MSWI-BA in Cement-based Materials Review

Subjects: Construction & Building Technology
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Waste management is a vital environmental issue in the world today. Municipal solid wastes (MSWs) are discarded in huge quantities on a daily basis and need to be well controlled. Incineration is a common method for reducing the volume of these wastes, yet it produces ashes that require further assessment. Municipal solid waste incineration bottom ash (MSWI-BA) is the bulk byproduct of the incineration process and has the potential to be used in the construction sector

Keywords: municipal waste ; bottom ash ; concrete ; cement mortar ; sustainability ; sustainable construction materials ; waste in construction ; waste management ; circular economy

1. Introduction

Waste management is becoming one of the most important environmental issues worldwide. Municipal solid wastes (MSWs) include materials that are discarded in everyday residential, commercial, and institutional activities. The world produces around 3.5 million tons of MSW every day [1]. For managing these wastes, some countries such as Japan and the European Union member states are implementing developed environmental policies [2]. However, due to the increase in population growth and urbanization, MSW is increasing dramatically, with an expectation to reach 6.1 million tons daily by the year 2025 [3]. This rise in disposal of MSWs is leading to adverse social and environmental impacts [4].

In general, most countries dispose of MSW in landfills rather than using composting or incineration [5]. Poor MSW management leads to the emission of greenhouse gases that contribute to about 5% of worldwide emissions [1]. It also triggers climate change and pollution [6]. Very recently, the COVID-19 worldwide outbreak has created new challenges for MSW management, where related practices must improve to control the pandemic [7]. The outbreak also caused some changes to the volume and sources of MSW [8]. Therefore, a suitable method for the treatment of MSW must be followed to mitigate its negative consequences. Two of the major methods available for the treatment of MSWs are thermal treatment and landfilling.

Landfilling is the most common method used to manage MSW. It is the process of an established dumping of wastes in an assigned area located far from residential areas [9]. It is estimated that there are around 150,000 landfills in Europe containing more than 30 billion cubic meters of MSW [10]. There are two types of landfills: open landfills and sanitary landfills. An open landfill permits the exchange of materials between the landfill and the environment, whereas a sanitary landfill is completely isolated [11]. Some common concerns of landfilling include groundwater pollution and soil contamination [12].

On the other hand, thermal treatment involves a change of the chemical and physical structure of MSW by high temperatures. The most widespread type of thermal treatment used for MSW is incineration. In countries like Japan, Denmark, Sweden, and Switzerland, more than 50% of MSWs are incinerated [13]. According to Lu et al. [14], there were 1179 MSW incineration plants around the world by 2015, where their total capacity exceeded 700,000 tons per day. Incineration is expected to reduce the volume of MSWs by 90% [15]. The leftovers are transformed into two types of residues: fly ash (FA) and bottom ash (BA) [16]. FA is usually excluded from the recycling application for its inclusion of hazardous elements [17]. In contrast, BA is made of incombustible materials and comprises around 80% of the leftovers.

Reduction in landfill space is the main advantage of incineration; however, this is not the final solution for MSW, since discarded ashes must be suitably managed [18]. Since the greatest portion of the incineration process byproduct is municipal solid waste incineration bottom ash (MSWI-BA), there has been an extensive effort by researchers in different fields to investigate applications rather than landfilling. MSWI-BA is mainly recycled in road base applications. For example, MSWI-BA was proved to be a suitable alternative for aggregates in road embankment applications [19]. It also contributes to the reduction of construction costs. Lynn et al. [20] demonstrated that MSWI-BA meets the minimum requirements of bearing capacity and abrasion resistance to be used as a subbase in road pavement. The main concern of this utilization is the possible leaching of contaminants into the environment, where pretreatment of the material is recommended to alleviate the leaching consequences [21].

In addition to the road base, MSWI-BA could by recycled in different applications. In India, for example, it was found that MSWI-BA could be used efficiently as a low-cost adsorbent for different types of dyes [22]. MSWI-BA was also utilized for gas purification, where it was implemented to remove reduced sulfur compounds from landfill gas [23]. Other applications of MSWI-BA include ceramic tile production [24], bricks [25], and glass [26].

Concerning the utilization of MSWI-BA as aggregates in concrete, research on this topic started at least more than twenty years ago [27][28]. Natural aggregates (NA), mainly sand and gravel, constitute about 80% of concrete by volume [29]. Due to the increased demand of concrete, huge amounts of NA are being extracted, triggering considerable environmental damage [30]. This includes damaging biodiversity, water supplies, and landscapes [31]. Therefore, recycling waste materials in concrete is becoming a popular method for the reduction of natural resource consumption [32]. MSWI-BA, being the bulk of the incineration process of MSW, has the potential to alleviate the mentioned environmental impacts if used properly.

2. Properties of MSWI-BA

2.1. Physical Properties

MSWI-BA is a gray to black amorphous material. Its quality depends on several factors, including (1) the waste content, (2) type of combustion unit, and (3) type of air pollution control device used in the incinerator [33]. According to Dou et al. [34], more than 60% of the particles were in the typical range of NA between 0.02 and 10 mm and around 5–15% were in the form of silt and clay. The authors also disclosed that MSWI-BA may contain up to 30% of particles larger than 10 mm.

Additionally, MSWI-BA has a specific gravity ranging from 1.5 to 2.0 for fine particles and 1.8 to 2.4 for coarse particles [35]. The water absorption ranges from 2.4% to 15%, with an average of 9.7% [20]. Therefore, when compared with typical NA, MSWI-BA has a lower specific gravity but much higher water absorption. However, little effort has been made by researchers to improve the physical properties of MSWI-BA to be utilized as aggregates [36]. The variations in the main physical properties of MSWI-BA are represented in Table 1 based on data selected from the different literature [37][38][39][40][41].

Table 1. Physical properties of MSWI-BA from the selected literature [37][38][39][40][41].

Content (%)	Reference					Range
	[37]	[38]	[39]	[40]	[41]	
Fineness modulus	**2.52**	**3.10**	**-**	**2.51**	**1.55**	**1.55–3.10**
Specific gravity	**2.20**	**2.15**	**2.20**	**2.20**	**2.30**	**2.15–2.30**
Water absoprtion (%)	**12.8**	**-**	**9.2**	**12.8**	**10.0**	**9.2–12.8**

2.2. Chemical Properties

Studies show great variation in the composition of MSWI-BA due to samples obtained from different countries and at different times [42]. Table 2 shows the variation in chemical composition of MSWI-BA selected from different countries [43][44][45][46][47]. Although other samples from different studies might show different content in the material, it can be concluded that the main oxides that comprise MSWI-BA are SiO_2, Al_2O_3, CaO, and Fe_2O_3, regardless of the source of the waste. Also, high loss on ignition (LOI) is detected in some samples.

Table 2. Chemical composition of MSWI-BA from selected literature [43][44][45][46][47].

Content (%)	Reference					Range
	[43]	[44]	[45]	[46]	[47]	
SiO_2	**60.2**	**37.3**	**23.2**	**21.1**	**49.6**	**21.1–60.2**
Al_2O_3	**8.2**	**6.6**	**6.2**	**13.1**	**11.0**	**6.2–13.1**
CaO	**9.9**	**21.3**	**58.4**	**35.9**	**17.3**	**9.9–58.4**

Content (%)	Reference					Range
	[43]	[44]	[45]	[46]	[47]	
Fe_2O_3	**5.0**	**2.9**	**2.9**	**8.1**	**5.4**	**2.9–8.1**
MgO	**1.3**	**1.5**	**2.3**	**1.4**	**2.1**	**1.3–2.3**
SO_3	**-**	**1.6**	**2.3**	**0.3**	**1.2**	**0.3–2.3**
K_2O	**1.0**	**1.7**	**0.6**	**0.1**	**1.6**	**0.1–1.7**
Na_2O	**1.1**	**2.3**	**-**	**0.5**	**6.0**	**0.5–6.0**
Cl^-	**2.4**	**1.2**	**-**	**1.7**	**-**	**1.2–2.4**
LOI [1]	**2.6**	**16.3**	**4.2**	**15.6**	**-**	**2.6–16.3**

[1] Loss on ignition.

In addition to the mentioned main elements, there are several toxic elements found in MSWI-BA [20]. Heavy metals such as Pb, Zn, Al and many others are present and may cause leaching problems that have adverse effects on the environment [42]. The leachate pH is considered the most important factor that influences the leaching of heavy metals in MSWI-BA [48]. Ferrous metals are found in the range of 7–15% of the MSWI-BA while non-ferrous metals are only around 2% [49].

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