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Environmental impacts of the use of bottom ashes from municipal solid waste incineration: A review

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ABSTRACT

This paper presents a literature review concerning the performance from an environmental viewpoint of construction related products made with municipal solid waste incinerator bottom ash. It starts with an initial assessment of the bottom ash, and how it performs when used as aggregate substitute in cement-based products, as cement constituent and as raw feed in cement production. Evaluation of the material's environmental performance when used as aggregate replacement in unbound and cement-bound base and subbase layers for road pavement construction, as well as in asphalt concrete layers, is also undertaken. This paper also appraises the behaviour of ceramic-based products, including glass, glass-ceramics, and general ceramics. As a result of the high quantities of potentially leachable contaminants inherent to the bottom ash, the environmental assessment carried out throughout this paper is mostly based on the materials' leaching behaviour, but also based on life cycle assessments and gas emission analyses. The results of several leaching trials, conducted according to various specifications, were reviewed and paralleled with corresponding regulations, with the objective of establishing the products' viability from an environmental point of view.

1. Introduction

The worldwide generation of municipal solid waste (MSW) is significantly large; in 2012, the production of this waste was about 1.3 billion tonnes and is expected to increase to 2.2 billion tonnes, by 2025 (Hoornweg and Bhada-Tata, 2012). MSW is comprised of a wide array of constituents, including food, plastics, paper, metals, glass, and textiles, the amount of which varies according to the practices of different cultures, policies and legislation concerning the management of wastes, and on the main economic sectors of different regions (Burnley, 2007; Liu et al., 2006; Wu et al., 2016).

The incineration of MSW with energy recovery is a fundamental stage of the material's life cycle and management as it allows reducing the mass and volume of MSW by 70% and 90%, respectively (Tillman, 1989). For this reason, it is considered as the best cost-effective approach for treating MSW and conserving landfill space area. Of the initial total mass of MSW, most of it is released in the flue gas (about 70%) and a smaller amount turns into residues caught in the air pollution control (APC) systems (Brunner and Rechberger, 2015). The main compounds existing in these emissions include: hydrogen chloride (HCl); nitrogen oxides (NO_x); carbon monoxide (CO); dioxins - polychlorinated dibenzo-*p*-dioxins (PCDD); furans - polychlorinated dibenzofurans (PCDF) (Alonso-Torres et al., 2010). The plant must be designed and operated in such a way that the flue gas resulting from the combustion process must be subjected to a temperature of at least 850 °C for two seconds in order to ensure proper breakdown of toxic organic substances (CEU, 2000). The temperature requirements increase to 1100 °C for at least two seconds, when incinerating hazardous wastes with a content of more than 1% of halogenated organic substances, expressed as chlorine (CEU, 2000). After the incineration process, close to 25% of the initial total mass of MSW are municipal solid waste incinerator bottom ashes (MIBA) (Brunner and Rechberger, 2015). This fraction, however, depends on several variables including the characteristics of the MSW itself (e.g. content of inert materials), the type of furnace (e.g. moving grate, rotary kiln, fluidized bed), the efficiency of the combustion process, among others, which also affect the properties of the resulting MIBA (Chang and Wey, 2006; Collivignarelli et al., 2017). Considering the high quantities of MIBA generated as a result of the combustion of MSW, rather than being looked upon as useless wastes and disposing them in landfills, there have been noteworthy efforts in establishing effective valorisation techniques and using them as substitute for natural resources in construction applications and into

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the manufacturing of new materials (Reijnders, 2007b). Indeed, even from an economic perspective, they are more appealing when compared with their natural counterparts; in Portugal, for example, in some cases, the MIBA producer does not charge for the product, since most of the revenue from its production comes from selling the recovered metals.

However, fly ashes and bottom ashes from MSW incineration may contain high amounts of hazardous constituents, which may leach out when exposed to e.g. rainwater and can contaminate nearby sensitive recipients, including water bodies, groundwater systems, and, subsequently, fauna and flora (Fuchs et al., 1997; Shih and Ma, 2011a, 2011b, Huang et al., 2017; Huber and Fellner, 2018). For this reason, in the value adding process of MIBA, in addition to the evaluation of their technical feasibility, leachability, ecotoxicity testing and life cycle assessments (LCA) must also be performed simultaneously in order to increase public confidence and acceptance (Breslin et al., 1993). Therefore, this paper seeks to provide an overview of the environmental impacts of different types of construction materials containing MIBA, based on the results of several studies, which were compiled, reorganized and subsequently evaluated. These applications include its use as aggregate or as raw material in the production of cementitious composites, as aggregates in road construction and in the manufacture of ceramic-based products. The majority of the evaluation made throughout this paper was built upon the MIBA-containing materials' leaching behaviour, as it was, undoubtedly, the most popular approach within the literature to assess their environmental performance. Nevertheless, appraisal to the material's environmental impact was also made on the varying gas emissions (e.g. volatilization of heavy metals and organic compounds) as a result of specific manufacturing techniques and based on LCA studies that have compared its use with more conventional scenarios.

2. Methodology

The preparation of this review followed a specific strategy. The initial phase consisted of gathering publications based on various aspects: relevance of the title in terms of environmental impacts of MIBA-containing materials; type of application including MIBA; and existence of significant data for analysis. In the light of the great number of publications, it became necessary to perform an initial appraisal to ascertain which publications were worth pursuing, based on their contents' quality. An analysis was performed for each publication to establish how relevant its contents were (e.g. tests performed, main results, and conclusions) to the theme of this paper. This information was subsequently identified and written in a spreadsheet. Based on this information, a preliminary table of contents was made, which served as a guide for the upcoming investigation. This led to a comprehensive examination of the information regarding the environmental impacts of the use of MIBA in the manufacture of cement-based and ceramic products, and the construction of road pavements.

3. Treatment processes of MIBA

After the process of MSW incineration, MIBA may be subjected to a number of different treatments to reduce the potentially high mobility of hazardous constituents. Such treatment procedures, which depend on the intended application of MIBA, include washing, particle density-based separation, heat treatment (e.g. hydrothermal solidification, vitrification), stabilization with the addition of hydraulic binders, natural weathering, among others (Dhir et al., 2018). The latter, being the most widely applied treatment process, is given greater emphasis here. The other treatments, in spite of their importance under certain circumstances, are not described in detail here as this was already made in other publications (Dhir et al., 2018) and it is not within the scope of this paper.

By stockpiling the fresh MIBA for a certain period before its use (usually at least three months) will allow the occurrence of biodegradation, carbonation and hydration reactions (Arickx et al., 2010, 2006; Baciocchi et al., 2010; Dijkstra et al., 2006). The reaction between the alkaline material and the atmospheric CO_2 results in the formation of carbonates (Arickx et al., 2006; Baciocchi et al., 2010; Costa et al., 2007), mainly calcite (Freyssinet et al., 2002). Further hydration reactions result in the material's greater stabilization (Cornelis et al., 2008; Gori et al., 2011; Marchese and Genon, 2009), through the formation of mineral species capable of encapsulating certain toxic constituents, resulting in improved leaching behaviour (Baciocchi et al., 2010; Cornelis et al., 2006, 2012, Shimaoka et al., 2007; Wei et al., 2014, 2011a, 2011b).

Another treatment process, applied to MIBA in only some cases, is exposing them to high temperatures, leading to changes of the mineral and chemical phases' configuration. The output of this process is a less porous and denser material, exhibiting lower ecotoxicity due to the thermal destruction of organic compounds and lower mobility of heavy metals (Chandler et al., 1997; Cheng et al., 2002, 2007; Kuo et al., 2003; Yang et al., 2003). Nevertheless, despite the high efficacy of thermal processes, these have high energy demands with their own considerably high environmental impacts associated (Gomez et al., 2009; Miyagoshi et al., 2006) and would only make sense if they are already incorporated to the intended application's production process (i.e. ceramic products).

4. Cement-based products

There have been several studies on the solidification/stabilization (S/S) of MIBA with the use of cementitious binding systems (Li et al., 2018), in order to encapsulate hazardous elements and ensure minimum leaching criteria for safe landfill disposal. However, in this paper, emphasis is made on studies that have used processed MIBA into the manufacture of a value-added construction material, namely its use as natural aggregate replacement in cementitious products, as pozzolanic addition, and as raw feed in the production of cement clinker. Table 1 presents the main results based on the leachability behaviour evaluated in those studies.

One should be aware that, even though some of the leaching tests presented in Table 1 have been withdrawn and replaced with up-to-date procedures, they have nonetheless provided concrete evidence at the time of the study and should not be discarded based on that criteria. Furthermore, the evaluation here and throughout the paper is made based on the relative performance of the materials within the same study, which were analysed under the same conditions, and should not to be interpreted as a comparison of results between different testing methods. Aggregate replacement

The use of MIBA as aggregate replacement may involve its conversion to a safe and industry-fit aggregate, which normally involves sorting, crushing, grading, pelletisation, thermal treatment and/or binding the material with cement to produce granules. In the latter S/S process, the lower mobility of hazardous elements is attributed to the significantly reduced surface area exposed to a leaching agent and to mineralogical changes, wherein those elements become physically or chemically bound in the matrix. Reasonably dense cement-stabilized MIBA will exhibit enhanced leaching behaviour and thus the results of its evaluation are more representative of the material's performance during its life cycle, in comparison with the assessment made on the same material, but crushed to a smaller particle size (Sorlini et al., 2017). However, at the end of the product's life, it is likely to be crushed into a granular form thereby making it important to ascertain its leachability, since, from an environmental viewpoint, the leached concentrations would be less favourable (Reijnders, 2007a; Sorlini et al., 2017). Indeed, it has been established, by means of an LCA, that the use of MIBA as partial aggregate replacement in the production of cement-based products can be less preferable when compared to its use in road pavement construction, due to the considerable leaching of