consequence of economic growth, a growing middle-class, and changing consumer patterns, the amounts of municipality waste are also increasing, in particular in the large urban areas but also in rural areas.

As a consequence of insufficient waste collection and treatment, an estimated 1.29 million tons of waste ends up in the ocean negatively affecting the marine and coastal environment as well as the fishery and tourist industries. About 80% of the marine debris is estimated to come from land-based sources through waterways and from coastal cities. To improve the waste management situation, the Government of Indonesia has embarked on a 12 City Programme that includes a plan to construct 12 waste-to-energy (incineration) power plants in larger cities across the country.

Fly Ash and Bottom Ash (FABA) are by-products of waste incineration, and safe and secure handling of FABA is a requirement for any modern incineration plant to minimize negative environmental, hazardous, or unhealthy impacts on the environment and humans. On this background, the Ministry of Environment and Forestry (KLHK) has issued a new Minister Regulation (Permen LHK Nomor 26 Tahun 2020) that aims to regulate the management of FABA as by-products from waste incineration plants in Indonesia.

Indonesia and Denmark have since 2018 worked as partners in a Strategic Sector Cooperation (SSC) within the circular economy and waste management. The SSC Programme focuses on the circular economy, extended producer responsibility, waste management, including waste banks and waste data management, and other related issues. Waste incineration is one energy-recovery option, among others, which the Government of Indonesia is pursuing to improve the management of large and increasing amounts of municipal waste in larger cities. Although waste incineration is not a focus theme for the SSC Programme, KLHK has requested advice from Danish EPA (DEPA) on issues related to FABA from waste incineration since Denmark has many years of experience in operating large-scale waste incineration plants as well as managing the incineration residues in an environmentally sound matter.

On the 3rd-5th November 2020, a webinar on FABA was held with the participation of app. 15 technical and legal staff from the Directorate General of Solid Waste, Hazardous Waste, and Hazardous Substances Management in KLHK as well as DEPA and the Danish Embassy. Presentations were made by experts from Babcock & Wilcox Vølund, Rambøll, Haldor Topsøe, Danish Waste Solutions (DanWS), and DEPA on selected topics related to legislation, classification, technical design, treatment processes and post-handling, flue gas cleaning, monitoring, and other issues.

A follow-up meeting was held on 26th November 2020 with the participation of KLHK, DEPA, and the Danish Embassy. Based on the request from KLHK, it has been agreed that DEPA will provide KLHK with expert advice on issues related to the handling of FABA.

Objectives of the study

The main objective of this assignment, named "Strategic and Practical Advice on Fly Ash & Bottom Ash from Incineration of Waste" (in Danish Strategisk og teknisk rådgivning på flyve- og bundaske i affaldsforbrænding, Indonesien) was to provide strategic and technical advice to KLHK, and if necessary other Indonesian authorities, on legislative, organizational and technical issues related to management of FABA from waste incineration. More specifically, the assignment focused on:

- Providing an updated overview of management options for FABA applicable worldwide;
- Selection of the most appropriate management solutions for Indonesia considering both the pre-selected methods specified in the FABA Regulation (Permen LHK Nomor 26 Tahun 2020) and expected flue gas cleaning technology to be applied by the newly constructed incineration plants;
- A detailed description of the management of BA in unbound applications/road construction; guidance on sampling, analysis, data evaluation, and data management;
- The applicability of different leaching test methods for the evaluation of environmental impacts from different utilization scenarios.

Organization of the study

The work was carried out by Jiri Hyks (DanWS, project manager) with inputs from Ole Hjelmar (DanWS). To avoid an overly technical description of some parts of the management system (e.g. different treatment methods, leaching characterization, sampling), this report is divided into six thematic chapters and relies on the use of in total twelve annexes containing supplementary information, drawings, and data tables. The work in progress was discussed with representatives of KLHK and DEPA and finally presented to various stakeholders on a ZOOM-webinar, held on the 5th November 2021.

Main outcomes of the study

The starting point of this report is the current situation in Indonesia, where new legislation concerning the management of FABA from waste incineration has been passed in 2020 (Permen LHK Nomor 26 Tahun 2020). Most importantly, the new regulation included a list of preferred treatment methods for both BA and FA and a tabulated overview of limit values to be complied with by the treated FA. It should be noted that similar limit values were not set for BA.

Based on knowledge of the different management options available at full-scale (discussed in detail in Annex 2) and taking into consideration their overall environmental performance and suitability (Chapter 4.1, 4.2, and Annex 7), chelate treatment followed by landfilling of stabilized FA/APC residues was suggested by the consultant as the preferred management options for FA/APC residues in Indonesia. Where available, this management option might be supplemented by water-washing followed by the utilization of washed FA/APC residues in cement manufacturing. Implementation of the chelate treatment is in agreement with the currently proposed monitoring system which is based on the US EPA´s Toxicity Characteristic Leaching Procedure (TCLP) while for the washing followed by the utilization in cement manufacturing no environmental testing is necessary.

It is noted by the consultant that although the methodology behind setting up the TCLP compliance limit values in the current version of the legislation is unclear and considering the limitations of the TCLP (cf. Chapter 3.2) to accurately represent different disposal conditions (especially those where decomposing garbage is absent), using TCLP in Indonesian conditions might be sufficient to simulate plausible worst-case leaching conditions. At the same time, to address or to estimate the leaching behavior of both untreated and treated BA, FA, and/or APC residues in other than landfill- or disposal scenarios, other tests than TCLP were suggested in Chapter 3.2 to be used and development of different sets of limit values were suggested.

At least three management options were listed for BA under the new legislation while several other options and treatment principles were discussed in Annex 8. Most importantly, it was noted by the consultants that none of these options can be directly implemented for *untreated* BA since there isn´t any management option available for BA worldwide that would be feasible for untreated BA (except for plain landfilling). Regardless of the intended management option, basic mechanical treatment including removal of metals (ferrous, non-ferrous), crushing of oversize particles, removal of unburnt organic matter, and ageing need to be applied to the BA. In addition, removal of soluble salts may be required or at least preferable if the intended management scenario includes utilization in cement manufacturing or as filler in asphalt applications. Based on several decades of experience from many European countries (cf. Annex 10 and Annex 11), it was suggested to use the most robust BA management system consisting of removal of metals, ageing, and utilization of the bulks of BA as unbound aggregates in the subbase of road constructions (i.e. as a substitute for natural gravel). Currently, this option is considered the most feasible in terms of complexity (medium), costs (low), and environmental benefits (high). As indicated in the previous paragraph, implementation of this option in Indonesia would require the development of a set of dedicated leaching limit values (LV) which the BA must comply with before being utilized. This is depicted in Figure 0.1 which illustrates the simplified schematics of the suggested future management of FABA in Indonesia.

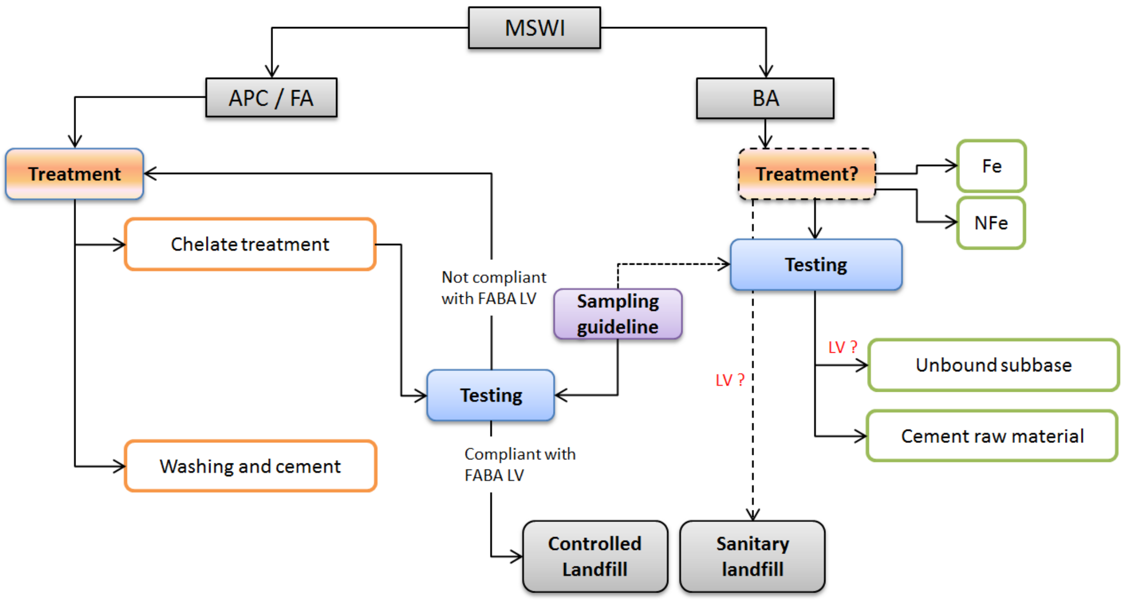

Figure 0.1 Simplified schematics of the suggested FABA management in Indonesia

Finally, for educational purposes of both technical and non-technical staff, Annex 4 includes a basic overview of the sampling techniques and important considerations related to sampling. This text is not intended for specialists in the field of sampling; its purpose is to help the staff/management of municipal solid waste incineration plants as well as other stakeholders to understand the practicalities of representative sampling and the most important factors affecting the results of the sampling. Likewise, in Chapter 6 an outline of the monitoring and evaluation system is given regarding test methods, instrumental methods, monitored parameters as well as suggestions for a manageable data storage and treatment system.

- This page is intentionally blank –

1 Introduction to Municipal Solid Waste Incineration residues

1.1 Municipal solid waste incineration residues

Although municipal solid waste incineration (MSWI) reduces the volume of the waste by 90% and the weight by 70-80%, incineration creates various types of solid residues some of which arise directly from the incineration process while others arise from the flue gas cleaning (FGC) system (Table 1.1).

Table 1.1Main types of residues and their quantities arising from the MSWI plants [1].

Origin	Material	Description	Typical amounts per tonne waste
Incineration process	Bottom ash	Bottom ash is the solid residue removed from the combustion chamber after the waste has been incinerated	150-350 kg including Fe/NFe
	Siftings	Siftings (or riddlings) are particles that have fallen through the grate during incineration. In some cases, they are fed again to the furnace.	
	Boiler ash	Boiler ash is the part of the fly ash that is removed from the boiler; it is often treated together with the fly ash. In some countries (the UK and the Netherlands for example), it may be treated together with the bottom ash.	2-10 kg
	Fly ash	Fly ash comprises the particles from the combustion chamber or formed within the flue-gas stream that are transported in the flue-gas	15-40 kg
FGC system	Flue gas cleaning (FGC) residues	FGC residues, sometimes also referred to as air-pollution-control (APC) residues, are a mixture of the pollutants originally present in the flue-gas and the substances that are used to remove those pollutants.	20-50 kg in case of a semi-dry scrubber; 15-60 kg for a dry scrubber
	Spent catalyst	The used catalyst that has been replaced.	-
	Sludge	Sludge is the solid residue from the physicochemical treatment of waste water from the wet flue-gas treatment	1-15 kg

Contrary to the technology of the mass incineration process which is relatively comparable between different facilities, the FGC residues or air-pollution-control (APC) residues from waste incineration plants exist in many different varieties depending on the type of the incinerator, the composition of input, and the FGC system installed. Overall, two different types of residues exist [2]:

- **Residues from dry and semi-dry systems** where slaked lime is injected into the flue gas, either in dry form or as a slurry. This is done to neutralize acidic components in the flue gas and is typically done before removing the fly ash from the flue gas. Fly ash, reaction products, and unreacted lime are typically removed in fabric filters. Activated coal may be injected for dioxin removal and removed together with the fly ash. Dry and semi-dry systems typically generate a single residue.
- **Residues from wet systems** where fly ash is typically removed before neutralizing acidic components. After this, the flue gas is scrubbed in one, two, or a multistage arrangement of scrubbers. The scrubber solutions are then treated to produce sludge and gypsum. Wet systems typically generate more than one residue.

Table 1.2 provides an overview of individual components in the two overall APC residue types.

Table 1.2 Presence of individual components in residues from the two major types of FGC systems [2].

Component	Dry and semi-dry systems	Wet systems
Fly ash	Always	Always
Boiler ash	Always	Always
Excess lime	Always (usually included)	
Reaction products (salts)	Always (usually included)	Always (in wastewater)
Dioxin sorbent	Optional (usually included)	Optional (usually handled separately)
Sludge	-	Always (sometimes mixed with fly ashes)
Gypsum	-	Optional (recovery possible)
Chloride salts	-	Optional (recovery possible)

1.2 Residues within the scope of this report

In this report, the main focus will be on management techniques and technology for the treatment of **bottom ash** (BA) and **air-pollution-control residues** (APC residues) generated in MSWI plants equipped with **dry and/or semi-dry FGC systems** since, based on the information provided by KLHK, the so-called wet FGC systems are not being constructed in Indonesia and, therefore, are not discussed in detail in this report, unless noted specifically. An example of an MSWI plant equipped with a semi-dry FGC system is given in Figure 1.1.

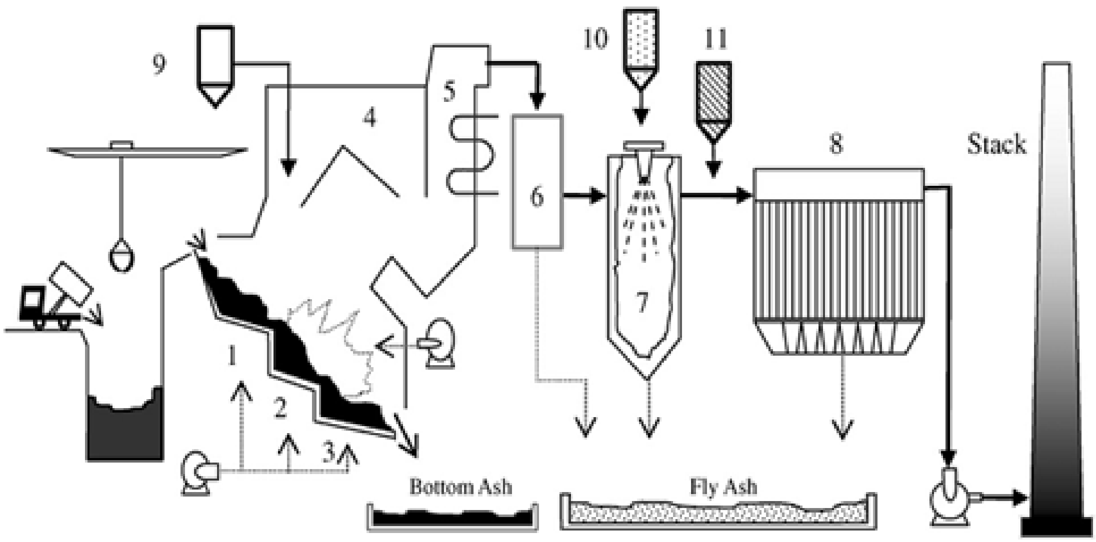

Figure 1.1 Sketch of an MSWI plant (mass-burning; semi-dry FGC system): (1-3) moving grate, (4) boiler, (5) superheater, (6) heat exchanger, (7) semi-dry reactor, (8) baghouse filter, (9) urea (NO_x control), (10) lime, (11) activated carbon; source: [3].

1.2.1 Bottom ash

Bottom ash (BA) could be described as a slag-like residue collected from the combustion chamber. As a result of quite similar operational conditions BA generated in different incinerators (assuming mass combustion) are rather uniform in composition. Table 1.3 provides typical ranges of important BA components.

A lower amount of potential pollutants and rather satisfactory mechanical properties make BA usable as e.g. road construction material. However, freshly quenched BA is geochemically unstable and the aggregates remaining after the recovery of metals should not be utilized outside of landfills before their geotechnical properties as well as environmental properties – most importantly the leaching of metals and metal compounds – improve. Therefore, the leaching of monitored substances and elements (e.g. chloride, sulfate, As, Ba, Cd, Cr, Cu, Hg, Ni, Pb, Sb, Se, and Zn) must stabilize and must comply with the leaching limit values set for the utilization of BA.

Table 1.3 BA elemental composition – observed ranges (mg/kg); adopted from [4] and [5]

Major elements		Minor and trace elements	
Al	14,000-79,000	As	0.12-190
Ca	8,600-170,000	Ba	69-5,700
Fe	3,100-150,000	Cd	0.3-70
K	660-16,000	Cu	190-25,000
Mg	240-26,000	Cr	20-3,400
Mn	7.7-3,200	Mo	2.5-280
Na	2,200-42,000	Ni	7-4,300
P	440-10,500	Pb	75-14,000
Si	90,000-308,000	Se	0.05-10
Ti	2,600-9,500	Sn	2-470
		Tl	0.0077-0.23
		V	16-120
		Zn	10-20,000

Significant spontaneous stabilization of BA takes place over time through the process of weathering (or ageing); cf. Chapter 5. Carbonation[1], which is the most important reaction during the ageing, results in a decrease of BA´s pH which is followed by a significant decrease in solubility of many trace metals. Consequently, the release of pollutants from weathered BA is generally not considered a major problem and a large fraction of the generated BA can be utilized. This is discussed in detail in Chapter 5.

1.2.2 APC residues

As indicated earlier APC residues is *a general term* describing materials derived from processes such as:

i. dry and semi-dry scrubber systems involving the injection of an alkaline powder or slurry to remove acid gases, particulates, and flue gas condensation/reaction products (scrubber residues);
ii. fabric filters in baghouses, which may be used downstream of the scrubber systems to remove the fine particulates (baghouse filter dust);
iii. the solid phase generated by wet scrubber systems (scrubber sludge).

As such, the so-called “dry” or “semi-dry APC residues” is a mixture of fly ash[2], unreacted lime, and products from acid-gas neutralization collected in baghouse filters. Based on the actual set-up of the flue-gas-cleaning system (dry-, semi-dry-, wet-system), the fly ash/APC residues correspond to 1-5% of the incinerated waste mass [5].

APC residues are of fine particle size, ranging from light grey to dark grey, and generally contain high concentrations of heavy metals and soluble/volatile salts. They will also contain hazardous organic compounds such as chlorinated dioxins (PCDD) and furans (PCDF). As noted earlier, contrary to mass-combustion technology, the FGC technology is rather plant-specific mostly reflecting legislative requirements and the period of its installation. In addition, the amount of contaminant in APC residues depends on the characteristics and composition of MSW, the incineration temperature, and the removal efficiency of the APC system. Consequently, APC residues produced in different incinerators vary in composition, water content, pH, etc. Table 1.4 provides typical ranges of important ash components.

Typically, the mass of pollutants per kilogram of weight is lower in dry/semi-dry APC residues than in “pure” fly ash (FA; see next section) due to the dilution of the APC residues with unreacted lime and the neutralization products. Nevertheless, the high alkalinity (pH > 12 and above), the high leachability of heavy metals, and the high level of soluble anions, such as chlorides, make both the APC residues and “pure” FA (from wet-FGC systems) potentially hazardous and particularly difficult waste streams which can rarely be disposed of without any pre-treatment; this is discussed in detail in Chapter 4.

[1] Carbonation can be defined as transformation of the originally present alkaline (hydr)oxides to carbonates via uptake of atmospheric CO_2

[2] Fly ash consists of finely divided particles that are removed by a combination of precipitators and cyclones before any further treatment of the gaseous effluents. For instance, “pure” fly-ash is collected in an electrostatic precipitators used at MSWI plants equipped with wet-FGC system.

Table 1.4 Typical ranges of important residue components [5]. Units in mg/kg.

Element	Fly ash	Dry/semi-dry APC
Al	49,000-90,000	12,000-83,000
As	37-320	18-530
Ba	330-3100	51-14,000
Cd	74,000-130,000	110,000-350,000
Cd	50-450	140-300
Cl	29,000-210,000	62,000-380,000
Cr	140-1100	73-570
Cu	600-3200	16-1700
Fe	12,000-44,000	2600-71,000
Hg	0.7-30	0.1-51
K	22,000-62,000	5900-40,000
Mg	11,000-19,000	5100-14,000
Mn	800-1900	200-900
Mo	15-150	9-29
Na	15,000-57,000	7600-29,000
Ni	60-260	19-710
Pb	5300-26,000	2500-10,000
S	11,000-45,000	1400-25,000
Sb	260-1100	300-1,100
Si	95,000-210,000	36,000-120,000
V	29-150	8-62
Zn	9000-70,000	7000-20,000

1.3 The terminology used in this report

Henceforth, dry/semi-dry APC residues will be referred to as “APC residues”.

Fly ash, which consists of finely divided particles that are removed by a combination of precipitators and cyclones before any further treatment of the gaseous effluents in wet-FGC systems will be referred to as “FA”.

Bottom ash (BA) from MSWI plants equipped with wet discharge systems (i.e. where the hot BA is quenched) is a thermodynamically unstable material that is undergoing a rather significant spontaneous transformation and stabilization over time. Therefore, it is often necessary to distinguish between different “stages” of BA. In agreement with the technical literature, BA will in this report be referred to as:

- *fresh BA* when first removed from the incinerator;
- *raw BA* while awaiting treatment incl. separation of metals and ageing; and
- *aged BA* ash when it has been treated and then stored/aged for some time.

2 General introduction to the management of MSWI residues in different regions

2.1 General considerations

The high mineral content of incineration residues (BA, FA, and APC residues) can make them potentially suitable for use as secondary mineral material in many applications. However, it should be kept in mind that use is possible only if the material complies with both **technical criteria** (functional criteria) of the material it is replacing and **environmental criteria**. This requires an optimization of the ash quality through different measures. The options for recovery and reuse of solid residues depend on many factors; e.g. [1]:

- The content of organic compounds;
- The total content of heavy metals;
- The leachability of salts and heavy metals;
- Physical characteristics and functional properties (e.g. particle size distribution and comprehensive strength);
- Market factors, regulations and policies concerning their use, and specific local environmental issues

Residue treatment methods generally aim to optimize one or more of these parameters to mimic the quality of primary construction materials. After suitable treatment, residues from modern waste incineration plants fulfill the environmental and technical/functional requirements for these quality parameters. Regulatory and political barriers are sometimes the main barriers to the use of (in particular) BA from suitably designed/operated installations.

The general treatment techniques for waste incineration residues (i.e. BA and FA/APC residues) include:

- Ageing;
- Mechanical treatment;
- Washing;
- Thermal treatment;
- Stabilization.

The various treatment techniques are discussed in detail in Annex 2, and Annex 5 – 7.

Many questions have to be addressed when assessing the benefits but also the obstacles of a given treatment process [1]:

- Does the process result in a significant quality improvement?
- Does the process cause any significant health, safety, or environmental impacts?
- Are there secondary residues and where do they end up?
- Is there a final product of high quality?
- Is there a long-term market for that product?
- What are the costs (financial and/or environmental) of the process?

Naturally, where legislation requires certain residues to be sent for disposal, there is less incentive for adopting techniques that would improve the quality and recyclability of the residues.

On the global scale, there are large regional differences in the approach towards the management of different types of incineration residues such as BA, FA, and APC residues. Consequently, the full-scale management options may differ considerably between the different continents/regions as indicated in Annex 1 on the example of: the European Union, the USA, Japan, and China.

3 Management of BA and APC residues in Indonesia

3.1 MSW incineration in Indonesia

Twelve MSWI facilities are planned to be constructed in Indonesia in coming years while the first of them, located in Surabaya city, has recently become operational. An overview of the planned facilities is given in Table 3.1 together with information about planned capacity, the estimated amount of the APC residues (assuming dry/semi-dry FGC), and the estimated amount of BA generated over 8000 hours of operation per year which is typically guaranteed by the technology provider. Overall, 130-330 thousand tons of APC residues and 1,2-1,7 million tonnes of BA per year are expected to be generated from the twelve facilities once operational.

Table 3.1 Capacity of the planned MSWI plants in Indonesia in terms of estimated generation rates of BA and APC residues.

Location	MSW	APC residues		BA	
	tonne/day	tonne/day	ktonne/year	tonne/day	ktonne/year
Surabaya	1000	20-50	6,7-17	180-250	60-83
Surakarta	400-450	9-23	3,0-7,5	81-113	27-38
Denpasar (Sarbagita)	1200	24-60	8,0-20	216-300	72-100
DKI Jakarta	6000	120-300	40-100	1080-1500	360-500
Palembang	1200	24-60	8-20	216-300	72-100
Bekasi	2200	44-110	15-37	396-550	130-180
Bandung, (West Java Region)	1820	36-91	12-30	330-455	110-150
Tangerang	2000	40-100	13-33	360-500	120-170
Semarang	800-900	18-45	6-15	162-225	54-75
Makassar	1000	20-50	6,7-17	180-250	60-83
Tangerang selatan	1000	20-50	6,7-17	180-250	60-83
Manado	1000	20-50	6,7-17	180-250	60-83

3.2 Legislation concerning BA, FA, and APC residues

In 2020, a new regulation was drafted by the Ministery of Environment and Forestry of the Republic of Indonesia concerning "Management of bottom ash and fly ash from thermal waste processing" (Annex 3). This regulation will in the following text be referred to as the "FABA regulation".

The most important points of the FABA regulation – as obtained from a translation provided by KLHK – are listed below:

1. *Bottom Ash and Fly Ash are defined as residues from a waste treatment activity.*
2. *Handling of Bottom Ash is implemented through:*
   a. *Utilisation; and/or*
   b. *Final processing.*
3. *Bottom ash utilization is done through utilization as road tar raw material, as cement raw material, or using other method as technological development allows.*
4. *Bottom ash final processing is done through returning the bottom ash produced from previous activity to the environment safely through Sanitary Landfill and Controlled Landfill.*
5. *Handling of Fly Ash including continued treatment and final processing.*
6. *Continued treatment is performed at the location of the activity or at the facility of the thermal incineration facility and may be done through:*
   a. *Chelate;*
   b. *Acid extraction;*
   c. *Solidification;*
   d. *Melting/dissolving;*
   e. *Sintering;*
   f. *Other methods as technological development allows.*
7. *Facility owner is responsible in complying to the quality standard of the Fly Ash. The compliance shall refer to laboratory test in an accredited laboratory.*
8. *Fly Ash final processing is done towards Fly Ash that have complied the Fly Ash quality standard.*
9. *Handling of FABA is to be reported by including information about:*
   a. *The amount of waste treated through the Thermal Facility.*
   b. *Amount of generated FABA.*
   c. *The method of FABA handling.*
   d. *Fly Ash laboratory test results.*
10. *The report in point 9 will be part of Environmental Permit report and shall be submitted at least once in every six months to the official issuing the Permit. When such Permit is issued by Governor or Mayor then a copy of the report is delivered to Minister of Environment and Forestry.*
11. *Minister, Governor and/or Mayor shall monitor the activity as reported minimum once every six months.*

In Annex I to the FABA regulation, the limit values for FA (and APC residues) are listed. An overview of the limit values is given in Table 3.2. According to the information received from KHLH, the limit values presented in Table 3.2 are related to the so-called Toxicity Characteristic Leaching Procedure (TCLP) by US EPA (US Method 1311).

According to the KLHK, the limit values which the waste (i.e.; treated APC residues) must comply with were selected "less strict compared with the acceptance criteria for hazardous waste"; however, no additional information on the decision-making process involving setting up the criteria are available. For comparison, the last column in Table 3.2 contains the US EPA´s maximum concentration of contaminants for toxicity characteristics.

Table 3.2 Fly ash quality parameters proposed by the new regulation.

No	Parameter	Original name	Units	Maximum	US EPA limits
1	As	Arsen	mg/L	0,5	5
2	Ba	Barium	mg/L	35	100
3	Be	Berilium	mg/L	0,5	
4	Cd	Kadmium	mg/L	0,15	1
5	Cl	Klorida	mg/L	12.500	
6	Cr^{6+}	Krom Valensi Enam	mg/L	2,5	5 [a)]
7	Cu	Tembaga	mg/L	10,0	
8	Hg	Merkuri	mg/L	0,05	
9	Ni	Nikel	mg/L	3,5	
10	Pb	Timbal	mg/L	0,5	5
11	Se	Selenium	mg/L	0,5	1
12	Zn	Seng	mg/L	50,0	

a) Applies to chromium and not specifically to the hexavalent-form

Currently (September 2021) there is no information available about the performance of the residues collected at Surabaya city in the TCLP prescribed in the FABA regulation and carried out in Indonesia.

It should be noted that the TCLP is not used in Europe and has (historically) been used predominantly in the USA and several Asian countries. The procedure uses an acetic acid solution as a leachant and is designed to simulate plausible worst-case leaching conditions that might occur in a landfill containing putrescible waste. The major disadvantage of the TCLP includes its well-known inability to accurately represent different disposal conditions, especially those where decomposing garbage is absent (e.g. ash monofill, subbase layer of road construction, utilization in highway ramps, noise barriers, etc.). Recent studies [6,7] showed that TCLP does not consistently provide the most conservative estimate of leaching as, in some cases, the SPLP[3], the EN 14405 or Method 1314 (Table 3.3) procedures provided higher concentrations relative to TCLP. As a consequence, the TCLP´s role as a regulatory driver in the management of MSWI ashes has been re-evaluated and the US EPA recently promulgated a new suite of characterization tests, based on known European standards (Table 3.3), under the abbreviation LEAF (Leaching Environmental Assessment Framework)[4].

LEAF can be understood as a leaching evaluation tool/system, which consists of four leaching methods (three of which are shown in Table 3.3), data management tools, and scenario assessment approaches designed to work individually or to be integrated to describe the release of inorganic constituents of potential concern for a wide range of solid materials. Associated LEAF "How-To Guide" describes how the LEAF method results can be used to develop screening level assessments of constituent release or to develop more accurate estimates of release in specific use or disposal scenarios.

Using TCLP in Indonesian conditions, that is, assuming a certain level of degradable organic waste being present in landfills containing treated FA/APC residues might be sufficient to simulate plausible worst-case leaching conditions since dedicated ash-monofills are probably not considered as the main disposal option. At the same time, to address or to estimate the leaching behavior of both untreated and treated BA, FA, and/or APC residues in specific use or disposal scenarios, different types of tests should be used and different sets of limit values should be developed.

We suggest KLHK consider revising the legislation and base any future testing and evaluation of FA/APC residues as well as BA (discussed in Section 5.2) on the European leaching standards (EN 12457-1, EN 14997 or EN 14429, and EN 14405) which have been designed to describe the release of inorganic constituents of poten-

[3] Synthetic precipitation leaching procedure (SPLP) is similar to the TCLP, but using synthetic rainwater instead of acetic acid

[4] www.epa.gov/hw-sw846/leaching-environmental-assessment-framework-leaf-methods-and-guidance#dataman

tial concern for a wide range of solid materials while considering the effect of key environmental conditions and waste properties on leaching. Similar methods have recently also been implemented in the USA. In our opinion, changing the testing and evaluation system from the TCLP to the other types of tests still might be possible considering that the incineration residues are currently being produced only at one facility and it may take several years before these residues will be produced in large quantity at different locations in Indonesia.

Table 3.3 Comparison between the EN standards used within the EU and the new LEAF tests promulgated by the US EPA.

EU test	LEAF (US EPA)	Description of test principles
EN 14429 Characterization of waste. Leaching behavior test. Influence of pH on leaching with initial acid/base addition EN 14997 Characterization of waste - Leaching behavior test - Influence of pH on leaching with continuous pH control	Method 1313 - Liquid-Solid Partitioning as a Function of Extract pH Using a Parallel Batch Extraction Procedure	These types of tests are designed to evaluate the partitioning of constituents between liquid and solid phases at or near equilibrium conditions over a wide range of pH values. The methods typically consist of 8-10 parallel batch extractions of solid material at various target pH values.
EN 14405 Characterization of waste - Leaching behavior test - Upflow percolation test (under specified conditions)	Method 1314 - Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio for Constituents in Solid Materials Using an Up-Flow Percolation Column Procedure	A percolation column test designed to evaluate constituent releases from solid materials as a function of cumulative liquid-to-solid ratio. The method consists of a column packed with granular material with moderate compaction. Eluent is pumped up through the column to minimize air entrainment and preferential flow.
CEN/TS 16637-2:2014 - Construction products - Assessment of release of dangerous substances - Part 2: Horizontal dynamic surface leaching test	Method 1315 - Mass Transfer Rates of Constituents in Monolithic or Compacted Granular Materials Using a Semi-Dynamic Tank Leaching Procedure	These methods are semi-dynamic tank leaching procedures used to determine the rate of mass transport from either monolithic materials or compacted granular materials as a function of time using deionized water as the leaching solution.

3.3 Overview of treatment options listed in the FABA regulation

Several treatment routes have been preselected for FA/APC residues in the FABA regulation. A graphical overview of the possible FA/APC residues management outline including the management of BA is provided in Figure 3.1. It can be seen from the schematic overview that compliance testing has been intended for FA/APC residues only. Materials complying with the limit values shown in Table 3.2 would be deposited at landfills Class 2. Materials exceeding the limit values must be treated further.

The individual preselected treatment options for the APC residues including “other suitable methods” are discussed in Chapter 4 and, in larger detail, in Annex 5 – 7. As the management route for FA/APC residues includes testing using the TCLP, general guidance to good sampling is provided in Annex 4. This guidance is not intended to be used by the personnel of the certified analytical laboratories instead of their actual sampling procedures, but to allow the managers/operators of the MSWI plants to better understand the principles of good sampling and the impact of the different choices on the results. Specifically, to collect samples for the TCLP procedure, the sampler also *may* want to refer to dedicated guidance provided by US EPA[5].

[5] www.epa.gov/hw-sw846/guidance-sampling-and-analysis-municipal-waste-combustion-ash-toxicity-characteristic

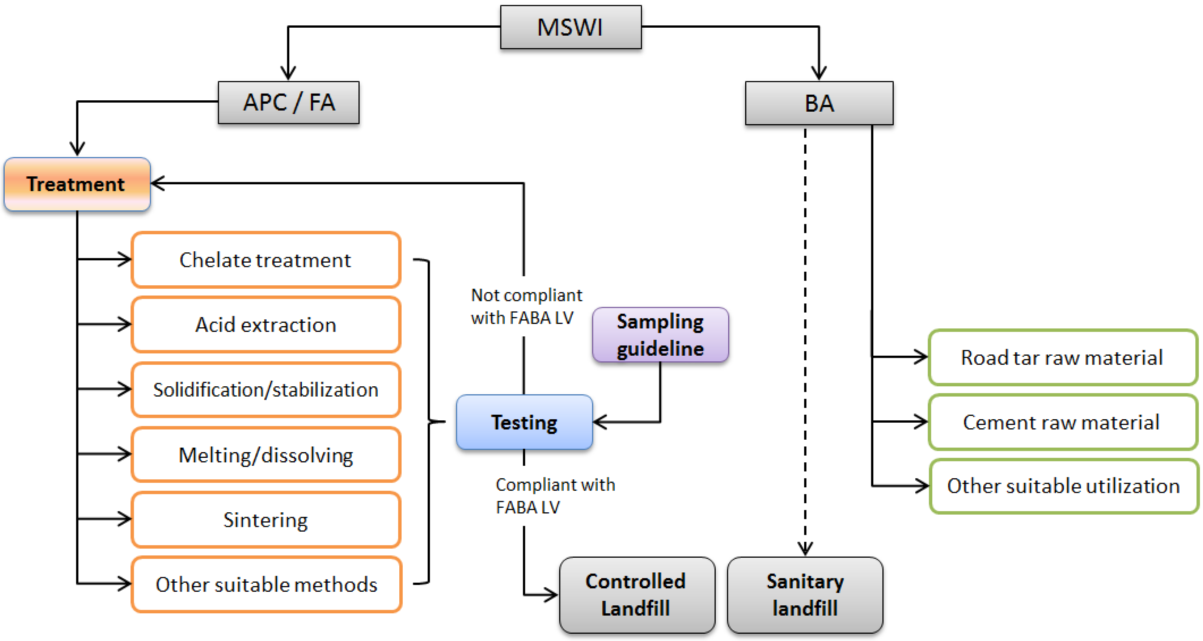

Figure 3.1 Schematics of the management system proposed in the FABA regulation.LV stands for limit values.

The preselected treatment options for BA include utilization as filler in road tar applications, raw material in cement manufacturing and/or other suitable methods. Although sampling/testing is not prescribed for the BA in the FABA regulation at the moment, it is expected that utilization of BA in any application mentioned in the FABA regulation or other applications will require certain pretreatment of BA (explained in detail in Chapter 5) and likely also some level of testing to assess BA's functional and environmental properties. This is indicated in Figure 3.2 below. Note that the principles of good sampling presented in Annex 4 apply also to sampling and analysis of BA.

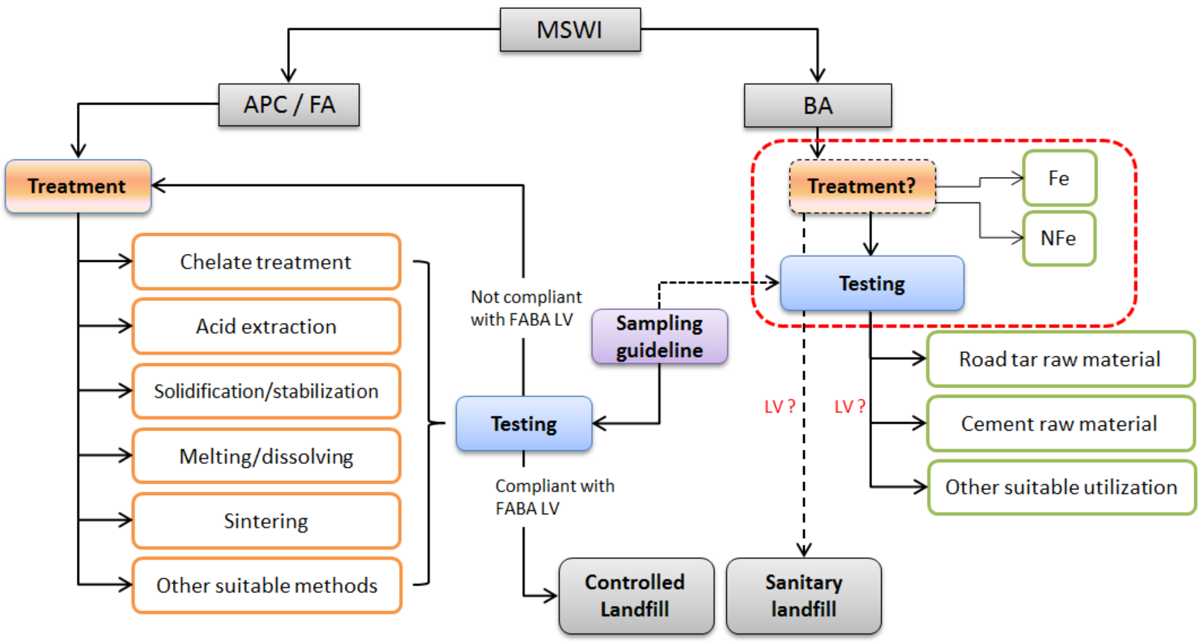

Figure 3.2 Schematics of the management system proposed in the FABA regulation considering necessary pretreatment and testing of BA before the utilization (or landfilling).LV stands for limit values.

- This page is intentionally blank -

4 Technologies of APC residues management

4.1 Preselected methods in FABA regulation

As outlined in Figure 3.1, several methods/treatment principles were preselected in the draft of the FABA regulation (cf. Annex 3). These were:

- Chelate treatment;
- Acid extraction;
- Solidification;
- Melting/dissolving;
- Sintering; and
- Other methods as technological development allows.

4.2 Further criteria for selection of suitable technologies for Indonesia

To narrow down the list of possible technologies and to provide an overview of solutions that are applicable on large scale, the techniques/technology selected for further discussion within the scope of this report should at a minimum:

I. be suited for dry/semi-dry APC residues; and

II. have a TRL[6] ≥ 6; i.e. be nearly market-ready (with finished/documented pilot-scale test) or already established on the market as operational full-scale installations or installations under construction; and

III. have a treatment capacity of at least 10,000 – 20,000 tonnes FA/APC residues per treatment unit when implemented directly into the MSWI plant or when installed as a stand-alone installation. Moreover, the capacity of the stand-alone process should be easy to expand by e.g. running several parallel lines; and

IV. generate residues that at least comply with the European Criteria for waste acceptable at landfills for hazardous waste (WAC_{haz}) (Annex 1) or better yet the Criteria for waste acceptance of stable, non-reactive hazardous waste at non-hazardous waste landfills ($WAC_{haz\text{-}stable}$) (Annex 1) or the residues should be present in a form which allows their further (re)use in another application; and

V. be sound from the overall life-cycle-assessment (LCA) point of view.

Criteria I-IV are technical and do not require further explanation. Criterion V is included to ensure that a treatment method performs well from the overall LCA perspective which becomes an integral part of the decision-making process in many countries. In line with the principles of LCA, better waste management should not only ensure more efficient resource use and a reduced burden on the natural environment, but it should also offer a way to reduce greenhouse gas (GHG) emissions. Consequently, the overall balance of energy-related GHG emissions is among the most important parameters for the outcomes of any LCA of waste management systems.

In 2010, Danish Technical University carried out an LCA of different treatment options for APC residues including [8]: a) backfilling into salt mines; b) neutralization of APC residues using waste acid and landfilling; c) filler application in asphalt; d) the Ferrox-process; e) vitrification; and f) melting with automotive shredder residue. LCA modelling showed that thermal processes – i.e. e) and f) – were associated with the highest loads in the non-toxicity categories (energy consumption), while differences between the remaining alternatives were small and generally considered insignificant. Hence, although thermal treatment processes may provide the best results concerning stabilization of the APC residues and compliance with WAC, they have the highest energy consumption from all treatment processes resulting in the worst GHG emissions balance which, in turn, has been the dominating disadvantage of their potential application, especially in Europe [8].

Similarly, in 2018, Technical University Vienna carried out a comparative LCA of five treatment options for the management of FA [9]: a) underground storage; b) stabilization with cement and landfilling at a non-hazardous waste landfill; c) the FLUREC process; d) thermal treatment in a dedicated furnace heated by coal; and e) thermal treatment together with combustible hazardous waste (e.g. car shredder residues) in a rotary kiln. The results indicated that in comparison to thermal co-treatment in an existing facility (scenario d), thermal treatment in a furnace dedicated to this purpose (scenario e) has a remarkable environmental impact. Even a fuel switch from hard coal to natural gas did not improve the performance of this treatment and disposal option sufficiently. As a result of the high energy requirement and the associated greenhouse gas emissions, this treatment process should be avoided [9].

[6] Technology Readiness Level (TRL) is a globally accepted benchmarking tool for tracking progress and supporting development of a specific technology through the early stages of the technology development chain, from blue sky research (TRL1), system demonstration in a pilot-scale plant (TRL 6), to the actual demonstration over the full range of expected conditions (TRL9).

4.3 Pre-selected full-scale technologies considered non-suitable in Indonesia

4.3.1 Thermal processes

As indicated in previous section, when LCA is considered, the thermal treatment methods (e.g. vitrification, melting, plasma treatment) have the highest environmental impacts related to the high energy consumption (hundreds to thousands of kWh per tonne). In addition, these methods are also rather costly. In an older article from Japan from the year 2000 [10], the then-used thermal treatment technologies were summarized including an overview of treatment costs (in 2000-prices):

- Electric melting using a plasma-arc system: 160-500 USD/tonne;
- Electric melting using electric resistance: <120 USD/tonne;
- Burner using a reflecting surface: 50-500 USD/tonne;
- Burner using a rotating surface: 83-166 USD/tonne

Note that the costs do not include the management of the treated residues. For illustration, a detailed overview of different thermal treatment processes in terms of capacity, energy consumption, and operation cost is provided in Annex 5 together with process unit inventories for the three most used types of processes. Nevertheless, in the context of this report, high-temperature processes are considered "non-suitable" for application in Indonesia although they certainly comply with criteria I-IV.

4.3.2 Other non-suitable full-scale processes

In recent years, some older processes re-gained attention in Europe as the focus had shifted from simple "stabilization and landfilling" to "stabilization with resource recovery". The most interesting improvements/extensions include improved recovery of salts and/or selected metals for recycling; e.g.:

- FLUWA process (https://aiktechnik.ch/dienstleistungen/kvas/)
- FLUREC extension of the FLUWA process (https://www.kebag.ch/abfall-energie/flurec.html)
- HALOSEP process (https://www.halosep.com/)
- Renova process (https://www.renova.se/)
- Norsep process (https://www.norsep.no/)

However, concerning the situation in Indonesia, it should be noted that the majority of the processes which were optimized in recent years are based on acid extraction/washing of FA/APC residues using acid scrubber liquid combined with neutralization of the remaining solid material. As such, these processes are tailored to MSWI plants equipped with wet FGC systems which are – reportedly – not being constructed in Indonesia.

One exception of a full-scale process (TRL 9) that might have been suitable in Indonesia, but which is not discussed further is the so-called Geodur process which is based on chemical stabilization using a proprietary mix of chemicals and subsequent landfilling of the stabilized material. Geodur process has been particularly popular in Switzerland in the 1990s before some of the Swiss plants started to export the APC residues to the German salt mines. Waste materials treated by the Geodur process include MSWI APC residues, contaminated soils, galvanic sludges, and other industrial residues. In April 2013, all Geodur's patents and activities were sold to LAB SA, a company providing flue-gas cleaning equipment to MSW incineration plants within the CNIM Group (a worldwide supplier of waste-to-energy systems). At the moment, the process does not seem to be operated anywhere anymore. For more information about the Geodur process, see Annex 6.

4.4 Overview of full-scale technologies considered suitable in Indonesia

In Table 4.1 several processes/methods are shown which comply with the selection criteria discussed in Sections 4.1 and 4.2. The processes with the highest TRL are shown first. Although these processes are all intended for the treatment of hazardous waste, they are based on different philosophies as there are:

- "Pure" stabilization processes - i.e. processes focused primarily on irreversible immobilization of contaminants (without recovery of resources) and landfilling of the treated residues (i.e. Chelating-based processes, CIP, NOAH, S/S-cement, standard VKI process, Ferrox-process);

- Stabilization processes focused on irreversible immobilization of contaminants including "economically-sound" recovery of resources which is followed by landfilling of the treated residues (modified VKI process);

- A stabilization process focused on the utilization of the APC residues (cement manufacturing after washing, O.C.O. process).

The individual processes mentioned in Table 4.1 are described in detail in Annex 7.

4.5 Summary and evaluation of the selected technologies

When evaluating the different management options outlined in Table 4.1 (next page), it is important to consider the differences in their concept or philosophy in terms of, on one hand, removing, stabilization, and landfilling of the FA/APC residues and, on the other hand, using the residues as input material to industrial processes or even upgrading the FA/APC residues into products as done in the O.C.O. process. In a short-term horizon, the following two options are recommended as applicable in Indonesia:

- chelate treatment / CIP followed by landfilling of stabilized FA/APC residues; and/or
- washing followed by the utilization in cement manufacturing

The key advantages and disadvantages of either option are summarized in Table 4.2.

Table 4.1 Recommended options for the management of FA/APC residues in Indonesia.

Process	Advantage	Disadvantage	Final recommendation
Chelating / CIP	Robust, low-tech, scalable Does not consume cement Many providers to select from (price competitive) Easy testing of environmental performance	Consumes landfill space Preferably a properly designed monofill needed	Recommended as a basic treatment scenario for the management of FA/APC residues in Indonesia
Washing and use in cement manufacturing	Robust, well-developed solution Avoided landfilling of a large part of the FA/APC residues Destruction of organic pollutants No testing of environmental parameters is necessary	Higher costs compared with chelating / CIP Centralized solution in the vicinity of a cement plant Wastewater treatment required May require landfilling of the treatment sludge	Recommended as an optional scenario at locations allowing for synergy with cement manufacturing

Both options are TRL 8-9 with low to moderate costs. Chelate treatment is a cheap, robust, technically non-problematic, scalable solution that could be implemented both at each MSWI plant as well as a centralized solution in the vicinity of a landfill. When washing and utilization in cement manufacturing would be implemented, it allows for avoided landfilling while the content on metals in the residues would be effectively dissolved in a large mass of primary material to very low levels. The organic pollutants incl. POPs will be destroyed during the cement manufacturing process.

The O.C.O process which is gaining more and more attention in the UK as it results in avoided landfilling and upcycling is, in our opinion, not recommendable at the moment, due to largely unresolved “issues” related to the conversion of the presumably hazardous waste stream containing among other things POPs such as dioxins/furans into marketable products. This way, the POPs which have been trapped and concentrated in a relatively small waste stream are dispersed into the environment again which is, in our opinion, fundamentally wrong. In addition, despite a total dilution factor of 25 between the composition of the incoming FA/APC residues and the products manufactured using the M-LS aggregate from the O.C.O process (cf. Chapter 6 in Annex 7), the level of some trace metals such as Zn may still be above 1,000 mg/kg in the final products.

Table 4.2 Overview of suitable full-scale processes for the management of FA/APC residues from MSWI plants equipped with dry-semidry APC systems.

Technology	Principle(s)	Description	Provider	TRL	Cost/tonne, USD[a)]	Final management
Chelating	Stabilization, chelating	Chemical stabilization using dithiocarbamic salt. Stabilized residues intended for landfilling	Different providers	9	90-140	Landfill
CIP	Stabilization, chelating	Chemical stabilization/immobilization of FA/APC-residues using proprietary additives to convert heavy metals into their least soluble form and/or to facilitate heavy metals' substitution and/or adsorption into various mineral species.	ZA (Singapore)	8-9	40-120	Landfill
NOAH	Acid washing, neutralization, stabilization	Solidification/stabilization of FA/APC residues using waste sulphuric acid and landfilling of the residues. The residues are suspended in water and then mixed with waste sulphuric acid and lime at a pH of about 5-7. At this point gypsum precipitates. Finally, pH is increased to around 8-10 by the addition of hydrated lime. Heavy metals are co-precipitated with gypsum, which is landfilled.	NOAH (N)	9	Low compared to any other option	Landfill
S/S with cement	Solidification	May or may not include washing of salts combined with stabilization using cement. Stabilized residue intended for landfilling.	Different providers	9	~25	Landfill
Utilization as raw material in cement production	Washing	Washing of salts followed by utilization of washed residues as raw material input to the cement manufacturing process	Tayheiyo Cement Corporation (Japan)	9	Unknown	Cement
O.C.O	Solidification, stabilization	Solidification/stabilization of APC residues using (accelerated) carbonation followed by use of stabilized aggregates in concrete products.	O.C.O Technology Ltd (UK)	9	140	Concrete products
VKI	Washing, stabilization	Washing of salts (without recovery, but it could be included) combined with chemical stabilization using either H3PO4 or CO2. Stabilized residue intended for landfilling.	DHI (DK)	6-7	90-120	Landfill
Ferrox	(Acid) washing, neutralization, stabilization	Residues are washed with water to extract easily soluble salts, then heavy metals are fixed with Fe-oxides. The residues are finally dewatered and landfilled. The process chemically binds heavy metals to the residue matrix thereby minimizing leaching after the final placement.	Babcock & Wilcox Vølund Aps (DK)	6-7	80-100	Landfill

[a)] Illustrative ranges – not exact amounts as the treatment price depends on the type of contract

5 Technologies of BA management

5.1 Characteristics of MSWI BA

Only BA produced by wet discharge systems is considered relevant f in Indonesia. As mentioned in Section 1.2.1, BA from MSWI plants equipped with wet discharge systems (i.e. where the hot BA is quenched) is a thermodynamically unstable material that is undergoing a rather significant spontaneous transformation and stabilization over time. Therefore, it is often necessary to distinguish between different “stages” of BA. In agreement with the technical literature, BA will in this report be referred to as:

- *fresh BA* when first removed from the incinerator;
- *raw BA* while awaiting treatment incl. separation of metals and ageing; and
- *aged BA* ash when it has been treated and then stored/aged for some time (cf. Box 5.1).

Fresh BA is collected from a quenching tank with water which serves two main purposes: cooling of the material while preventing tertiary air from entering the combustion chamber. Quenching is also a crucial starting point for the natural stabilization of BA via ageing (Box 5.1).

Fresh/raw BA contains the solids remaining after the incineration process including in some cases grate siftings and boiler ashes. The constituents of BA can be classified as non-combustible materials (waste glass, soil minerals, metals, and metal alloys) and melt products (glasses, silicate minerals, and oxide minerals). The mineral fraction of the BA is typically light to dark gray and is a granular material although it may also contain large fused lumps. The particle size distribution is typical of well-graded materials and generally conforms with that of sandy gravel, with a content of 40-mm oversize particles commonly below 5% by total mass, as well as a low portion of fines (< 63 mm). The bulk density of uncompacted BA is typically 1,2-1,8 tonne/m^3. The pH value of fresh BA is 11,5-12,3 and the moisture content is between 18 and 25 %, with the majority of the moisture content allocated to the fine fraction. The main constituents of BA are typical ash-forming elements (e.g. Si, Al, Ca, and Fe) and a variety of other minor and trace elements; some of them of environmental concern (see Table 1.3). Nevertheless, it is generally acknowledged that the total metal content of the BA is not related to the potential environmental impact exerted by the material in its use or the disposal site. Metals are typically considered of concern once they are released into the environment by leaching.

Rather than a waste to be landfilled, BA is a valuable resource that can replace raw materials and from which valuable metals can be recovered and recycled. Apart from a small fraction of unburnt organic material (typically < 1 %), BA consists primarily of two types of resources: metals[7] (typically 8-10 % as ferrous metals and 2-5 % as non-ferrous metals) and a mineral fraction (sometimes referred to as aggregates), which is a heterogeneous mixture of non-combusted materials such as waste glass, waste/soil minerals and melt and sintered products of various mineral composition, all with highly variable particle sizes. The mineral fraction, which in the worst-case scenario has to be landfilled, constitutes 80-85 % of the IBA.

Fresh/raw BA cannot be utilized directly and a certain level of pretreatment is always required. Likewise, it is not recommendable to deposit fresh BA in a sanitary landfill, since fresh BA is known to express elevated leaching of several trace metals e.g. Pb and Zn as indicated in Figure 2 in Box 5.1. Landfilling at the controlled landfill is possible, however, not recommended due to the large volumes of BA and limited landfilling capacity.

[7] The content of especially metals may vary in BA produced in Indonesia due to differences in composition of the incoming waste.

Box 5.1 Weathering of BA (ageing).

When BA is intended for application as unbound aggregates, a significant stabilization of (quenched) BA may be achieved spontaneously via a natural process referred to as weathering (or ageing) which is, by far, the most used process in the management of BA, since it applies to the large mass of BA at low costs. Weathering consists of many sub-processes, including dissolution/precipitation of salts, glass corrosion, oxidation of elemental metals, hydrolysis of oxides, slaking of lime, carbonation, hardening, and hydraulic cementation reactions, the formation of clay-like minerals from glasses, sorption, complexation, etc. Typically, weathering takes place during stockpiling of BA in open-air conditions (Figure 1) for a minimum of 4 – 10 weeks, although the more common weathering period may last from several months up to a year, depending on climate conditions and storage space capacity issues.

Figure 1. Ageing of IBA in 5000-tonne piles (AFATEK, DK)

Many of the above-mentioned processes are exothermic causing temperature rise to 85-90 ºC for several weeks inside large BA piles. Therefore, the initial moisture content of BA decreases, partly thanks to evaporation and partly thanks to water-consuming chemical reactions. A key part of the weathering process includes carbonation, which – most importantly – results in a decrease of the BA's pH in contact with water to pH 10-10,5 (initially pH > 12) and, in turn, leads to further improvement of geotechnical properties of BA and reduced leaching of some cation forming trace metals e.g. Cd, Cu, Co, Ni, Pb, and Zn (Figure 2). On the other hand, some oxyanion-forming elements such as Sb and Cr may become mobilized if pH drops below 10.

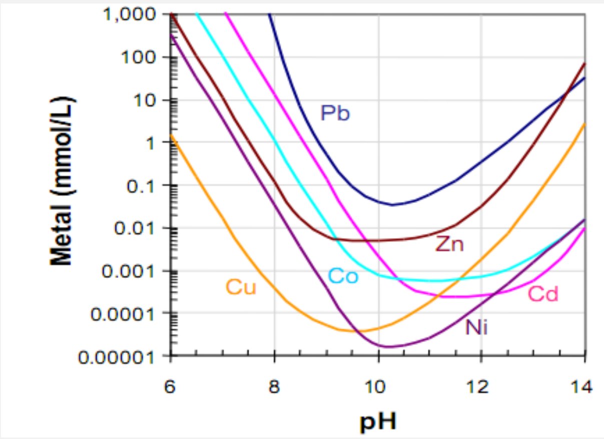

Figure 2. Solubility of selected metals as a function of solution pH (Stumm and Morgan, 1996)

5.2 Pre-selected methods in FABA regulation

As outlined earlier in Figure 3.1 and 3.2 and as summarized in Figure 5.1 for the case of BA, several utilization scenarios were preselected in the draft of the FABA regulation (cf. Annex 3):

- Utilization in road tar material;
- Utilization in cement manufacturing;
- Other methods as technological development allows.

Contrary to the management of FA/APC residues, no testing and compliance with any limit values were prescribed for BA in the current version of the FABA regulation. Likewise, it is unclear, whether the BA was intended to be subject to any pretreatment incl. separation of ferrous and non-ferrous metals and ageing. Unfortunately, except for landfilling – which is not recommended due to unnecessary consumption of landfill capacity – BA is not suitable for any type of the preselected (or other) management options indicated in Figure 5.1A without a certain level of treatment as indicated schematically in Figure 5.1B. Furthermore, the decision regarding the BA management option depends on several parameters which are currently unknown since the information available for BA produced in Indonesia lacks data on: (i) the content of organic compounds; (ii) the leachability of metals and salts; and (iii) physical characteristics, e.g. particle size and strength.

It is clear, that where legislation allows or requires BA to be “just” sent for disposal, there is less incentive for adopting techniques that would improve the quality and recyclability of the residues.

Generally speaking, BA may be used in construction for different applications mainly involving an aggregate in either unbound (i.e. as a loose “gravel”) or bound forms (i.e., BA is used in mixtures with a binder such as cement or asphalt) for the construction of layers of roads, harbor areas, parking lots, and others and for the formulation of structural cement or concrete products. Unbound applications are well established in several countries such as Denmark, Belgium, Germany, Sweden, Taiwan, The Netherlands, and Japan. The the application of BA as a bound aggregate in concrete products has also gained interest, although the final technical properties of the products may be of concern. Nevertheless, a certain minimal pretreatment of BA is always necessary in order to improve the functional and environmental properties of BA. This is discussed in the next section.

5.3 BA processing

Annex 8 provides an overview of different processing and treatment techniques and principles applied to BA [4]. The techniques are discussed there concerning their recycling potential as well as their potential effects on the leaching behavior of the material. The processing methods that are routinely applied to incinerator BA have two main goals: (i) the separation of valuable fractions (basically, the mineral and metal fractions) to be reused in different applications; and (ii) improvement in technical and environmental behavior (e.g. ageing) of BA to meet the requirements set by technical standards for the use and regulatory thresholds for the reduction of potential environmental impacts.

The exact combination of treatment options that are used in the pretreatment depends on the composition of the waste feed material and the end uses of the treated BA. A holistic approach is necessary when assessing BA processing and treatment, as high recovery rates of certain materials may be outweighed by high energy consumption and/or potential downstream environmental burdens, since, in the end, all fractions of the bulk ash materials need to be managed [4]. In general, BA may be subject to different types of active pretreatment aimed at improving its geotechnical and environmental properties; e.g.: washing to remove soluble salts; removal of certain particle size fraction to limit leaching of trace metals; addition of cement/hydraulic binders to stabilize leaching and improve geotechnical properties; and thermal treatment to improve the leaching of metals and organic compounds. In short, regardless of the utilization scenario, basic mechanical treatment including removal of metals (ferrous, non-ferrous), crushing of oversize particles, removal of unburnt organic matter, and ageing is always applied to BA (Figure 5.2).

The choice of pretreatment depends on the intended application. In some countries, the fine fraction of BA may need to be removed, because the presence of this fraction (often enriched with trace elements) may hamper the utilization of the mineral fraction in the construction sector [11]. Naturally, by removing the fine fraction a new waste stream (contaminated with e.g. trace metals) is generated and needs to be managed properly. On the other hand, in other countries, where BA is utilized as unbound aggregate in e.g. road constructions, removing the fine fraction may not be necessary and may even be undesirable, since this may negatively affect the particle size distribution of the IBA-gravel, limit its suitability for construction applications and ultimately lead to landfilling of large bulks of BA.

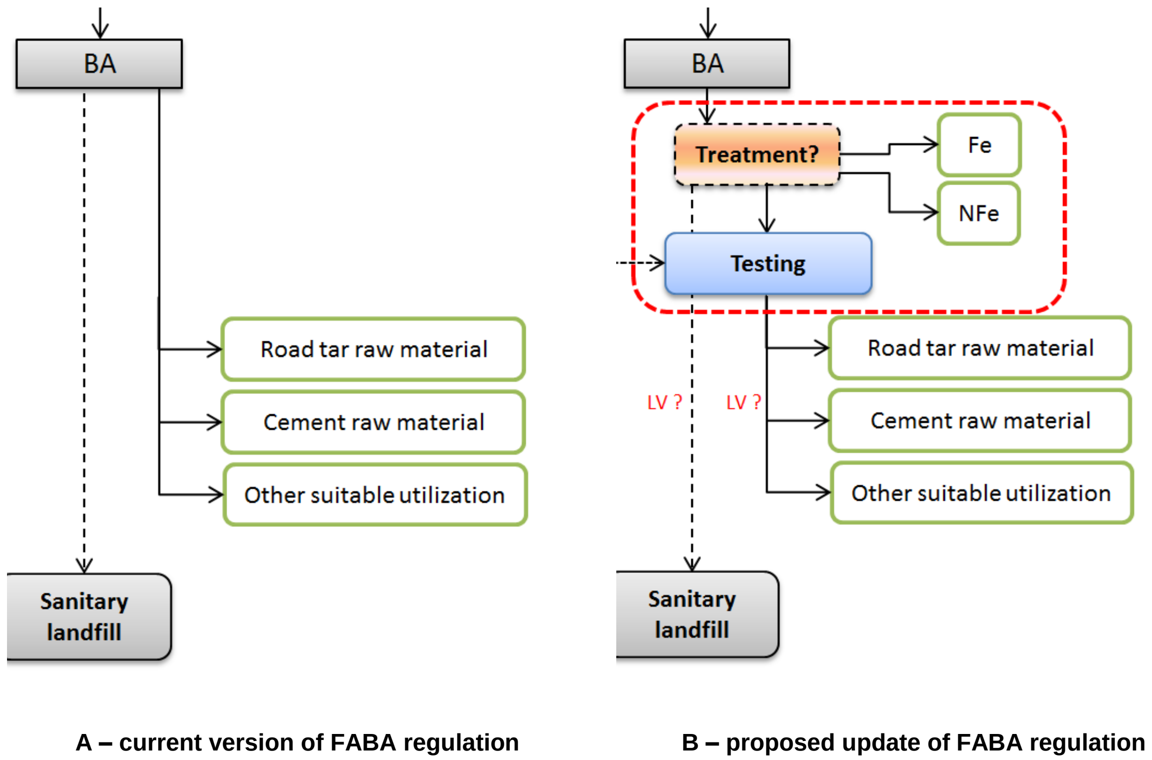

Figure 5.1 Schematics of the management system proposed by the FABA regulation. Left: current situation. Right: Possible update.

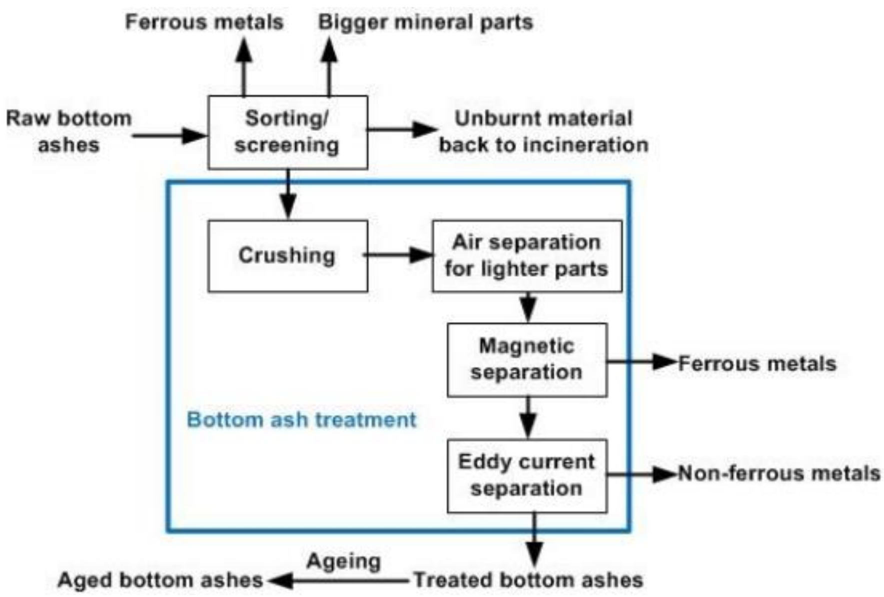

Figure 5.2 Flowsheet of an example BA treatment process with some mechanical separation stages used for the treatment of bottom ash [1].

As indicated in Figure 5.2, metals are recovered routinely from BA (cf. Annex 8), regardless of the origin of the BA being an incinerator equipped with a dry or wet discharge. As for the management of the residual mineral fraction of BA, the utilization options include (ordered according to the decreasing scale of use):

- use as unbound aggregates;
- use ad bound aggregates;

    - use in cement bound applications;
    - use in bitumen bound applications;
- use as an admixture in cement manufacturing;
- production of alkali-activated materials (geopolymers), adsorbents, ceramics, glass-ceramics, bricks, tiles, and numerous types of low-strength building elements in general.

As already discussed for the case of FA/APC residues, different forms of thermal treatment can – undoubtedly – improve the stability and environmental quality of BA by causing changes in the BA matrix and result in physical and chemical fixation of metals as well as the disintegration of (trace) organic compounds [12-14]. However, because of the high energy consumption and associated emissions [15], the thermal processes have mostly been used in Japan, as they often do not compete well against the more traditional BA management options when considered in a full life-cycle assessment context.

The advantages and disadvantages of the different options listed above are discussed in detail in Annex 9. <u>Except for the use as unbound aggregates (and occasionally as cement bound applications), none of the above-mentioned options has shown truly feasible on both a large scale and for the bulk of BA as these processes often require a certain type of material with a certain quality (both environmental and technical). In other words, the main management option applicable to the bulk of quenched BA – which is the dominant BA type produced worldwide – on a large scale has been the use of BA as unbound aggregates; i.e., replacing virgin raw materials in specific construction works, such as e.g. subbase in road constructions.</u> In addition, the use in an unbound application is inexpensive and applicable to the bulks of BA and hence preserves natural resources and saves landfill space. Consequently, the utilization as unbound aggregate in construction is discussed first regardless of its position under the “other methods as technological development allows” mentioned in the FABA regulation.

5.3.1 Utilization as unbound aggregates

Treated (e.g. removal of metals, crushing of oversize fraction) and aged BA has excellent mechanical properties, including a well-graded particle size distribution, that allows it to replace virgin materials (sand, gravel, crushed rock) in several structural engineering applications such as subbase in road construction, highway ramps and noise reduction barriers. BA, however, also contains mainly inorganic substances that may potentially be harmful to the environment and human health, if the BA is not pretreated sufficiently and not used under proper conditions.

The main potential risk to the environment is the release of salts (mainly chlorides and sulphates) and trace elements into percolating rainwater that may subsequently migrate to contaminate soil, groundwater, and surface water. Therefore, pretreatment of BA aims at reduction of the leaching of contaminants while application conditions for BA as unbound aggregates should be regulated in such a manner that unacceptable impacts on groundwater and surface water from leaching of substances are prevented.

The main potential risk to human health is exposure by direct contact (mainly if the BA has not been carbonated and is strongly alkaline) and by ingestion by children (due to a content of potentially hazardous elements and, of course, also if it is alkaline). Therefore, pretreatment must include carbonation, and application conditions must prevent direct exposure to humans. While leaching of undesired substances can be significantly reduced by pretreatment and unacceptable impacts of leaching and direct exposure to BA can be prevented by proper (regulatory) conditions for the use of BA as unbound aggregates, this also means that so-called *free use* of BA is unacceptable and should not be allowed.

The use of BA in unbound applications is well established in many countries since the utilization of metal-sorted and weathered BA has proven feasible concerning both the functional and the environmental requirements for the use in road base and subbase [16] provided that:

- the residual metals are separated; and
- the BA has weathered/aged; and
- it is used in specific applications under specified conditions where the potential negative impacts from e.g. leaching or direct exposure/ingestion are limited; and
- the BA complies with leaching criteria based on the actual risk associated with the application scenarios.

A comprehensive overview of no less than 20 different field tests using BA in unbound applications in Sweden, France, Denmark, the USA, The United Kingdom, Italy, and The Netherlands is provided in Annex 10.

Additional information about the utilization of BA specifically in road constructions is provided in Annex 11. Briefly, in addition to the guidelines and regulatory criteria aimed at environmental protection, the national authorities responsible for the application of unbound aggregates in e.g. road construction often define functional geotechnical criteria that BA must fulfill to be accepted as a construction material. These may vary in different countries, but for illustration, the criteria defined in 2012 by the Danish Road Directorate for such uses are listed below:

- no particle > 45 mm (crushing may be applied on-site); and
- content of particles > 31.5 mm is < 15 %; and
- content of particles < 0.063 mm is < 9 %; and
- a normative reference to EN 13285: GN (PSD curve), OC85 (oversize fraction), UF9 (max. amount of fine particles), and LFN (min. amount of fine particles); and
- TOC < 3 % (based on EN 13137); and
- < 15 cm^3/kg of material with density smaller than water (based on EN 933-11) in a representative sample of the fraction 4/63 mm.

5.3.2 Utilization as bound aggregates

Due to the typical relative content of the major oxides SiO_2, CaO, and Al_2O_3, BA may display some pozzolanic behavior in the presence of $Ca(OH)_2$. In general, hydraulically bound applications consist of those using cement (so-called cement bound applications) and those using other binder treatments (e.g. lime, coal fly ash). Historically, cement-bound applications were used to improve the mechanical and environmental quality of different wastes including BA [17,18]. More recently, the applicability of BA has been investigated in connecting with the development of cement-based aggregates for the replacement of natural aggregates in road subbase [19] or aggregate replacement in concrete [20]. A detailed overview of the technical parameters (e.g. optimum dry densities, compaction strength, deformation properties, expansion, abrasion, stiffness, etc.) of different mixtures using various substitution rates and binders is beyond the scope of this document but it could be found elsewhere [19]. Similarly, for an extensive summary of the environmental impacts of BA in bound applications refer to [21] and references therein.

Note that before the use of BA in bound applications, the pozzolanic properties of BA may need to be improved via activation, which could be mechanical (e.g. wet grinding, milling), thermal (e.g. sintering), and/or chemical (e.g. addition of $CaCl_2$) [4]. In addition, the material needs to be weathered (i.e. ageing) or wet grinding of BA was shown to decrease the risk of hydrogen-caused expansion and swelling reactions which may occur in the fresh concrete if aluminium (and zinc) particles are present in the BA [22]. Another way to improve the pozzolanic properties of BA is to combine it with other incinerator ashes or mineral additions [22].

The addition of cement/hydraulic binders results in stabilization of the leaching from BA, but the mass of the residues increases (sometimes significantly) which can be a factor when these are intended for landfills. In addition, salts may need to be removed before the stabilization thereby creating additional waste streams. Converting BA to products such as concrete pavement blocks via stabilization with cement may pose a higher risk of increased environmental impacts compared with using BA as unbound aggregate in road construction subbase [23]. On the other hand, BA bound in bituminous applications (e.g. filler in asphalt mixtures for road pavements) seems to fulfill required specifications for both technical properties and leaching behavior (see Section 5.3.3).

5.3.3 Use as aggregate in asphalt admixtures

Substitution of natural aggregates in bituminous mixtures has been investigated extensively in the USA and the United Kingdom; for examples of case studies see Annex 12.

Overall, the rate of natural aggregates substitution in asphalt found in the literature varies from 10 % to 100 % [19]; nevertheless, it is suggested that, to assure proper performance of the pavement materials, less than 20-25 % BA should be used in the binder course or base layer whereas less than 10-15 % should be used when applied to the surface layer of asphalt concrete [24,25]. The major drawback of the bitumen-bound application of BA seems to be the porous nature of BA that requires increased bitumen content compared to natural aggregates. As a rule of thumb, the change in bitumen is at a rate of 1 % for every 1 % BA. For example, 20 % of BA requires a 20 % increase in the bitumen content from 5 % to 6 %, compared to what is required for natural aggregate mixes [19]. Overall, the content of bitumen in mixtures with BA rarely exceeds 10 % while the typical range found in the literature is between 3 and 7 % [4].

5.3.4 Admixture in cement manufacturing

Waste materials with high contents of SiO_2, Al_2O_3, and CaO generated at municipal solid waste incinerators (i.e. FA) have been used in the production of Portland cement clinker because they allow for the reduction in the use of limestone[8] while significantly reducing the CO_2 emissions of cement manufacturing [26].

The application of BA as a raw feed in cement clinker manufacturing has been investigated with a substitution rate of up to 40 % BA in the raw feed [27]. On the other hand, a rather small substitution rate (1,75 % and 3,50 %

[8] Approximately 1.6 tonnes of limestone are consumed per tonne of cement.

for unwashed FA and BA, respectively) was reported by [20] when the maximum allowable limits of chloride (<100 ppm in this case) was considered to protect a full-scale cement kiln from corrosion. According to some sources, removal of chlorides by pre-washing, which must be done for FA/APC residues (cf. Annex 7, Chapter 5), may not be necessary for BA, provided the BA has been quenched [20,26] and the general conclusion is that BA seems suitable for cement production at a substitution rate up to 6 % BA which does not seems to cause any negative effect on clinker phase composition. Nevertheless, the *real-life* substitution rate of *washed* BA and FA/APC residues applied at full-scale cement plants in Japan is <1 % (cf. Chapter 5 of Annex 5); i.e. at a significantly lower level.

5.4 Summary and evaluation of BA treatment technologies

Several BA utilization scenarios were pre-selected in the draft of the FABA regulation:

- Utilization in road tar material;
- Utilization in cement manufacturing;
- Other methods as technological development allows.

Key advantages and disadvantages of the most suitable BA treatment options are summarized in Table 5.1.

Table 5.1 Recommended options for the management of BA in Indonesia

Process	Advantage	Disadvantage	Final recommendation
Unbound aggre-gates in road constructions	Decades of well-documented performance Robust, low-tech, cheap, scalable Applicable to the bulk of BA Easy testing of environmental performance Avoided landfilling	Requires (low-cost) pretreatment: e.g. crushing, removal of metals, ageing	Recommended as the main treatment scenario for the management of BA in Indonesia
Washing and use in cement manufacturing	Robust, well-developed solution, used in Japan and partially also Italy Avoided landfilling of a large part of the BA Destruction of organic pollutants No testing of environmental parameters is necessary	Higher costs compared with the utilization as unbound aggregates Centralized solution in the vicinity of a cement plant Crushing and removal of metals required May required wastewater treatment if washing is included May require landfilling of the treatment sludge if washing is included	Not needed in case of a working system based on the utilization as unbound aggregates in road constructions, but could be used locally in connection with the existing cement manufacturing sites
Road tar application	Robust, tested in the US, UK Good encapsulation of potential contaminants	Not applicable to the bulk of BA Very low substitution rate compared with the utilization as unbound aggregate Pretreatment necessary (crushing, removal of metals, washing of salts) Higher consumption of bitumen in the mixture (increased costs)	Not needed in case of a working system based on the utilization as un-bound aggregates in road constructions

Overall, no BA management option exists which would apply to bulk mass of BA without pretreatment consisting of, at least, the removal of residual metallic items, crushing of oversize particles, and ageing. In addition, the only BA management option which has proven applicable to the bulks of BA at full-scale is the utilization as unbound aggregates in, for instance, road constructions. Considering the development in Indonesia and the expected amounts of BA to be produced in the future (cf. Section 3.1), we strongly suggest implementing a BA management system similar to that operated in many European countries (e.g., Denmark, Germany, France, Czech Republic, Finland, etc.) which includes following steps: crushing of oversize fraction, sorting of metals, weathering/ageing in large piles, and utilization in subbase layer of road constructions provided the material complies with a given set of leaching limit values.

The use of BA in the unbound applications has proven feasible at full-scale concerning both the functional and the environmental requirements provided that:

- the residual metals are separated;
- the IBA has weathered/aged;
- it is used in specific applications under specified conditions where the potential negative impacts from e.g. leaching or direct exposure/ingestion are limited: and
- the BA complies with leaching criteria based on the actual risk associated with the application scenarios.

6 Monitoring and evaluation system

Developing a testing program includes the selection of appropriate leaching tests, target analytes for evaluation, and analytical methods to sufficiently detect and measure chosen analytes. The testing program should be specified in a quality assurance project plan (QAPP) that addresses the tests and conditions to be conducted as well as testing and analytical QA/QC criteria used to support the testing program.

6.1 Material collection for the individual tests

Annex 4 gives an introduction to the basic principles of sampling. Here, only the most important points are summarized:

- The goal of material sampling and subsequent material preparation should be to obtain *representative* samples and subsamples, or aliquots, of the materials being disposed of or reused for use in the selected leaching tests.
- Initial sample collection should account for spatial and temporal variations in material characteristics through appropriate compositing of individual grab samples. For piles or accumulated quantities of a single material, grab samples should be obtained from different locations and depths within the accumulated material. For a material produced over time, representative grab samples should be obtained at predefined intervals over the evaluation period.
- Individual grab samples should have enough mass to be spatially or temporally representative. The goal should be to have a sufficient sample following preparation to meet the needs of the planned leaching testing and characterization needs of the project. Remember that depending upon variability in material composition, replicate testing may be needed.
- Often convenient field sample sizes and containers are 2-liter wide-mouth jars and/or plastic drums with tight-fitting re-sealable lids. The container materials (e.g., high-density polyethylene, glass) must not interfere with the analyte.
- Sample collection systems and subsequent handling should be designed to avoid changes in sample characteristics that may degrade the representativeness of the samples before analysis and can result in misleading results. For example, oxidation or carbonation of samples during collection and/or handling can result in changes in pH and constituent speciation and may significantly alter the leaching behavior of some constituents. Samples should be particle-size reduced and homogenized shortly before sub-sampling and testing to maximize the representativeness of results. Heterogeneity can result from variations in the solid material, aging of the cured materials, or exposure of leaching solutions to the atmosphere.

6.2 Test methods

6.2.1 Solid content analysis

When considering the utilization of BA as unbound aggregate in the subbase of road construction, it is important to realize that direct contact of the BA with many compartments of the environment (e.g. fauna, people, flora) is limited and transfer of possible contaminants from the BA into the surrounding environment happens predominantly via leaching (i.e. dissolution and transport in aqueous phase). Therefore, the knowledge of the exact composition of the solid phase is, in this case, not critical since it is not the total content of a contaminant in question which is of interest, but rather the "soluble fraction" of this contaminant. Hence, in several countries including Finland, France, Netherlands, and Germany, there are no limit values for the total content of metals in the BA utilized in the subbase. In all countries which allow for the utilization of waste, however, the BA must be classified as non-hazardous waste.

In Denmark, a small number of metals (As, Cd, Cr, Cu, Ni, Pb, Zn) are monitored, however, it is the performance of the BA in the leaching tests, which determines whether or not the BA may be utilized in a given scenario.

6.2.2 Leaching tests

For (i) the basic characterization of leaching properties of solid materials either landfilled or used in different utilization scenarios and (ii) collecting data necessary for calculating leaching limit values associated with the different utilization scenarios, we suggest the same leaching tests/framework as used in the EU and lately also in the USA (see Section 3.2):

- EN 14997 Characterization of waste - Leaching behavior test - Influence of pH on leaching with continuous pH control <u>or</u> EN 14429 Characterization of waste - Leaching behaviour test - Influence of pH on leaching with initial acid/base addition.
- EN 14405 Characterization of waste - Leaching behavior test - Upflow percolation test (under specified conditions).

The above-mentioned tests are used primarily to collect input data necessary for hydro(geo)chemical modeling used to calculate leaching limit values similar to the WAC (cf. Annex 1) and are not needed in daily operation and compliance testing. For compliance testing of BA, we suggest a simple (cheap) batch leaching test;

- EN 12457-1 Characterisation of waste - Leaching - Compliance test for leaching of granular waste materials and sludges - Part 1: One stage batch test at a liquid to solid ratio of 2 l/kg for materials with high solid content and with particle size below 4 mm (without or with size reduction)

6.3 Monitored parameters

6.3.1 Basic characterization test

The typical range of parameters monitored in eluates from basic characterization tests includes:

- pH, conductivity
- chloride, fluoride, sulphate
- Al, Si, Ca, Na, K, As, Ba, Cd, Cr, Cu, Hg, Mg, Mn, Mo, Ni, P, Pb, S, Sb, Se, V, Zn
- dissolved organic carbon (DOC or NVOC)

Optionally, redox potential may be determined.

6.3.2 Compliance tests

As summarized in [28], the typical range of parameters monitored in eluates from compliance leaching tests includes in most European countries which allow the utilization of BA includes:

- pH, conductivity
- chloride, fluoride, sulphate
- As, Ba, Cd, Cr-tot, Cu, Hg, Mo, Ni, Pb, Sb, Se, Zn

We suggest using the same list of parameters in future testing in Indonesia should the compliance testing based on the EN 12457-1 or similar be implemented.

Less often-used parameters monitored in some of the countries include:

- Total dissolved solids
- phenol index
- bromide
- cyanide
- Na, K, Mn

6.3.3 Analytical methods

Whenever possible, standardized methods should be used. As a part of the service, the analytical laboratory responsible for the measurements will suggest the best-suited methods and provide the client with all necessary information.

6.4 Quality Assurance/Quality Control

Quality assurance for leaching tests should consider the following steps:

- Obtaining representative material sample(s) for testing;
- Execution of leaching tests with test-level quality assurance/control QA/QC evaluations;
- Chemical analysis of test eluates following accepted methods and QA/QC procedures; and
- Data management in a manner that minimizes human error and allows for validation relevant to data quality objectives.

Chemical analysis of leaching test eluates should include the specification of reporting limits that are less than the applicable threshold values that will be used in subsequent decision-making. Management of values less than the reporting limits (e.g., less than the LOD or LOQ) should be reported and used in calculations in a manner consistent with the relevant regulatory or another applicable evaluation program. Options for reporting and using values less than the reporting limits include using the reporting limit, one-half the reporting limit, or one-tenth the reporting limit.

Commercial analytical laboratories have internal QA/QC control procedures that comply with their accreditation programs. When contracting with an analytical laboratory, it is encouraged to review the QA/QC procedures, measured QA/QC solutions, and evaluation frequencies with the contracted analytical laboratory. These quality assurances and quality control procedures should be considered for the leaching assessment project QAPP and data quality objectives.

6.5 Data storage and treatment

Below are the most important points to take into consideration when talking about data collection.

6.5.1 Data review

Before the use of analytical data, the end-user should review analytical QA/QC results to ensure accuracy and consistency in the evaluation of analytical blanks, spike recoveries, and analytical duplicates.

Similarly, the results from leaching tests should be reviewed graphically for consistency in trends within and between test replicates. Abnormal jumps or discontinuities in interrelated data may indicate potential testing or analytical errors.

6.5.2 Data storage

Because multi-point testing and comprehensive chemical analysis create a considerably large data set of interrelated leaching measurements, it is suggested to design and distribute tools for collecting, managing, and reporting data. Microsoft Excel® spreadsheets can be provided as templates to assist laboratory personnel in the preparation of tests and collection bench and analytical data. These templates can be used to import directly into a central database, should it be decided beneficial.

Using the Microsoft Excel® workbooks allows for easy incorporation of the data into reports and other documents. Furthermore, these can be used to facilitate the process of compiling data from testing, compare leaching results within and between tests or material replicates and between different materials, and formulate standardized tables and graphics for data reporting.

6.5.3 Data treatment

There are many ways to treat the data from the basic characterization tests, monitoring, compliance testing, etc. Nevertheless, in connection with the use of the European standard leaching tests (or their US alternatives under the LEAF; cf. Section 3.2) it would be beneficial to use LeachXS Lite™ data management and visualization tool[9], which is an essential part of the LEAF. The tool allows users to evaluate and characterize the release of material constituents based on comparisons derived from leaching test results for a wide range of materials and waste types (e.g., secondary or recycled materials, stabilized waste, and construction materials). LeachXS Lite is a simplified – and free – version of the full software package LeachXS™.

The program provides facilitated data management, visualization, and analysis through:

- Direct import of leaching test data using formatted data templates,
- Comparison of leaching data from different materials or leaching tests,
- Comparison of material-specific leaching data to a statistical representation for a class or group of materials, and
- Uniform data presentation and graphic output to Microsoft Excel® spreadsheets.

The current version of LeachXS Lite includes data templates written in Microsoft Excel used for importing data from the different leaching test methods.

7 References

[1] Neuwahl F, Cusano G, Benavides JG, Holbrook S, Roudier S. Best Available Techniques (BAT) Reference Document for Waste Incineration. EUR 29971 EN, doi:10.2760/761437. 2019.
Ref Type: Bill/Resolution

[2] Astrup T. Management of APC residues from W-t-E Plants: An overview of management options and treatment methods. second edition. 2008. Copenhagen, Denmark, Working Group on Thermal Treatment of Waste. The International Solid Waste Association (ISWA).
Ref Type: Serial (Book,Monograph)

[9] https://www.vanderbilt.edu/leaching/leach-xs-lite/

[3] Chang FY, Wey MY. Comparison of the characteristics of bottom and fly ashes generated from various incineration processes. Journal of Hazardous Materials 2006; 138(3): 594-603.

[4] Astrup T, Muntoni A, Polettini A, Pomi R, Van Gerven T, Van Zomeren A. Treatment and Reuse of Incineration Bottom Ash. In: Prasad MNV, Kaimin Shih, eds, Environmental Materials and Waste. Elsevier Inc. 2016; 607-45.

[5] Chandler AJ, Eighmy TT, Hartlem J, Hjelmar O, Kosson DS, Sawell SE et al. Municipal solid waste incinerator residues. Amsterdam: Elsevier Science. 1997.

[6] Clavier KA, Liu Y, Intrakamhaeng V, Townsend TG. Re-evaluating the TCLPΓÇÖs Role as the Regulatory Driver in the Management of Municipal Solid Waste Incinerator Ash. Environ Sci Technol 2019; 53(14): 7964-73.

[7] Intrakamhaeng V, Clavier KA, Roessler JG, Townsend TG. Limitations of the toxicity characteristic leaching procedure for providing a conservative estimate of landfilled municipal solid waste incineration ash leaching. null 2019; 69(5): 623-32.

[8] Fruergaard T, Hyks J, Astrup T. Life-cycle assessment of selected management options for air pollution control residues from waste incineration. Science of the Total Environment 408, 4672-4680. 2010.
Ref Type: Journal (Full)

[9] Huber F, Laner D, Fellner J. Comparative life cycle assessment of MSWI fly ash treatment and disposal. Waste Management 2018; 73: 392-403.

[10] Ecke H, Sakanakura H, Matsuto T, Tanaka N, Lagerkvist A. State-of-the-art treatment processes for municipal solid waste incineration residues in Japan. Waste Management & Research 2000; 18(1): 41-51.

[11] Arickx S, Van Gerven T, Boydens E, L'hoest P, Blanpain B, Vandecasteele C. Speciation of Cu in MSWI bottom ash and its relation to Cu leaching. Applied Geochemistry 2008; 23(12): 3642-50.

[12] Arickx S, Van Gerven T, Knaepkens T, Hindrix K, Evens R, Vandecasteele C. Influence of treatment techniques on Cu leaching and different organic fractions in MSWI bottom ash leachate. Waste Management 2007; 27(10): 1422-7.

[13] Schneider J, Vehlow J, Vogg H. Improving the MSWI bottom ash quality by simple in-plant measures. In: Goumans JJJM, van der Sloot HA, Aalbers ThG, eds, Environmental Aspects of Construction with Waste Materials. Elsevier Sci, Amsterdam. 1994; 605-20.

[14] Hyks J, Nesterov I, Mogensen E, Jensen PA, Astrup T. Leaching from waste incineration bottom ashes treated in a rotary kiln. Waste Management & Research 2011; 29(10): 995-1007.

[15] Gomez E, Rani DA, Cheeseman CR, Deegan D, Wise M, Boccaccini AR. Thermal plasma technology for the treatment of wastes: A critical review. Journal of Hazardous Materials 161[2-3], 614-626. 2009.
Ref Type: Journal (Full)

[16] Forteza R, Far M, Segu-¦¦ü C, Cerd+í V. Characterization of bottom ash in municipal solid waste incinerators for its use in road base. Waste Management 2004; 24(9): 899-909.

[17] Chen QY, Tyrer M, Hills CD, Yang XM, Carey P. Immobilisation of heavy metal in cement-based solidification/stabilisation: A review. Waste Management 2009; 29(1): 390-403.

[18] Glasser FP. Fundamental aspects of cement solidification and stabilisation. Journal of Hazardous Materials 1997; 52(2-3): 151-70.

[19] Lynn CJ, Ghataora GS, Dhir OBE RK. Municipal incinerated bottom ash (MIBA) characteristics and potential for use in road pavements. International Journal of Pavement Research and Technology 2017; 10(2): 185-201.

[20] Pan JR, Huang CP, Kuo JJ, Lin SH. Recycling MSWI bottom and fly ash as raw materials for Portland cement. Waste Management 2008; 28(7): 1113-8.

[21] Lynn C, Ghataora GS, Ravindra KD. Environmental impacts of MIBA in geotechnics and road applications. Environmental Geotechnics 5[1], 31-55. 2018.
Ref Type: Journal (Full)

[22] Bertolini L, Carsana M, Cassago D, Curzio AQ, Collepardi M. MSWI ashes as mineral additions in concrete. Cement and Concrete Research 2004; 34(10): 1899-906.

[23] Allegrini E, Vadenbo C, Boldrin A, Astrup TF. Life cycle assessment of resource recovery from municipal solid waste incineration bottom ash. Journal of Environmental Management 2015; 151(0): 132-43.

[24] Chen JS, Chu PY, Chang JE, Lu HC, Wu ZH, Lin KY. Engineering and environmental characterization of municipal solid waste bottom ash as an aggregate substitute utilized for asphalt concrete. Journal of Materials in Civil Engineering 2008; 20(6): 432-9.

[25] Luo HL, Chen SH, Lin DF, Cai XR. Use of incinerator bottom ash in open-graded asphalt concrete. Construction and Building Materials 2017; 149: 497-506.

[26] Lam CHK, Barford JP, Mckay G. Utilization of municipal solid waste incineration ash in Portland cement clinker. Clean Technologies and Environmental Policy 2011; 13(4): 607-15.

[27] Kikuchi R. Recycling of municipal solid waste for cement production: pilot-scale test for transforming incineration ash of solid waste into cement clinker. Resources Conservation and Recycling 2001; 31(2): 137-47.

[28] Blasenbauer D, Huber F, Lederer J, Quina MJ, Blanc-Biscarat D, Bogush A et al. Legal situation and current practice of waste incineration bottom ash utilisation in Europe. Waste Management 2020; 102: 868-83.