Utilisation of Incineration Bottom Ash (IBA) from Waste Incineration

– Prospects and Limits –

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Approximately 247 million tonnes of municipal solid waste (MSW) were generated in 2016 by the EU28, according to Eurostat [21]. The current main treatment options are recycling (29 %), incineration with energy recovery (28 %), landfilling (24 %), composting (16 %) and others (3 %) – percentages as of 2016 [21]. Incineration with energy recovery, however, is not a final management step, since it produces residues, including incineration bottom ash (IBA), corresponding to 15 – 25 % of the incinerated waste mass. Therefore, the 68 million tonnes of the MSW managed by incineration by the EU28 in 2016 resulted in the generation of roughly between 11 and 17 million tonnes of IBA. As incineration with energy recovery is likely to be part of the circular economy for several years to come, it may be predicted that about 15 to 20 million tonnes of IBA will have to be managed annually over the next decade(s) within the countries currently constituting the EU28.

Over the past decades of IBA management, it has become increasingly clear that rather than a waste to be landfilled, IBA is a valuable resource that can replace increasingly rare raw materials and from which valuable metals can be recovered and recycled. Apart from a small fraction of unburnt organic material (typically < 1 %), IBA consists primarily of two types of resources: metals which can be divided into ferrous metals (8 – 10 %) and non-ferrous metals (2 – 5 %), and aggregates or minerals, 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 typically constitutes 80 – 85 % of the IBA [10].

Metals have routinely been recovered from IBA with increasingly efficient equipment, as described elsewhere in the other sections of this book. The main recycling option for the mineral part of the IBA has been and currently is application as unbound aggregate, replacing virgin raw materials in construction works, such as e.g. subbase in road construction. This is reflected by this paper which discusses the composition and properties of IBA, the functional and environmental protection aspects of IBA application as unbound aggregates as well as various pre-treatment options, but also briefly addresses hydraulically and bitumen bound IBA applications and the use of IBA as an admixture in cement production.

1. IBA composition and properties

Given the variation in waste composition, furnace configuration, combustion temperature, retention time and quenching process, the elemental composition of IBA from different origins are fairly similar as bulk chemical analyses of ashes from different plants usually fall within one order of magnitude [11, 42]. On the other hand, the physical appearance of IBA is rather inhomogeneous and may – depending on the quenching technology – vary from a granular material to large fused lumps.

Most of the mineralogy and petrography studies have been carried out in the 1990's and early 2000s [9, 20, 22, 30, 50]. More recent studies [5] have confirmed the results of the older ones while new analytical methods have helped to improve our knowledge of IBA composition. The knowledge obtained from these studies is summarised in the following text. Generally speaking, fresh IBA consists of two major groups of particles: the non-combusted waste products with high melting points (i.e., waste glass, waste/soil minerals and waste metals) and the melt products, i.e. new phases formed as a consequence of high-temperature combustion. The melt products – described as irregularly formed lumps with grain sizes in the range from mm to cm [50] – include the products resulting from melting/partial melting of the waste and the minerals that have crystallised from the melt. The melt products consist of silicate glasses, melilite-group minerals, pyroxenes, spinels, oxides, and carbonates. High glass-content of IBA results from rapid cooling (quenching) of the hot, partly molten material. Because of the rapid cooling, the major part of the silicate material consists of porous, thermally fractured particles, with fractures originating from the escape of gases during combustion and from quenching. The phase assemblage that is present after rapid combustion, cooling, and quenching, is far from thermodynamic equilibrium, and it is characteristically metastable under ambient conditions [5]. Therefore, fresh IBA (when quenched) is generally unsuitable for direct use *as it is* and should be processed before being used. In addition to the removal of the ferrous and non-ferrous metals [6, 43, 53], the geotechnical and environmental properties of the material need to be improved prior to its utilisation.

A holistic approach is necessary when assessing IBA 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, IBA may be subject to different types of active pre-treatment aimed at improving its geotechnical and environmental properties; e.g.:

- washing in order to remove soluble salts,
- removal of certain particle size fraction in order to limit leaching of trace metals,
- addition of cement/hydraulic binders in order to stabilise leaching and improve geotechnical properties, and
- thermal treatment in order to improve leaching of metals and organic compounds.

Nevertheless, the choice of pre-treatment depends on the intended application. In some countries, the fine fraction of IBA may need to be removed, because the presence of this fraction (often enriched with trace elements) may hamper the utilisation of the mineral fraction in the construction sector [2]. 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 IBA is utilised 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 IBA. Another example is different forms of thermal treatment which can – undoubtedly – improve the stability and environmental quality of IBA by causing changes in the IBA matrix and result in physical and chemical fixation of metals as well as the disintegration of (trace) organic compounds [3, 8, 33, 47, 48]. However, because of the high energy consumption and associated emissions [29], the thermal processes have mostly been used in Japan [18] and not in Europe, as they often do not compete well against the more traditional IBA management options when considered in a full life-cycle assessment context.

2. The use of IBA as unbound aggregates

2.1. Environmental and functional requirements

After pre-treatment IBA 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 and under squares and ramps as well as in noise reduction barriers. IBA does, however, have a content of mainly inorganic substances that may potentially be harmful to the environment and human health, if the IBA is not pre-treated sufficiently and 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, pre-treatment of IBA should aim to reduce or minimise the leaching of contaminants, and application conditions for IBA as unbound aggregates should be regulated in such a manner that unacceptable impacts on groundwater and surface water from leaching of substances are prevented. Such precautions could include the conditions shown in Table 1, which refers to the well-known source-transport-receptor concept of risk or impact assessment.

Table 1: Examples of conditions that may be imposed on the use of IBA as unbound aggregates to reduce the impact on the environment. POC (point of compliance) is a reference point in the groundwater downstream of the application where general groundwater quality criteria must be observed

Imposed condition	Source	Pathway	Receptor
the material can only be used for specified purposes	can be influenced	can be influenced	may determine which receptors are relevant
take back the material after the service life	reduction in the time span to be considered	not affected	not affected
minimum distance to groundwater level	not affected	attenuation in the unsatu-rated zone may be taken into account	depends on POC
minimum distance to surface water	not affected	attenuation in the unsatu rated zone and the aquifer may be taken into account	depends on POC
restrictions on the height of application	may reduce source term	not affected	not affected
restrictions on the length and width of the application	may reduce the source term	not affected	not affected
restrictions on the allowed rate of infiltration	reduction of the flux (the load per time unit)	not affected	not affected

Adapted from: Hjelmar, O.; van der Sloot, H.A.; Comans, R.N.J.; Wahlström, M.: EoW Criteria for Waste-Derived Aggregates. Waste Biomass Valor 4:809-819, 2013

When using risk-related scenario calculations to set leaching-based regulatory criteria for the use of IBA as unbound aggregates, the conditions imposed must be incorporated into the calculation scenarios, and the resulting criteria must reflect these conditions, see e.g. [32].

The main potential risk to human health is exposure by direct contact (mainly if the IBA 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, pre-treatment must include carbonation, and application conditions must prevent direct exposure to humans.

While leaching of undesired substances can be significantly reduced by pre-treatment and unacceptable impacts of leaching and direct exposure to IBA can be prevented by proper (regulatory) conditions for the use of IBA as unbound aggregates, this also means that so-called *free use* of IBA is unacceptable and should not be allowed. Free use could, for example, result if IBA should gain End-of-Waste (EoW) status without restrictions and become a product rather than a waste in accordance with Article 6 in Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Should this happen, then IBA utilisation would no longer be controlled by waste legislation but rather by construction product legislation which in many European countries currently would make it difficult or impossible to ensure that proper conditions on the use are imposed to prevent unacceptable impacts on the environment and human health. It is therefore strongly advised not to seek EoW status for IBA, neither at EU level nor on a country by country basis.

Currently, there are no environmental protection criteria for the use of IBA as unbound aggregates at EU level, but several of the EU Member States have developed national guidelines or regulatory quality criteria for the use of IBA (and other aggregates) in unbound applications. The quality criteria, which in most cases include limit values on both content and leaching of certain substances, are in most cases accompanied by certain conditions on the use, and in several cases, there are more than one set of limit values, each reflecting different conditions of use – less restrictive limit values corresponding to more restrictive use conditions. Table 2 provides some examples of the types of quality criteria prescribed by legislation or given in guidelines in some EU Member States (adopted from [46]).

Table 2: Examples of regulatory rules and guidelines for utilisation of waste-derived aggregates in selected EU Member States

Country	Criteria on content*	Leaching criteria	Leaching test(s)
Austria	X	X	EN 12457-4
Belgium (Flanders)	X	X	EN 14405
Czech Republic	X	X	EN 12457-4
Denmark	X	X	EN 12457-1
Finland	X	X	EN 12457-3 and CEN/TS 14405
France	X	X	EM 12457-2 or EN 12457-4
Germany (Länder)	X	X	EN 12457-2/4 and DIN 19528
Italy		X	EN 12457-2
Spain (some regions)		X	EN 12457-4 and DIN 38414-S4
Sweden	X	X	EN 14405
The Netherlands	X	X	EN 14405

* Note that different analytical methods may be used in different countries to obtain the *elemental content*. Often the content of several inorganic elements may be determined after partial digestion using e.g. aqua regia or nitric acid rather than total digestion using e.g. $HCl+HF+HNO_3$.

Source: Savyen, H.; Eder, P.; Garbarino, E.; Muchova, L.; Hjelmar, O.; van del Sloot, H.; Comans, R.; van Zomeren, A.; Hyks, J.; Oberender, A.: Study on methodological aspects regarding limit values for pollutants in aggregates in the context of the possible development of end-of-waste criteria under the EU Waste Framework Directive. European Commission, Joint Research Centre, Institute for Prospective Technological Studies: Rep. No. JRC91036, 2014

Austria, Denmark, Finland, France, Germany, The Netherlands, and Sweden have more than one set of leaching criteria, reflecting different conditions of use (e.g. thickness of the application, requirements on cover and rate of infiltration of precipitation, area of application, distance to groundwater level, distance to drinking water extraction wells or the hydrogeological vulnerability of the environment at the site of application); for details refer to [46]. The legislation and guidelines typically cover several types of waste-derived aggregates, and often one of the sets of criteria refers to *free* or *nearly free* use of the unbound aggregate without restrictions. However, IBA generally cannot fulfil these criteria, particularly because of the low content of potentially problematic substances required, but also because of very strict requirements on leaching associated with free use.

It should be noted that some of the leaching criteria referred to in Table 2 were developed using pathway scenario risk assessments that take some degree of attenuation of released substances during transport in soil and groundwater into account [46 and references therein].

Some of the countries (e.g. Germany, Belgium, Spain and Italy) do not have any national legislation governing the use of IBA and, therefore, large regional differences may be encountered. Typically, in regions with an abundance of natural gravel, the IBA may be used as landfill construction material whereas in regions with a limited supply of natural gravel the IBA may be utilised in road constructions as a substitute for natural gravel.

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 generally define some functional geotechnical criteria that IBA must fulfil to be accepted. As an example of such criteria, those defined by the Danish Road Directorate for such uses are listed below [44]:

- no particle > 45 mm (crushing may be applied on-site),
- content of particles > 31.5 mm is < 15 %,
- content of particles < 0.063 mm is < 9 %,
- a normative reference to EN 13285 category GN, OC85, UF9, and LFN;
- 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.

2.2. Treatment of IBA prior to application as unbound aggregates

When IBA is intended for application as unbound aggregates, a significant stabilisation of (quenched) IBA may be achieved spontaneously via a natural process referred to as weathering (or ageing). Weathering is, by far, the most used process in the management of IBA, since it is applicable to the large mass of IBA at low costs. Weathering consists of a number of sub-processes, including dissolution/precipitation of salts, glass corrosion, oxidation of elemental metals to oxides, hydrolysis of oxides, slaking of lime, carbonation, hardening and hydraulic cementation reactions, the formation of clay-like minerals from glasses, sorption, complexation, etc. [5, 20, 22, 27, 36]. Typically, weathering takes place during stockpiling of IBA in open air conditions for a minimum of 3-4 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. As many of the above-mentioned processes are exothermic [35], the initial moisture content of IBA 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 – result in a decrease of the IBA's own pH in contact with water to pH 9-10.5 (initially above pH 12) and, in turn, leads to further improvement of geotechnical properties of IBA and to reduced leaching of some cation-forming trace metals (e.g. Cd, Cu, Pb, and Zn). On the other hand, some oxyanion-forming elements such as Sb and Cr may become mobilised if pH drops below pH 10 [14, 17].

During the last two decades, significant efforts have been spent to accelerate the slow natural weathering or, more specifically, the carbonation part of the weathering process. Indeed, when accelerated carbonation is investigated at laboratory scale, several process parameters are typically varied in the attempt to optimise the carbonation process: particle size of the carbonated material (i.e. the reaction interface), material humidity, CO_2-percentage in the air (i.e. partial pressure of CO_2) and air temperature [15, 23, 53].

Though promising, it has proven rather difficult to repeat the results of the laboratory scale investigations at full-scale where fine-tuning of different process parameters is complicated if not impossible. So far, only a few cases of successful up-scaling of accelerated carbonation of IBA, combining carbonation and washing of salts and showing its technical feasibility have been reported. The economic feasibility has been shown to depend on the availability of washing water and the possibility to discharge water with elevated salt concentrations [51]. For the moment, most of the natural weathering of IBA takes place in the form of passive systems, i.e. stockpiling for several months.

2.3. Lessons learned from the use of IBA aggregate in unbound applications

The use of IBA in unbound applications is well established in many countries since metal-sorted and weathered IBA complies with technical requirements for the use in road base and subbase [26]. A comprehensive overview of no less than 20 different field tests using IBA in unbound applications in Sweden, France, Denmark, USA, The United Kingdom, Italy and The Netherlands is provided by Lynn et al. [41].

The results of the individual studies are not discussed here, although it should be noted that they confirm good functional properties of IBA used in unbound applications. For the purpose of illustration, results of a recent Danish project focused on evaluation of the technical properties of IBA – not included in the above mentioned review article – are presented in larger detail, as they show that (i) the use of IBA in road construction may be allowed in roads with higher traffic load (more than 600 trucks/day) and (ii) the application of IBA may be *moving up* towards the use in the unbound base-layer (i.e., not only to be used as subbase). In this project, an experimental full-scale test road has been built in Copenhagen [25] in connection with the expansion of harbour area; ~10 million m^3 of soil are to be moved using trucks over 15-20 years. The test road has been constructed as a two-direction road with a *heavy* lane for incoming trucks and a *light* lane leaving trucks. Each truck is registered/weighted on the way in and out. The annual expected traffic load over the 15-year period places the road in the highest traffic class, T7 (over 1,500 trucks per day). The test road monitoring strip is 280 m long and consists of 6 individual sections (1 x 30 m and 5 x 50 m) where different combinations of materials (sand, gravel, crushed concrete, IBA) were used in the construction of both the subbase and the unbound base. The thickness of the subbase and the unbound base is 300 mm and 335 mm, respectively. The asphalt layer (total thickness 165 mm) consists of three individual material types (35 mm, 55 mm and 75 mm from the top to the bottom). Young's modulus has been monitored regularly in the subbase, unbound-base and the asphalt layer in all sections of both *heavy* and *light* lanes. In addition, rutting and smoothness have been monitored regularly in all sections of both lanes. The conclusions after two years (and 4,6 million tonnes of net *cargo* transported over 500 workdays) are that [25]: IBA is a good material for use as subbase and can be used in subbase of a road dimensioned to 900 trucks/day; IBA shows larger Young's modules than natural gravel (whilst crushed concrete gives the best results); good results for section 4 and 5 (where IBA was used in the unbound base layer instead of natural gravel or crushed concrete) indicate that IBA *ought to be* considered for application in the construction of the unbound base layer; very good results for rutting were obtained in both the *heavy* and *light* lane after two years (2,5 - 3,5 mm and 1,6 mm, respectively).

The environmental properties (e.g. leaching) of IBA in unbound applications have been studied in fewer studies; nevertheless, the overview provided by Lynn et al. [41] gives information about several studies in which the environmental properties of IBA have been evaluated in detail. One of these is a field-scale study carried out at Ydernæs (Denmark), where five test units (100 to 200 m^2 each) were constructed with IBA in the unbound subbase (0,5 m thick) and different types of cover allowing for different level of infiltration (pebbles – flagstones); for details refer to [31]. One of the test units was covered with asphalt and has functioned as a normal parking lot throughout the test period. The field test was initiated in 2002 and is still running. The leachate has been collected at regular intervals in order to provide long-term monitoring data, describing leachate concentrations as a function of the liquid to solid ratio (L/S) over a period of 16 years. One interesting observation was that the annual rate of filtration through the asphalt-covered IBA subbase has increased from less than 3 % of the annual precipitation in 2003 to more than 10 % of the annual precipitation in 2016 and 2017. Recently, the field data were used to evaluate the applicability of short-term laboratory leaching data for long-term predictions of field leaching [16].

3. Other applications of IBA

3.1. IBA use in hydraulically bound applications

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, the cement-bound applications were used to improve the mechanical and environmental quality of different wastes (including IBA) [13, 28]. More recently, the applicability of IBA has been investigated in connecting with the development of cement-based aggregates for replacement of natural aggregates in road subbase [41] or aggregate replacement in concrete [45].

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 provided elsewhere [41]. Similarly, for a summary of the environmental impacts of IBA in bound applications refer to [40 and references therein]. It is noted that prior to the use of IBA in bound applications, the pozzolanic properties of IBA 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, 24]. In addition, the material needs to be weathered (cf. Section 2.2) or, alternatively, wet grinding of IBA 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 IBA [7].

Finally, the risk of increased environmental impacts from using IBA in *concrete* pavement blocks as compared with using IBA as unbound aggregate in road construction subbase has been pointed out in a recent LCA study [1].

3.2. IBA use in bitumen bound applications

Substitution of natural aggregates in bituminous mixtures has been investigated extensively in the USA and the United Kingdom [e.g. 12, 19, 37, 52]. The rate of natural aggregates substitution in asphalt found in the literature varies from 10 % to 100 % [40]; nevertheless, it is suggested that, in order to assure proper performance of the pavement materials, less than 20-25 % IBA 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 [12, 39]. The major drawback of the bitumen-bound application of IBA seems to be the porous nature of IBA that requires increased bitumen content compared to natural aggregates. Lynn et al report that *the change in bitumen is at a rate of 1 % for every 1 % IBA. For example, 20 % of IBA requires a 20 % increase in the bitumen content from 5 % to 6 %, compared to what is required for natural aggregate mixes* [41]. Overall, the content of bitumen in mixtures with IBA rarely exceeds 10 % while the typical range found in the literature is between 3 and 7 % [4].

Information about the environmental performance of bituminous bound IBA has recently been summarised by Lynn et al. [40] who concluded that the hydrophobic nature of bitumen and restrictions on the feasible content of IBA due to the aforementioned technical requirements result in a limited release of potentially problematic constituents from bituminous bound applications.

3.3. IBA as an 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. fly ash) have been used in the production of Portland cement clinker because they allow for reduction in the use of limestone (1.6 tonnes of limestone are consumed per tonne of cement) while significantly reducing the CO_2 emissions of cement manufacturing [38 and references therein]. Application of IBA as a raw feed in cement clinker manufacturing have been investigated with a substitution rate of up to 40 % IBA in the raw feed [34]. On the other hand, a rather small substitution rate (1,75 % and 3,50 % for unwashed fly ash and IBA, respectively) was reported by [45] when the maximum allowable limits of chloride (<100 ppm in this case) was considered in order to protect a full-scale cement kiln from corrosion. Note that removal of chlorides by pre-washing, as done for fly ash, may not be necessary for IBA, provided it has been quenched [45, 38]. The general conclusion is that IBA is suitable for cement production, and the addition of up to 6 % IBA does not cause any negative effect on clinker phase composition. At higher substitution rates, the clinker composition may become less favourable (a drop in tricalcium silicate value is observed), although the environmental quality of such clinker does not worsen [38].

3.4. Additional applications

Apart from the most common management options listed above, which seem to be feasible for the bulk of produced IBA, both economically and environmentally, there are other more niche-type management options which will not be discussed in detail here. For further information, a comprehensive review of the latest development in using IBA in production of alkali-activated materials (geopolymers), adsorbents, ceramics, glass-ceramics, bricks, and tiles has been provided by Silva et al. [49] who concluded that although the use of IBA as partial or total substitute of comparable natural resources may lead to significant conservation of natural resources and to considerable financial advantages, the research on the use of IBA in these applications is still in somewhat early stages and further experimental data are needed to facilitate the wider use of such materials.

5. Concluding remarks

Although there may be several management options available for the IBA, the use in unbound application has proven feasible with respect to both the functional and the environmental requirements, provided that i) the residual metals are separated, ii) the IBA has weathered/aged, iii) it is used in specific applications under specified conditions where the potentially negative impacts from e.g. leaching or direct exposure/ingestion are limited, and iv) the IBA complies with leaching criteria based on the actual risk associated with the application scenarios. In addition, the use in unbound application is inexpensive and applicable to the bulks of IBA and hence preserves natural resources and saves landfill space. However, this must not prevent or discourage ongoing and future development of more advanced or alternative management options that may e.g. move IBA management upwards in the waste hierarchy, as long as such solutions are assessed in a lifecycle perspective (including end-of-life), accounting for all associated potential environmental impacts and consumption of resources.

6. References

[1] Allegrini, E.; Vadenbo, C.; Boldrin, A.; Astrup, T. F.: Life cycle assessment of resource recovery from municipal solid waste incineration bottom ash. In: Journal of Environmental Management, 151(0), 2015, pp.132-143

[2] 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. In: Applied Geochemistry, 23(12), 2008, pp. 3642-3650

[3] 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. In: Waste Management, 27(10), 2007, pp. 1422-1427

[4] Astrup, T.; Muntoni, A.; Polettini, A.; Pomi, R.; Van Gerven, T.; Van Zomeren, A.: Treatment and Reuse of Incineration Bottom Ash. In: Prasad, M. N. V.; Shih, K. (eds.): Environmental Materials and Waste, Elsevier Inc., 2016, pp. 607-645

[5] Bayuseno, A. P.; Schmahl, W. W.: Understanding the chemical and mineralogical properties of the inorganic portion of MSWI bottom ash. In: Waste Management 30[8-9], 2010, pp. 1509-1520

[6] Berkhout, S. P. M.; Oudenhoven, B. P. M.; Rem, P. C.: Optimizing Non-Ferrous Metal Value from MSWI Bottom Ashes. In: Journal of Environmental Protection 2, 2011, pp. 564-570

[7] Bertolini, L.; Carsana, M.; Cassago, D.; Curzio, A. Q.; Collepardi, M.: MSWI ashes as mineral additions in concrete. In: Cement and Concrete Research, 34(10), 2004, pp. 1899-1906

[8] Bethanis, S.; Cheeseman, CR.; Sollars, CJ.; Effect of sintering temperature on properties and leaching of incinerator bottom ash. In: Waste Management & Research 22, 2004, pp. 255–264

[9] Bethanis, S.; Cheeseman, C. R.; Sollars, C.: Properties and microstructure of sintered incinerator bottom ash. In: Ceramics International, 28(8), 2002, pp. 881-886

[10] CEWEP: http://www.cewep.eu/2017/09/08/bottom-ash-factsheet/, status 01-08-2018

[11] Chandler, A. J.; Eighmy, T. T.; Hartlem, J.; Hjelmar, O.; Kosson, D. S.; Sawell, S. E.; van der Sloot, H. A.; Verlow, J.: Municipal solid waste incinerator residues. In: Elsevier Science, Amsterdam, 1997

[12] Chen, J. S.; Chu, P. Y.; Chang, J. E.; Lu, H. C.; Wu, Z. H.; Lin, K. Y.: Engineering and environmental characterization of municipal solid waste bottom ash as an aggregate substitute utilized for asphalt concrete. In: Journal of Materials in Civil Engineering, 20(6), 2008, pp. 432-439

[13] Chen, Q. Y.; Tyrer, M.; Hills, C. D.; Yang, X. M.; Carey, P.: Immobilisation of heavy metal in cement-based solidification/stabilisation: A review. In: Waste Management, 29(1), 2009, pp. 390-403

[14] Cornelis, G.; Johnson, C. A.; Van Gerven, T.; Vandecasteele, C.: Leaching mechanisms of oxyanionic metalloid and metal species in alkaline solid wastes: A review. In: Applied Geochemistry, 23(5), 2008, pp. 955-976

[15] Costa, G.; Baciocchi, R.; Polettini, A.; Pomi, R.; Hills, C. D.; Carey, P. J.: Current status and perspectives of accelerated carbonation processes on municipal waste combustion residues.In: Environmental Monitoring and Assessment, 135(1-3), 2007, pp. 55-75

[16] Di Gianfilippo, M.; Hyks, J.; Verginelli, I.; Costa, G.; Hjelmar, O.; Lombardi, F.: Leaching behaviour of incineration bottom ash in a reuse scenario: 12 years-field data vs. lab test results. In: Waste Management 73, 2018, pp. 367-380

[17] Dijkstra, J. J.; van der Sloot, H. A.; and Comans, R. N. J.: The leaching of major and trace elements from MSWI bottom ash as a function of pH and time.In: Applied Geochemistry, 21(2), 2006, pp. 335-351

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

[19] Eighmy, T. T.; Crimi, D.; Zhang, X.; Gress, D. L.: Influence of void change, cracking, and bitumen aging on diffusional leaching behavior of pavement monoliths constructed with MSW combustion bottom ash. In: Transportation Research Record. 1486, Transportation Research Board, Washington, D.C., 1995, pp. 42–48

[20] Eighmy, T. T.; Eusden, J. D.; Marsella, K.; Hogan, J.; Domingo, D.; Krzanowski, J. E.; Stämpfli, D.: Particle petrogenesis and speciation of elements in MSW incineration bottom ash. Environmental Aspects of Costruction with Waste Materials, Proceedings of the international conference on environmental implications of construction materials and technology developments, Maastricht, The Netherlands, 1-3 June 1994

[21] Eurostat 2018: https://ec.europa.eu/eurostat/statistics-explained/pdfscache/10360.pdf

[22] Eusden, J. D.; Eighmy, T. T.; Hockert, K.; Holland, E.; Marsella, K.: Petrogenesis of municipal solid waste combustion bottom ash. In: Applied Geochemistry, 14(8), 1999, pp. 1073-1091

[23] Fernandez Bertos, M.; Simons, S. J. R.; Hills, C. D.; and Carey, P. J.: A review of accelerated carbonation technology in the treatment of cement-based materials and sequestration of CO(2). Journal of Hazardous Materials, 112(3), 2004, pp. 193-205

[24] Filipponi, P.; Polettini, A.; Pomi, R.; Sirini, P.: Physical and mechanical properties of cement-based products containing incineration bottom ash. In: Waste Management, 23(2), 2003, pp. 145-156

[25] Forsøgsstrækning på Nordhavnen: Forbrændingsslagge som bundsikring og ubundet bærelag til vejbygning, Rapport 522, Vejdirektoratet, 2014

[26] Forteza, R.; Far, M.; Segui, C.; Cerda, V.: Characterization of bottom ash in municipal solid waste incinerators for its use in road base. In: Waste Management, 24(9), 2004, pp. 899-909

[27] Freyssinet, P.; Piantone, P.; Azaroual, M.; Itard, Y.; Clozel-Leloup, B.; Guyonnet, D.; Baubron, J. C.: Chemical changes and leachate mass balance of municipal solid waste bottom ash submitted to weathering. In: Waste Management, 22(2), 2002, pp. 159-172

[28] Glasser, F. P.: Fundamental aspects of cement solidification and stabilisation. Journal of Hazardous Materials, 52(2-3), 1997, pp. 151-170

[29] Gomez, E.; Rani, D. A.; Cheeseman, C. R.; Deegan, D.; Wise, M.; Boccaccini, A. R.: Thermal plasma technology for the treatment of wastes: A critical review. Journal of Hazardous Materials 161[2-3], 2009, pp. 614-626

[30] Goumans, J. J. M.; van der Sloot, H. A.; Aalbers, Th. G.: Environmental Aspects of Construction with Waste Materials. Elsevier Science B.V., Amsterdam, The Netherlands, 1994

[31] Hjelmar, O.; Holm, J.; Crillesen, K.: Utilisation of MSWI bottom ash as sub-base in road construction: First results from a large-scale test site. In: Journal of Hazardous Materials, 139(3), 2007, pp. 471-480

[32] Hjelmar, O.; van der Sloot, H.A.; Comans, R.N.J.; Wahlström, M.: EoW Criteria for Waste-Derived Aggregates. In: Waste Biomass Valor (2013) 4, 2013, pp. 809-819

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

[34] Kikuchi, R.: Recycling of municipal solid waste for cement production: pilot-scale test for transforming incineration ash of solid waste into cement clinker. In: Resources Conservation and Recycling, 31(2), 2001, pp. 137-147

[35] Klein, R.; Baumann, T.; Kahapka, E.; Niessner, R.: Temperature development in a modern municipal solid waste incineration (MSWI) bottom ash landfill with regard to sustainable waste management. In: Journal of Hazardous Materials, 83(3), 2001, pp. 265-280

[36] Krzanowski, J. E.; Eighmy, T. T.; Crannell, B. S.; Eusden, J. D.: An analytical electron microscopy investigation of municipal solid waste incineration bottom ash. In: Journal of Materials Research, 13(1), 1998, pp. 28-36

[37] Ksaibati, K.; Zeng, M.: Evaluation of moisture susceptibility of asphalt mixtures containing bottom ash. In: Transportation Research Record. 1832, Transportation Research Board, Washington, D.C., 2003, pp. 25–32

[38] Lam, C. H. K.; Barford, J. P.; Mckay, G.: Utilization of municipal solid waste incineration ash in Portland cement clinker. In: Clean Technologies and Environmental Policy, 13(4), 2011, pp. 607-615

[39] Luo, H. L.; Chen, S. H.; Lin, D. F.; Cai, X. R.: Use of incinerator bottom ash in open-graded asphalt concrete. In: Construction and Building Materials, 149, 2017, pp. 497-506

[40] Lynn, C.; Ghataora, G. S.; Ravindra, K. D.: Environmental impacts of MIBA in geotechnics and road applications. In: Environmental Geotechnics, 5 (EG1), 2016, pp. 31-55

[41] Lynn, C.J.; Ghataora, G.S.; Dhir, R.K.: Municipal incinerated bottom ash (MIBA) characteristics and potential for use in road pavements. In: International Journal of Pavement Research and Technology 10, 2017, pp. 185-201

[42] Meima, J.; Comans, R. N. J.: The leaching of trace elements from municipal solid waste incinerator bottom ash at different stages of weathering. In: Applied Geochemistry 14[2], 1999, pp. 159-171

[43] Muchova, L.: Wet physical separation of MSWI bottom ash. PhD Thesis, Delft University of Technology, 2010

[44] Overgaard, T.: Anvendelse af forbrændingsslagge i Danmark. Presentation from Askdagen 2016

[45] Pan, J. R.; Huang, C. P.; Kuo, J. J.; Lin, S. H.: Recycling MSWI bottom and fly ash as raw materials for Portland cement. In: Waste Management, 28(7), 2008, pp. 1113-1118

[46] Savyen, H.; Eder, P.; Garbarino, E.; Muchova, L.; Hjelmar, O.; van del Sloot, H.; Comans, R.; van Zomeren, A.; Hyks, J.; Oberender, A.: Study on methodological aspects regarding limit values for pollutants in aggregates in the context of the possible development of end-of-waste criteria under the EU Waste Framework Directive. In: Rep. No. JRC91036, European Commission, Joint Research Centre, Institute for Prospective Technological Studies, 2014

[47] Schneider, J.; Vehlow, J.; Vogg, H.: Improving the MSWI bottom ash quality by simple in-plant measures. In: Goumans, J. J. J. M.; van der Sloot, H. A.; Aalbers, Th. G. (eds.): Environmental Aspects of Construction with Waste Materials, Elsevier Sci, Amsterdam, 1994, pp. 605-620

[48] Selinger, A; Schmidt, V; Bergfeldt, B; Vehlow, J; Simon, FG.: Investigation of sintering processes in bottom ash to promote the reuse in civil construction - Part 1: Element balance and leaching. In: Goumans, JJJM.; Senden, GJ.; van der Sloot, HA. (eds.): Waste Materials in Construction: Putting Theory in Practice. Amsterdam: Elsevier Science, 1997, pp. 41–49

[49] Silva, R. V.; de Brito, J.; Lynn, C. J.; Dhir, R. K.: Use of municipal solid waste incineration bottom ashes in alkali activated materials, ceramics and granular applications: A review. In: Waste Management, 68, 2017, pp. 207-220

[50] Speiser, C.; Baumann, T.; Niessner, R.: Morphological and chemical characterization of calcium hydrate phases formed in alteration processes of deposited municipal solid waste incinerator bottom ash. Environ. Sci. Technol., 34(23), 2000, pp. 5030-5037

[51] Steketee, J.; Timmerije, M.; van Aalten, J.: Accelerated carbonation and washing of MSWI bottom ash: pilot experiments and full scale applications. Wascon 2009, Lyon

[52] Styron, R. W.; Gustin, F. H.; Viness, T. L.: MSW ash aggregate for use in asphalt concrete. In: ASTM STP 1193, 1993, pp. 129–144

[53] Van Gerven, T.; Van Keer, E.; Arickx, S.; Jaspers, M.; Wauters, G.; Vandecasteele, C.: Carbonation of MSWI-bottom ash to decrease heavy metal leaching, in view of recycling. Waste Management, 25(3), 2005, pp. 291-300

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