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A review on the utilization of municipal solid waste incineration (MSWI) bottom ash as a mineral resource for construction materials

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ABSTRACT

In recent years, the widespread application of waste incineration technology has led to an increased generation of municipal solid waste incineration (MSWI) bottom ash. There is growing interest in the use of MSWI bottom ash as a mineral resource to produce construction materials. The utilization potential of MSWI bottom ash is determined by its chemical and mineralogical compositions, which can vary from incineration plant to incineration plant, and even from batch to batch within a single incineration plant. The quality of MSWI bottom ash often needs to be improved before it can be used as supplementary cementitious material (SCM) and precursor for alkali-activated materials (AAM). This review summarizes the composition of MSWI bottom ash sourced from different regions and the proposed treatments for quality upgrades of MSWI bottom ash. The reactivity of MSWI bottom ash as SCM and AAM precursor is discussed. Finally, the challenges regarding the use of MSWI bottom ash as a mineral resource for the production of construction materials are examined and possible solutions are provided.

1. Introduction

With continued global population and economic growth, municipal solid waste (MSW) generated in the world is expected to increase dramatically, reaching 3.4 billion tonnes by 2050 [1]. This estimated waste generation almost doubles the MSW collected in 2016 (around 2.01 billion tonnes) [1]. By converting waste to thermal energy, waste incineration plants provide a sustainable solution to the MSW that is difficult to compost or recycle [2–4]. Incineration is considered the best solution for MSW that requires landfills, especially in densely populated countries with limited land [5]. Over the past few decades, MSW processed by waste-to-energy plants around the world has accounted for an increasing proportion of the total MSW generation. In 27 European Union countries, MSW treated by incineration rose from 15% in 1995 to 27% in 2020 [6]. In the USA, the percentage of MSW combusted with energy recovery increased from zero in 1960 to 12% in 2018 [7]. In China, 62% MSW was sent to incineration plants in 2020 (146 million tonnes), while only 3% MSW was incinerated in 2004 (4.5 million tonnes) [8]. Every year, Indian waste-to-energy plants are burning more MSW to generate electricity. There is a linear increase in municipal waste energy capacity in India, from 53 MW in 2009 to approximately 217 MW in 2021 [9]. The global waste-to-energy market is predicted to grow at an annual rate of 7.4%, from USD 33

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billion in 2020 to USD 55 billion in 2027 [10].

The emission of air pollutants and the generation of residues are the primary environmental concerns of waste incineration [11]. The issue of air pollution can be addressed by installing an effective air pollution control system in waste incineration plants [12,13]. However, the disposal of incineration residues is still an issue that needs to be properly addressed. The residue generation is strongly influenced by waste incineration technology. It has been reported that the mass of the residues produced after MSW incineration can be around 20% of the waste input [14–16]. The incineration of MSW generates three types of residues: bottom ash, fly ash (including the economizer/boiler ash), and air pollution residue [16]. Among these residues, only bottom ash can be considered as non-hazardous waste [17]. The municipal solid waste incineration (MSWI) bottom ash is usually collected at the bottom of the combustion furnace and can account for 80–90 wt% of the total incineration residue [18,19]. Since the amount of municipal solid waste being incinerated is on the rise, the pressure to dispose of waste incineration residues will inevitably increase. Considering the wide availability of MSWI bottom ash, it is worth exploring the technical feasibility of recycling this industrial by-product.

The primary constituents in MSWI bottom ash are metals and minerals [20]. The metal scraps in MSWI bottom ash are recyclable. In addition to metal recovery, recycling the minerals present in MSWI bottom ash is also important. This action would help mitigate the depletion of primary mineral resources in the world, as terrestrial mineral deposits are not renewable over human timescales [21]. The minerals in MSWI bottom ash can be used in the production of ceramics [22–27] and construction materials (including cement clinker, aggregates, and binders) [28–34]. At present, the most common application of MSWI bottom ash is as aggregate for the construction of roads and embankments [35]. The utilization of MSWI bottom ash as supplementary cementitious material (SCM) or precursor for alkali-activate materials (AAM) remains challenging due to its diverse and complex composition. The physical and chemical properties of MSWI bottom ash strongly depend on the feedstock composition, the incineration technology, and the treatment method.

In order to promote the utilization of MSWI bottom ash as a mineral resource in the production of construction materials, it is necessary to provide an overview of the compositions of MSWI bottom ash produced in different regions and identify the factors that influence the reactivity of MSWI bottom ash as SCM and AAM. To the best of our knowledge, this topic has rarely been covered in previous review articles. Most of the review papers covered the quality-upgrade treatments of MSWI bottom ash. The main focus is the literature related to the separation of particles, removal of metals (including aluminum and zinc), and reduction of hazardous component leaching (including heavy metals and soluble salts) [36–41]. Little attention has been paid to the effects of quality-upgrade treatments on the composition and reactivity of MSWI bottom ash. Lam et al. [36], Dou et al. [38], and Joseph et al. [40] published review papers in 2010, 2017, and 2018, respectively. In these review articles, information on the chemical composition of MSWI bottom ash was collected. However, at that time, only very limited information was available, making it difficult to perform a comprehensive and systematic analysis of the chemical composition of MSWI bottom ash produced worldwide. To date, there is no specific summary of the mineral compositions of MSWI bottom ash.

In recent years, the number of publications about using MSWI bottom ash as a mineral resource in construction materials has increased dramatically. There is a need to update the most recent data on the composition of MSWI bottom ash and to provide an extensive review of the reactivity of MSWI bottom ash as SCM and AAM precursor. The following aspects are covered in this review paper.

- Properties of fresh MSWI bottom ash. The challenges of using fresh MSWI bottom ash as a mineral resource for construction materials are discussed.
- Quality-upgrade treatments conducted on fresh MSWI bottom ash at the plant scale. Special attention is paid to the effect of the stabilization (also called weathering) process on the compositions of MSWI bottom ash.
- Chemical and mineralogical compositions (including the metallic Al and Zn content) of weathered MSWI bottom ash produced worldwide. The composition of weathered MSWI bottom ash is compared with that of clinker, blast furnace slag, and coal fly ash.
- Lab-scale treatments proposed to improve the quality of MSWI bottom ash for its application as SCM or AAM precursor. The effects of different lab-scale treatments on the composition and reactivity of MSWI bottom ash are compared.
- Reactivity of MSWI bottom ash as SCM and AAM precursor. The test methods used by previous researchers are also discussed.

2. Properties of fresh MSWI bottom ash

Fresh MSWI bottom ash is referred to as the ash collected upon its discharge from the bottom of the municipal solid waste incinerator. In most waste-to-energy plants worldwide, MSWI bottom ash is discharged wet, also known as water quenching [42]. The wet-discharged fresh MSWI bottom ash consists of moist granulates with typical particle sizes ranging from 0.1 to 100 mm [3,43,44]. The composition of wet-discharged fresh MSWI bottom ash shows considerable heterogeneity. The materials found in wet-discharged fresh MSWI bottom ash can be broadly classified as glass cullet, synthetic ceramic fragments, minerals (quartz, calcite, lime, feldspars), metals (both paramagnetic and diamagnetic), and unburned organic materials (paper, textiles, plastics) [18].

Apart from heterogeneous composition, wet-discharged fresh MSWI bottom ash also has unstable phase assemblage and high leaching of contaminants into the environment, making its application as an ingredient for construction materials challenging. The phase assemblage of wet-discharged fresh MSWI bottom ash is generally in the metastable state under natural environmental conditions [20]. The phase alteration process immediately starts after quenching the hot bottom ash and will continue if the bottom ash remains wet [45–47]. The wet-discharged fresh MSWI bottom ash has a pH close to that of saturated portlandite solution [48–50]. At a pH above 12, lead (Pb), zinc (Zn), and copper (Cu) are the primary heavy metals that leach out from fresh MSWI bottom ash [49].

3. Plant-scale treatments

Fresh MSWI bottom ash is usually treated at the plant to recycle metal scraps and reduce the leaching of heavy metal ions into the environment. In this context, the treatments performed at the plant are referred to as “plant-scale treatments”. The plant-scale treatments of fresh MSWI bottom ash vary from plant to plant. Fig. 1 summarizes the plant-scale treatments usually performed on fresh MSWI bottom ash. These treatments include particle size reduction, metal extraction, stabilization, cleaning, and classification. As illustrated in Fig. 1, each plant-scale treatment is carried out through corresponding techniques.

3.1. Particle size reduction and metal extraction

The particle size of fresh MSWI bottom ash is reduced by crushing. This treatment aims to liberate the constituents that bond together during the incineration process. After pulverization, the material separation and classification become viable. The goal of metal extraction is to recover ferrous and non-ferrous metals. Magnetic separators are often used to extract Fe-enriched magnetic fractions [43,51]. Eddy current separators are developed to separate conductive metals, especially aluminum and copper [43,51].

3.2. Stabilization

Fresh MSWI bottom ash is stabilized by weathering, which is also called aging. Weathering with a duration of one to three months [52–68] is regarded as the most economical treatment available to stabilize fresh MSWI bottom ash. This process can be conducted before or after metal extraction [44,69–71]. During weathering, fresh MSWI bottom ash is stacked in a heap of 5–10 m high and is exposed to the wind and rain in the open air for months [44,69]. The fresh MSWI bottom ash stockpiles readily react with the oxygen, carbon dioxide, and water present in the environment. The reactions that can occur include dissolution and precipitation of salts, corrosion of the vitreous phases, and hydration and oxidation of the metal fragments [45].

The main purpose of stabilizing fresh MSWI bottom ash is to reduce the risk of heavy metal leaching. Fresh MSWI bottom ash usually has a pH ranging from 12.2 to 12.6 [48–50]. After one month of weathering, the pH drops to around 10.3 [48]. This pH decrease starts to slow down at the age of two months [48]. At 90 days, the pH falls within the range of 9.6–9.8 [49]. Within one and a half years, the pH can reach the lowest value, between 8 and 8.5. This value remains unchanged until the twelfth year [50]. The decrease of pH in fresh MSWI bottom ash, from high alkaline ($\geq$12) to almost neutral ($\approx$8–8.5), could prevent the redissolution of metal hydroxides, one of the main causes of heavy metal leaching from fresh MSWI bottom ash [49]. After the weathering process, the leaching of heavy metals, such as Pb, Zn, Ba, and Mo, was significantly reduced [45,46,49,50,59,72–74].

3.2.1. Effects of weathering on mineralogical compositions

During the weathering process, the reactive constituents in fresh MSWI bottom ash usually react, leading to the formation of secondary phases. Most of the secondary phases are physically and chemically stable and can contribute to the immobilization of heavy metals [46,73]. Table 1 summarizes the secondary minerals and gel phases detected after weathering of fresh MSWI bottom ash. The phases formed can be classified into two categories: secondary minerals and amorphous gel phases. There are four types of secondary minerals commonly found in weathered MSWI bottom ash: carbonate minerals, hydrous sulfate minerals, crystallized metal hydroxides, and zeolite minerals. The minerals that do not belong to any of these four groups are usually only present in one or two types of MSWI bottom ash. These minerals are classified into the fifth group named "other minerals". The amorphous gel phases of different

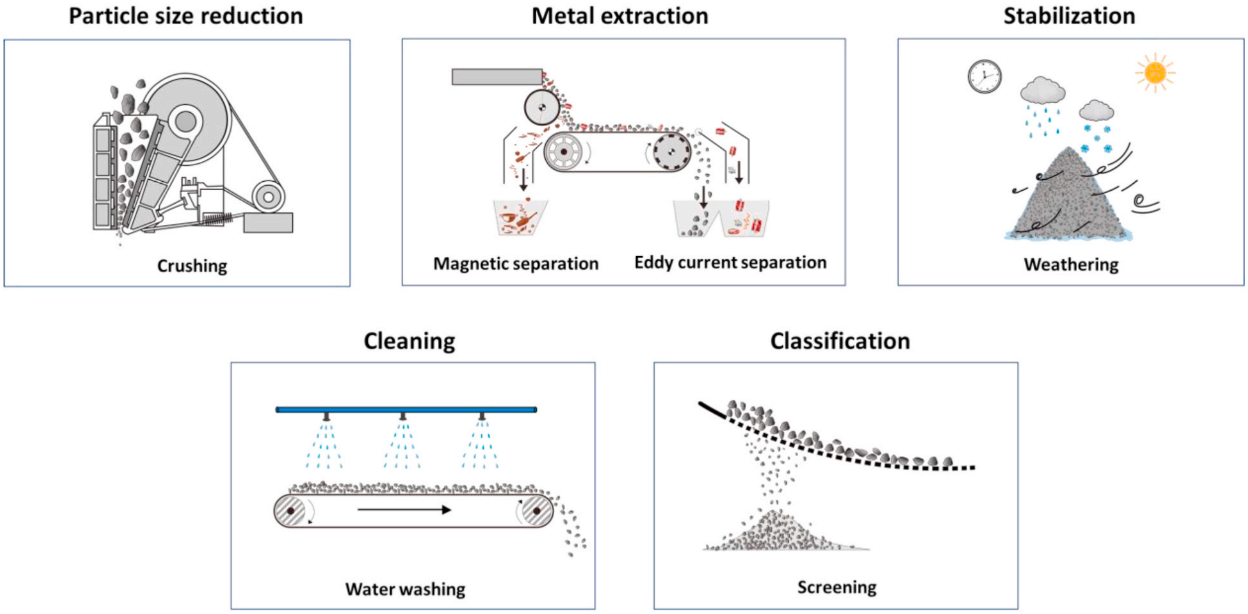


Fig. 1. Plant-scale treatments and corresponding techniques.

Table 1
Secondary mineral and gel phases formed during the weathering process.

Secondary phases	Categories	Most frequently detected phases
Secondary minerals	Carbonate minerals	Calcite [73,75–79]
	Hydrous sulfate minerals	Gypsum [59,75,79,80], ettringite [20,73,75,78–81]
	Crystallized metal hydroxides	Aluminum hydroxides: gibbsite [20,62,78,79], nordstrandite [78]
		Iron hydroxide: goethite [46,78,82], lepidocrocite [20,82], ferrihydrite [81]
	Zeolite minerals	Boggsite [78], chabazite [20,80], gismondine [78], heulandite [79], and laumontite [78,79]
	Other minerals	Tobermorite [20]
		Weddellite [78,79]
Amorphous gel phases	Amorphous aluminum hydroxide and iron hydroxide [46,76,83,84]	
	Al–Si-rich gel [83], Ca–Al–Si-rich gel [45,83], Fe–Si-rich gel [82], Fe–Al–Si-rich gel [83]	

types are usually distinguished according to their chemical compositions.

- Carbonate minerals

As illustrated in Table 1, the most frequently detected carbonate in weathered MSWI bottom ash is calcite. Calcite can be considered as a precipitate formed after the carbonation of $Ca(OH)_2$ in fresh MSWI bottom ash [73,75–79]. The carbonate ion formed after the dissolution of CO_2 in the pore water can also combine with heavy metal cations, retaining these metal cations in the insoluble carbonates. The metals that can be immobilized in carbonates include Fe, Zn, Pb, Cu, Mg, Ni, Cd, Co, and Mn [49,50,78,79,85,86].

- Hydrous sulfate minerals

The hydrous sulfate minerals commonly found in weathered MSWI bottom ash are gypsum and ettringite. These two hydrous sulfates are secondary minerals that can retain SO_4^{2+} [81]. Gypsum can be the hydration product of anhydrite [87]. Anhydrite may already exist in municipal solid waste [78], but it can also form after the oxidation of S and SO_2 in the waste incinerator [88]. Ettringite is sensitive to the pH changes of fresh MSWI bottom ash. With the penetration of atmospheric CO_2, the pH of fresh MSWI bottom ash drops gradually. At a pH of 10–11.5, ettringite can form after gypsum reacts with aluminum hydroxide [20,49,73,78]. When pH is further decreased to below 10.5, ettringite starts to dissolve [89] and tends to carbonate, decomposing into calcite, gypsum, and aluminum hydroxide [78,90,91]. The dissolution of ettringite is believed to be complete at a pH of 8.6 [84]. Ettringite is usually present in small quantities as a secondary mineral in weathered MSWI bottom ash. Apart from gypsum and ettringite, sulfate anion also precipitates other metals, such as Fe, Mg, Cr, and Zn, forming hydrous metal sulfates [78,79]. The formation of these hydrous metal sulfates may be related to the oxidative weathering of the sulfide minerals [92]. Due to the diversity of the metal cations, there is a wide variety in the types of hydrous metal sulfates present in weathered MSWI bottom ash [78].

- Crystalized and amorphous metal hydroxides

The commonly detected metal hydroxides in weathered MSWI bottom ash are aluminum hydroxide and iron hydroxide. These two metal hydroxides are usually formed when residual metallic aluminum or iron in fresh MSWI bottom ash reacts with water and oxygen [47,81]. Aluminum hydroxide and iron hydroxide are insoluble under alkaline conditions and can exist as crystals or amorphous gels. After weathering, the content of amorphous aluminum hydroxide was found to increase [76,84], while a significant decrease in metallic aluminum content was detected [71,93]. The crystalline aluminum hydroxide usually refers to gibbsite, but it can also be nordstrandite. The iron hydroxide can have a crystal structure of goethite, lepidocrocite, or ferrihydrite. The amorphous iron hydroxide can have various morphologies [46]. In addition to aluminum hydroxide and iron hydroxide, heavy metals, such as Mg, Ni, Cu, Pb, Zn, and Cd, can also precipitate as hydroxides. During the weathering process, the solubility of these metal hydroxides reaches the lowest value when the pH of fresh MSWI bottom ash is almost neutral, which helps to reduce the leaching of heavy metals [49].

- Zeolite minerals

Zeolite minerals formed due to weathering vary widely in crystal structure and chemical composition. As reported by previous researchers, the zeolites found in weathered MSWI bottom ash can be boggsite, chabazite, gismondine, heulandite, or laumontite. Considering the high alkalinity of fresh MSWI bottom ash, zeolites are thought to be formed due to alkaline hydrolysis of the glass in fresh MSWI bottom ash [75,78,79]. It is worth mentioning that amorphous aluminosilicate with compositions similar to zeolite is also detected in weathered MSWI bottom ash [94].

- Other minerals

There are some minerals only detected in specific kinds of weathered MSWI bottom ash. These minerals are grouped as “other minerals”. For example, if the fresh MSWI bottom ash contains cement clinker. Tobermorite (C–S–H phase), the hydration product of cement clinker, can be found after weathering [20]. When oxalic acid is detected in the fresh MSWI bottom ash [95], weathering may facilitate the precipitation and crystallization of weddellite (Ca-oxalate) [78,79].

Apart from amorphous aluminum hydroxide and iron hydroxide mentioned above, the amorphous gel phases can be classified into Al–Si-rich gel, Ca–Al–Si-rich gel, Fe–Si-rich gel, and Fe–Al–Si-rich gel. The formation of these gel phases is usually associated with the hydration of residual metals or glass in fresh MSWI bottom ash. These secondary gel phases can contribute to the immobilization of heavy metals via ion exchange [20] or ion absorption [81].

3.3. Cleaning and classification

Cleaning by water washing is to remove the fine contaminants attached to the coarse MSWI bottom ash particles. Classification is realized by mechanical screening, where MSWI bottom ash is separated into multiple grades according to particle size. By adjusting the sieving mesh size, the optimal particle size distribution similar to the natural aggregates can be obtained [70].

4. Compositions of weathered MSWI bottom ash

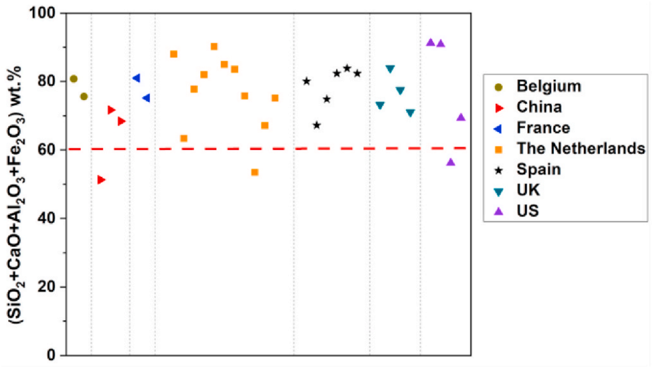
Compared with fresh MSWI bottom ash, weathered MSWI bottom ash produced after plant-scale treatments shows greater potential for being used as an ingredient for construction materials due to its lower leaching of contaminants [45,46,49,50,59,72–74]. The compositions of weathered MSWI bottom ash determine its reactivity as SCM and precursor for AAM. The chemical and mineralogical compositions of weathered MSWI bottom ash used in previous research are summarized in this section. The composition of weathered MSWI bottom ash is also compared with that of Portland cement clinker, blast furnace slag (BFS), and coal fly ash (both Class C and Class F). BFS and coal fly ash are the most commonly used supplementary cementitious materials [96] and AAM precursors [97,98].

4.1. Chemical composition

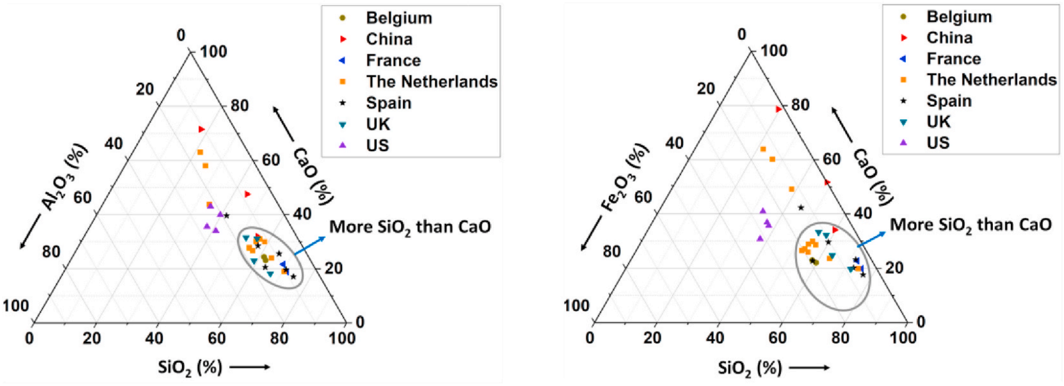
The chemical compositions of weathered MSWI bottom ash were taken from the X-ray fluorescence (XRF) results. Fig. 2 compares the contents of the main components in the weathered MSWI bottom ash sourced from different regions. The weathered MSWI bottom ash came from Belgium [99,100], China [101–103], France [104,105], the Netherlands [52,53,60,61,106–108], Spain [56,58], the United Kingdom (UK) [64–68], and the United States (US) [46]. The ranges of all the components in weathered MSWI bottom ash are given in Table 2, together with those of coal fly ash (both Class C and Class F), BFS, and Portland cement clinker.

4.1.1. Main components

The main components in weathered MSWI bottom ash are SiO_2, CaO, Al_2O_3, and Fe_2O_3. These four components together account for more than 60% of the total weight of weathered MSWI bottom ash (Fig. 2 (a)). The weight percentages of SiO_2, CaO, Al_2O_3, and Fe_2O_3 were plotted in the SiO_2 - CaO – Al_2O_3 and SiO_2 - CaO – Fe_2O_3 ternary diagrams after renormalization to 100%. The ternary diagram graphically depicts the ratios of three components as positions in an equilateral triangle. As illustrated in Fig. 2 (b) and (c), all



(a) Total contents of the main elements



(b) SiO_2-CaO-Al_2O_3 ternary diagram

(c) SiO_2-CaO-Fe_2O_3 ternary diagram

Fig. 2. Comparison of the main components in weathered MSWI bottom ash produced in Belgium [99,100], China [101–103], France [104,105], the Netherlands [52,53,60,61,106–108], Spain [56,58], the UK [64–68], and the US [46]. The ternary diagram is plotted according to the weight percentages of the oxides.

Table 2
Ranges of the components present in weathered MSWI bottom ash [46,52,53,56,58,60,61,64–68,99–103,106–108], coal fly ash [109], granulated blast furnace slag [110], and Portland cement clinker [111].

Compound (wt.%)	Weathered MSWI bottom ash	Class C coal fly ash	Class F coal fly ash	Granulated blast furnace slag	Portland cement clinker
SiO_2	10.2–59.3	11.8–46.4	37–62.1	30–40	21
CaO	13.6–48.1	15.1–54.8	0.5–14	30–50	67
Al_2O_3	4.2–16.3	2.6–20.5	16.6–35.6	7–20	6
Fe_2O_3	1.3–20.2	1.4–15.6	2.6–21.2	0–2.5	3
Na_2O	0.0–8.1	0.2–2.8	0.1–3.6	–	–
Na_2O_e	0.8–9.0	–	–	–	0.7
MgO	1.6–3.3	0.1–6.7	0.3–5.2	0–21	1
SO_3	0.6–6.8	1.4–12.9	0.2–4.7	–	$\leq$3.5–4[a]
S	–	–	–	0–2	–
P_2O_5	0.3–3.5	0.2–0.4	0.1–1.7	–	–
TiO_2	0.3–2.5	0.6–1.0	0.5–2.6	–	–
K_2O	0.4–3.7	0.3–9.3	0.1–4.1	–	–
ZnO	0.2–1.3	–	–	–	–
CuO	0.1–0.9	–	–	–	–
Cl	0.1–9.5	–	–	–	$\leq$0.1[a]
MnO	0.1–1.9	0.03–0.2	0.03–0.1	0.2–2.5	<0.5
PbO	0.2–0.4	–	–	–	–
LOI	2.7–30	0.3–11.7	0.3–32.8	–	<3

[a] Value required by standard EN196-2 [112].

the dots in the ternary diagrams are far from the vertex representing 100% Al_2O_3 and 100% Fe_2O_3. This observation indicates that the percentage of Al_2O_3 or Fe_2O_3 is much lower than that of SiO_2 or CaO in weathered MSWI bottom ash. Most of the dots in the ternary diagram are in the region where the percentage of SiO_2 is larger than that of CaO, indicating that most of the weathered MSWI bottom ash contains more SiO_2 than CaO.

The contents of SiO_2, CaO, Al_2O_3, and Fe_2O_3 in weathered MSWI bottom ash are within the same range as those in coal fly ash, especially the type of Class C (see Table 2). The SiO_2 content of weathered bottom ash varies from 10.2 to 59.3 wt%. This significant variation can also be observed in the SiO_2 content of coal fly ash (both Class C and Class F) [109]. The weathered MSWI bottom ash contains 13.6 to 48.1 wt% CaO, almost the same as Class C coal fly ash. The Al_2O_3 content in weathered MSWI bottom ash ranges from 4.2 to 16.3 wt%, which is close to that in Class C coal fly ash (between 2.6 and 20.5 wt%), but much lower than that in Class F coal fly ash (between 16.6 and 35.6 wt%) [109]. In weathered MSWI bottom ash, the Fe_2O_3 content varies from 1.3 to 20.2 wt%, similar to the situation in coal fly ash (both Class C and Class F).

4.1.2. Soluble salts

The contents of Cl, Na_2O, K_2O, and SO_3 are higher in weathered MSWI bottom ash than in Portland cement clinker (see Table 2), indicating that weathered MSWI bottom ash contains more soluble salts. The chloride content in weathered MSWI bottom ash is above the upper limit (0.1 wt%) of Portland cement clinker, as set by the EN196-2 standard [112]. The equivalent sodium oxide ($\% Na_2O_e = \% Na_2O + 0.658 \times \% K_2O$) content of weathered MSWI bottom ash is between 0.8 and 9.0 wt%, whereas this value changes within the range of 0.22–1.06 wt% for Portland cement clinker [113]. The amount of SO_3 in weathered MSWI bottom ash is between 0.6 and 6.8 wt%. Among available data, three types of weathered MSWI bottom ash exceed the upper limit of SO_3 content (3.5–4 wt%) specified in the standard (EN196-2) [58,103,107].

The excessive soluble salts in weathered MSWI bottom ash may influence its application as SCM. Replacing Portland cement with weathered MSWI bottom ash could dramatically increase the contents of chloride, alkalis, and SO_3 in the binder of Portland cement concrete or mortar. An increase in chloride content can increase the risk of steel corrosion in Portland cement concrete [111]. Increasing the alkali content in binder could make the Portland cement concrete more susceptible to deterioration caused by alkali-silica reaction (ASR) [111]. The higher SO_3 content in the binder of Portland cement concrete may cause late formation of crystalline ettringite, resulting in expansion and cracking of hardened pastes [111].

The chloride content in weathered MSWI bottom ash is higher than in coal fly ash (both Class C and Class F) and BFS (see Table 2). Compared with coal fly ash and BFS, using weathered MSWI bottom ash to prepare AAM may increase the risk of steel corrosion in alkali-activated concrete. As shown in Table 2, the contents of Na_2O and K_2O are higher in weathered MSWI bottom ash than in BFS. Compared with coal fly ash (both Class C and Class F), the Na_2O content in weathered MSWI bottom ash changes within a wider range, indicating that the alkalinity of weathered MSWI bottom ash can be higher. In this case, replacing BFS or coal fly ash with weathered MSWI bottom ash in alkali-activated concrete and mortar may raise the risk of ASR-induced deterioration when reactive aggregates are used. The SO_2 content in weathered MSWI bottom ash is close to that in Class F coal fly ash (see Table 2). The risk associated with late formation of ettringite may not be a problem when weathered MSWI bottom ash is used as AAM precursor. In previous studies, ettringite was not formed in the AAM prepared with weathered MSWI bottom ash [32,114].

4.1.3. Heavy metal and organics

As shown in Table 2, the content of components related to the heavy metals in weathered MSWI bottom ash is generally higher than that in Portland cement clinker, BFS, and coal fly ash (both Class C and Class F). Using weathered MSWI bottom ash as SCM or AAM precursor poses the risks of soil and underground water contamination due to excessive leaching of heavy metals [32,114,115].

The organics in MSWI bottom ash also contribute to heavy metal leaching from MSWI bottom ash, such as the leaching of Cu from humic acid-bound Cu and fulvic acid-bound Cu [116,117]. The content of organic matter in weathered MSWI bottom ash is usually determined by the LOI (Loss on Ignition) method at a temperature of 500–550 °C [118]. The organic matter detected by previous researchers varies from 2.7 to 30 wt% [46,60,107,108].

The LOI value in weathered MSWI bottom ash is similar to Class F coal fly ash [109]. The polycyclic aromatic hydrocarbons (PAHs) adsorbed in coal fly ash are the main organic compounds harmful to the environment and human health, due to their toxicity, mutagenicity, and carcinogenicity [119]. This is different from the situation in MSWI bottom ash. Until now, there is no research indicating that organic compounds are responsible for heavy metal leaching from coal fly ash.

4.2. Mineralogical composition

4.2.1. Crystalline phases

The mineralogical composition of weathered MSWI bottom ash is mainly determined by three factors: composition of the original waste feed, incineration techniques, and weathering strategies. Weathered MSWI bottom ash contains a wide variety of minerals, which can be classified into 11 categories (Table 3). These categories are silicon dioxide (SiO_2), iron oxides (FeOx), silicates, carbonates, sulfates, chloride salts, phosphates, non-ferrous metal oxides, hydroxides, sulfides, and other minerals. The minerals that belong to silicates are further divided into four sub-groups: melilite, feldspar, pyroxene, and other silicates. The group named "other minerals" includes minerals that are unique in specific kinds of bottom ash and only present in rare cases. The detection of quartz, calcite, silicates, and iron oxides is most frequently reported in the literature (see Table 3).

Rietveld-based quantitative X-ray diffraction (QXRD) analysis is widely used to evaluate the abundance of individual crystalline phase and calculate the amount of amorphous phase in weathered MSWI bottom ash. Appendix Table 1 summarizes the results of QXRD analyses of weathered MSWI bottom ash. The quartz content in weathered MSWI bottom ash can vary from 4.7 to 21 wt%. The weight percentage of quartz is usually higher than that of other crystalline phases detected in weathered MSWI bottom ash. However, in the fine fraction (<2 mm) of weathered MSWI bottom ash produced in the Netherlands [80] and Spain [120], calcite is the most abundant crystalline phase. There is a significant difference in the calcite content of weathered MSWI bottom ash collected from different regions. The weathered MSWI bottom ash can contain 0.9 to 22.7 wt% calcite. The total silicate content in weathered MSWI bottom ash is generally below 15 wt%. The silicates commonly found in MSWI bottom ash are gehlenite, akermanite of the melilite group, albite, anorthite of the feldspar group, and diopside, wollastonite of the pyroxene group. Weathered MSWI bottom ash usually contains less than 5 wt% iron oxides, of which magnetite is the largest component.

4.2.2. Amorphous phase

The amorphous phase makes up 30.8 to 81.3 wt% of the weathered MSWI bottom ash used in previous research (see Appendix Table 1). The amorphous content in weathered MSWI bottom ash can be similar to that in coal fly ash, as the amorphous content in coal fly ash ranges between 50 and 95 wt% [127]. However, the amorphous phase in weathered MSWI bottom ash is less than that in BFS, which usually contains more than 90 wt% amorphous phase [128,129]. The amorphous phase is the primary reactive phase in weathered MSWI bottom ash [31,130]. Given that the content of CaO, Al_2O_3, and SiO_2 in the amorphous phase determines the reactivity of coal fly ash and BFS [131], the reactivity of weathered MSWI bottom ash may also depend on the chemical composition of its amorphous phase. It is worth noting that previous studies mainly focused on quantifying the amorphous phase. The chemical composition of this phase was rarely examined.

Table 3
Classifications of minerals present in weathered MSWI bottom ash.

Categories			Typical minerals
1	Silicon dioxide (SiO_2)		Quartz [28,32,46,56,58,59,61–65,68,72,73,75,79,80,82,99–101,103,104,108,114,120]
			Cristobalite [20,58,59,75,79]
2	Iron oxides (FeO_X)		Magnetite and hematite [28,32,46,50,58,59,61,63,64,68,72,75,78,80,82,99,100,104,108,120,121]
			Wustite [50,58,59,63,80,82,99,104,120]
3	Silicates	Melilite	Gehlenite and akermanite [28,32,46,58,59,61–64,72,73,75,80,99,100,104,108,114,121]
		Feldspar	Albite and anorthite [28,46,58,73,99,100,103,108,114,120]
		Pyroxene	Diopside and wollastonite [32,58,59,62,63,72,80,104]
		Other silicates	Mullite [58,101,122], zeolite [20,80]
4	Carbonates		Calcite [28,32,56,58,59,61–65,68,72,73,75,78–80,82,99–101,103,108,114,120,121]
			Dolomite [28,60,75,114]
5	Sulfates		Ettringite, gypsum, and anhydrite [46,59,62,63,72,73,75,79,80,82,99,100,103,104,108,114]
6	Chloride salts		Halite (NaCl) and sylvite (KCl) [28,62,72,73,99,103,108,123–125]
7	Phosphates		–
8	Non-ferrous metal oxides		Rutile [20,28,80], corundum [20], zincite [50]
9	Hydroxides		• Iron hydroxide
			Goethite [46,82], lepidocrocite [20,82], ferrihydrite [81]
			• Aluminum hydroxide
			Gibbsite [20,62,78,79]
10	Sulfides		Copper sulfides [20,126], iron sulfides [20]
11	Other minerals		–

4.2.3. Metallic aluminum and zinc (Al/Zn) content

Unlike coal fly ash and BFS, weathered MSWI bottom ash can contain metallic Al and Zn. The metals detected in weathered MSWI bottom ash are residues that cannot be removed during the metal extraction process of plant-scale treatments [71]. Metallic Al and Zn oxidize under the alkaline conditions in blended cement pastes and alkali-activated pastes. This redox reaction releases hydrogen gas, resulting in volume expansion and strength reduction of hardened pastes [107,130]. In previous research, metallic Zn is only detected in fresh MSWI bottom ash and is present in the form of Al–Zn alloy [132]. The detection of metallic Zn is not reported in the studies of weathered MSWI bottom ash. Only the metallic Al content of weathered MSWI bottom ash is mentioned in the literature (seeTable 4).

The content of residual metallic Al is usually measured with the water displacement method [65]. In this test, weathered MSWI bottom ash is immersed in sodium hydroxide (NaOH) solution, and the hydrogen gas released after the oxidation of metallic Al is collected. The volume of hydrogen gas is measured and used to calculate the percentage of metallic Al by following the stoichiometry of Equation (1). As shown in Table 4, the metallic Al content is below 2 wt% in weathered MSWI bottom ash used in previous research. There is a wide variation in the percentage of metallic Al in MSWI bottom ash produced in different countries. The variation in the content of metallic Al is mainly caused by the difference in the composition of municipal solid waste, the metal recovery process, and particle size.

$$\mathbf{2Al + 2NaOH + 6H_2O \rightarrow 2NaAl(OH)_4 + 3H_2 \uparrow} \qquad \text{Equation 1}$$

5. Lab-scale treatments

In contrast to the plant-scale treatments discussed in section 3, the treatments performed in the laboratory are referred to as “lab-scale treatments”. The goal of lab-scale treatments is to improve the quality of MSWI bottom ash and enable its application as SCM and AAM precursor. Previous work tailored the lab-scale treatments according to the chemical and physical properties of the fresh or weathered MSWI bottom ash. Most of the MSWI bottom ash sent to the laboratory is produced after the plant-scale treatments of fresh MSWI bottom ash.

During lab-scale treatments, the following issues of MSWI bottom ash can be addressed: heterogeneous composition, presence of hazardous components (such as metallic Al, soluble salts, and heavy metals), and low reactivity. Lab-scale treatments can be classified into mechanical treatments, chemical treatments, and thermal treatments (see Fig. 3). In the following sections, the details of each method are introduced. The type of MSWI bottom ash (fresh or weathered) will only be mentioned when this information is included in the literature.

5.1. Mechanical treatments

Most of the mechanical treatments proposed in previous work consist of dry grinding and sieving. The goal of mechanical treatments is mainly to reduce particle size and obtain a homogeneous composition. Due to size reduction, the surface area of MSWI bottom ash is increased after grinding, resulting in improved reactivity. Sieving is performed after grinding to examine the particle size of ground MSWI bottom ash.

Metals embedded in MSWI bottom ash particles can also be removed during mechanical treatments. Current experience indicates that the effect of mechanical treatments on metal removal strongly depends on the parameter setting of the ball mill [135]. Short-time, low-speed dry milling of MSWI bottom ash is recommended, which can break brittle minerals into small fragments and meanwhile press ductile metals into plate-shaped scraps, making it easy to sieve out the metals [107,134]. Plate-shaped metal scraps sieved out from milled MSWI bottom ash are illustrated in Fig. 4. Chen et al. [134] and Sun et al. [136] reported that this method could remove around 80 wt% of the metallic Al present in weathered MSWI bottom ash.

The content of metallic Al in MSWI bottom ash can also be reduced by adding water during the grinding process. Bertolini et al. [33] found that water added for grinding could dissolve the alkalis from MSWI bottom ash, creating an alkaline condition to promote the

Table 4
Metallic Al content in weathered MSWI bottom ash produced in different countries.

Countries	Particle size (mm)	Metallic Al content (wt.%)	References
Belgium	0–2	1.5	[93]
	2–6	0.64	
	6–15	0.24	
	<8	1.1	[59]
Canada	Unknown	0.06	[133]
China	<2.36	0.048	[102]
Germany	2–8	1.22	[55]
	8–16	1.59	
	16–32	1.06	
Spain	0–1	0.38	[120]
	1–2	1.16	
The Netherlands	<2	0.44	[107]
	0–2	0.8	[134]
	1–4	0.1	[108]
	0.25–1	0.13	
	<0.25	0.12	

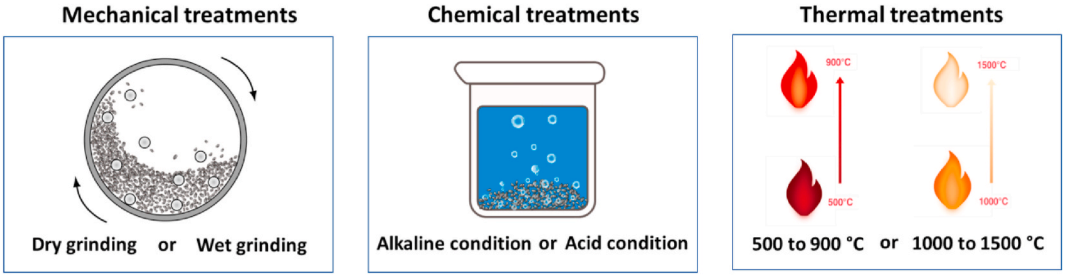


Fig. 3. Lab-scale treatments proposed to improve the quality of MSWI bottom ash for the application as SCM and AAM precursor.

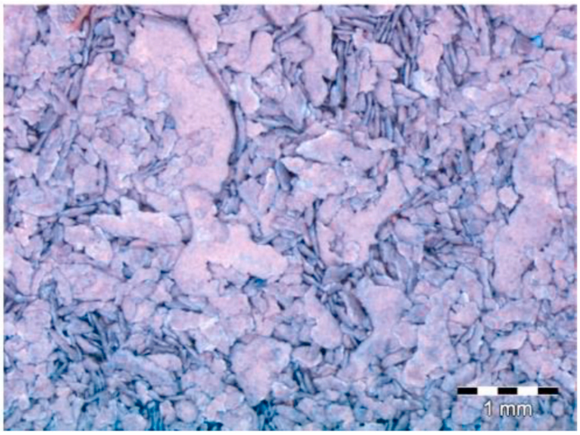


Fig. 4. The plate-shaped metals sieved out after the ball milling of MSWI bottom ash. Adapted and reprinted from Ref. [107] with permission from Elsevier.

corrosion of metallic Al [33]. However, only part of the metallic Al would oxidize during the period of wet grinding. When the slurry obtained after wet grinding of MSWI bottom ash was stored at room temperature, the time required for metallic Al to oxidize entirely at room temperature could vary from 2 days to more than 3 months [33]. The amount of metallic Al that can oxidize depends on the alkalinity of MSWI bottom ash and the parameter setting of the wet milling process.

5.2. Chemical treatments

Chemical treatments of MSWI bottom ash can be alkaline solution treatment, water treatment, or acid solution treatment. The alkaline solution treatment is used to reduce the content of metallic Al and Zn in MSWI bottom ash to zero. The most commonly used alkaline solution is NaOH solution [132,134,137–139]. The factors that influence the reaction rate between NaOH solution and metallic Al and Zn include the particle size of MSWI bottom ash, the concentration of NaOH solution, the liquid-to-solid ratio, and the heating temperature [132,138]. The MSWI bottom ash slurry obtained after NaOH solution treatment can be used directly to prepare alkali-activated materials [139]. However, for the application as SCM, the alkalis that remained in NaOH solution-treated MSWI bottom ash need to be removed by water washing [134,138]. According to Liu et al. [138], the pozzolanic reactivity of MSWI bottom ash was enhanced after the NaOH solution treatment and water washing, but the reasons for this reactivity enhancement were not explained.

The principle of water treatment is similar to alkaline solution treatment. Instead of adding an alkaline solution, water treatment is expected to create an alkaline environment by adding water to dissolve alkalis from MSWI bottom ash. The effectiveness and efficiency of water treatment depend on the particle size of MSWI bottom ash, the mass ratio between water and MSWI bottom ash, and the heating temperature. Joseph et al. [93] reduced the metallic Al content in fresh MSWI bottom ash via water treatment. After ground into powder, fresh MSWI bottom ash was immersed in water at the water-to-solid ratio of 5:1. The mixture was dried at 105 °C for 24 h to accelerate the oxidation of metallic Al. However, the extent to which water treatment reduces the metallic Al content in MSWI bottom ash was not demonstrated [93].

Acid washing combined with water washing is used to reduce the chloride and sulfate content in MSWI bottom ash. Lo et al. [140] washed MSWI bottom ash with water and 0.1 M acetic acid, followed by calcination at 1100 °C. After all these three steps, the chloride content decreased dramatically, from 2.78 wt% in the raw material to 0.09 wt% in calcined MSWI bottom ash. Meanwhile, there is a tenfold reduction in the sulfate content. However, the effectiveness of acid treatment on chloride and sulfate content reduction is not specified. In addition, Saikia et al. [100] found that adding Na_2CO_3 to water can promote the transformation of $CaSO_4$ into more soluble Na_2SO_4, making it easy to remove the sulfate salt from MSWI bottom ash. After Na_2CO_3 treatment, bottom ash particles were washed with deionized water and dried at about 100 °C.

5.3. Thermal treatments

Thermal treatment is usually applied to improve the quality of MSWI bottom ash by burning out the organic substances, promoting the formation of reactive phases, stabilizing heavy metals, and oxidizing metallic Al and Zn. The heating temperature determines the effectiveness of this treatment. In previous studies, the temperature ranges selected are 500–900 °C [65,67,68,107,130] and 1000–1500 °C [19,25,130,136,141,142].

When the heating temperature is between 500 and 900 °C, a substantial amount of harmful organic components can be removed [143]. Thermal decomposition of the dissolved organic carbon in MSWI bottom ash contributes to the decrease in the leaching of Cu [107,144]. The compressive strength of MSWI bottom ash blended cement pastes [100,107] and alkali-activated materials [139] increased significantly after removing organic substances. The retardation of MSWI bottom ash on cement hydration was mitigated after MSWI bottom ash was treated at 550 and 750 °C [107].

Moreover, heating MSWI bottom ash between 550 and 900 °C also promotes the transformation of crystalline phases [65,67,107] and the oxidation of metallic Al [107,130]. Qiao et al. [65,67] reported that heating weathered MSWI bottom ash at 700 °C promoted the formation of hydraulic minerals, such as lime (CaO), gehlenite ($Ca_2Al_2SiO_7$), and mayenite ($Ca_{12}Al1_4O_{33}$). The formation of lime increased the pH of MSWI bottom ash, which would lead to a decrease in the leaching of Sb [107]. Tang et al. [107] indicated that low-temperature thermal treatment could oxidize the surface of aluminum particles present in weathered MSWI bottom ash. However, Chen et al. [130] found that heating weathered MSWI bottom ash at 500 °C for 2 h only reduced the metallic Al content by 0.01 wt%, which was insufficient for the complete oxidation of metallic Al.

The primary purpose of calcinating MSWI bottom ash at 1000–1500 °C is to solve the problem of leaching and increase the amount of amorphous phase. High-temperature thermal treatment of MSWI bottom ash facilitates the decomposition of organic substances (such as organochloride and dioxin) and the volatilization of heavy metals (such as Cu, Pb, and Zn) [142,145]. MSWI bottom ash with an amorphous structure can be obtained when high-temperature calcination is followed by rapid cooling. Lin et al. [19] found that vitrified MSWI bottom ash was highly resistant to leaching, as the glass melts formed at high temperature could immobilize heavy metals. Additionally, when vitrified MSWI bottom ash was used as cement substitute, it exhibited pozzolanic reactivity. In contrast, the combination of high-temperature calcination with slow cooling will reduce the amount of amorphous phase in MSWI bottom ash, leading to a decrease in reactivity [130].

Another advantage of high-temperature thermal treatment is that it helps to solve the problem of metallic Al and Zn. Increasing the calcination temperature to more than 1000 °C prolongs the reaction between metallic Al and Zn with air [130,139]. For example, Sun et al. [136] decreased the metallic Al content by 92.5 wt% after heating weathered MSWI bottom ash at 1000 °C for 2 h. Besides, calcinating bottom ash into molten state facilitates the agglomeration of MSWI bottom ash [67,68,130]. As a result, the metallic Al and Zn could be covered either by glass melts or newly formed crystalline phases, preventing their exposure to the alkaline solution [130]. Chen et al. [130] performed thermal treatment on weathered MSWI bottom ash at 1000 °C for 2 h. The release of hydrogen gas was not detected after immersing thermally treated MSWI bottom ash in NaOH solution.

6. Reactivity of MSWI bottom ash

6.1. Pozzolanic reactivity

The pozzolanic reactivity of MSWI bottom ash is not always measured prior to its application as SCM. There is limited information about the pozzolanic reactivity of MSWI bottom ash. In previous work, pozzolanic reactivity was measured after grinding MSWI bottom ash into powder. The tested MSWI bottom ash was collected from Belgium [99,146], Italy [147], Portugal [148], Singapore [138], and the Netherlands [108].

The methods used to determine the pozzolanic reactivity of MSWI bottom ash include R^3 test [146], saturated lime test [108,138], Frattini test [147], modified Chapelle test [148], and lime reactivity test [99]. Among all these methods, the R^3 test is a newly developed standardized method (see ASTM C1897-20 [149]), and its result shows better correlations to the benchmark of 28-day relative strength than the other conventional standardized methods [150].

The R^3 test was used by Joseph [146] to assess the pozzolanic reactivity of fresh MSWI bottom and weathered MSWI bottom ash produced in Belgium. The test results indicated that the pozzolanic reactivity of weathered MSWI bottom ash was similar to that of Class F coal fly ash and natural pozzolans. Weathered MSWI bottom ash exhibited slightly lower pozzolanic reactivity than fresh MSWI bottom ash.

The saturated lime test is a simplified Frattini test [151]. The saturated lime test was used by Caprai [108] to measure the pozzolanic reactivity of weathered MSWI bottom ash produced in the Netherlands. The weathered MSWI bottom ash sent for testing showed higher pozzolanic reactivity than quartz of the same particle size. The saturated lime test was also used by Liu et al. [138] to assess the pozzolanic reactivity of MSWI bottom ash produced in Singapore. It was not specified in their work whether MSWI bottom ash was collected in a fresh state or after the weathering process. The test result showed that MSWI bottom ash was less reactive than silica fume [138].

Like Liu et al. [138], detailed information about the plant-scale treatments of the MSWI bottom ash tested by Filipponi et al. [147], Simões et al. [148], and Saikia et al. [99] was not provided in their research. Filipponi et al. [147] determined the pozzolanic reactivity of MSWI bottom ash produced in Italy with the Frattini test. The test result indicated that MSWI bottom ash had weak pozzolanic reactivity. The strength gain resulting from the hydration of MSWI bottom could only be detected after 28 days of curing and in blended cement prepared with more than 50 wt% MSWI bottom ash [147].

The modified Chapelle test and lime reactivity test were used by Simões et al. [148] and Saikia et al. [99], respectively, to examine the pozzolanic reactivity of MSWI bottom ash. Simões et al. [148] found that the pozzolanic reactivity of MSWI bottom ash was slightly lower than that of Class F coal fly ash. Saikia et al. [99] compared the lime reactivity of ground MSWI bottom ash with metakaolin. After 7 days, the Ca^{2+} ion consumed by MSWI bottom ash was almost half of that of metakaolin, indicating that the pozzolanic reactivity of MSWI bottom ash was much lower than metakaolin [99].

It should be noted that the CaO content is higher than the SiO_2 content in the MSWI bottom ash used by Liu et al. [138] and Caprai [108]. In comparison, the MSWI bottom ash collected by Joseph [146], Simões et al. [148], Saikia et al. [99], and Filipponi et al. [147] contains more SiO_2 (>40 wt%) than CaO (<26 wt%). In previous studies, MSWI bottom ash with high SiO_2, but low CaO content, was commonly used as SCM to prepare blended cement pastes [19,30,31,33,93,107,115,133,138,140,148,152–160].

6.2. Reactivity as AAM precursor

Very little information is available regarding the reactivity of MSWI bottom ash as AAM precursor. Currently, three methods are proposed in the literature to evaluate the reactivity of MSWI bottom ash as AAM precursor. These methods are the modified Chapelle test [161,162], chemical dissolution test [163], and the chemical attack test [58,164]. The modified Chapelle test is a standardized method designed to assess the pozzolanic reactivity of supplementary cementitious materials. In the research of Casanova et al. [161] and Carvalho et al. [162], the reactivity of MSWI bottom ash as AAM precursor was assessed by measuring the pozzolanic reactivity with the modified Chapelle test. The MSWI bottom ash used by Carvalho et al. [162] and Casanova et al. [161] is from the same plant in Portugal. Information about the plant-scale treatments was not provided. Their test results indicated that the pozzolanic reactivity of MSWI bottom ash was lower than that of Class F coal fly ash.

The chemical dissolution test is used to determine the content of reactive silica in cement and supplementary cementitious materials. This standardized testing method is not only used to determine the content of reactive SiO_2, but also used to quantify the content of reactive Al_2O_3 and CaO in blast furnace slag [163] and coal fly ash [165]. Huang et al. [163] measured the content of reactive SiO_2, CaO, and Al_2O_3 in MSWI bottom ash according to the test procedure described in the standard for determining reactive silica content. The MSWI bottom ash tested by Huang et al. [163] was produced in China and had been water-washed at the recycling station. Prior to the reactivity test, the received MSWI bottom was ground into fine powder in the lab. Huang et al. [163] reported that the reactive SiO_2 detected in MSWI bottom ash was 28.4 wt%, higher than that in blast furnace slag (18.7 wt%). In contrast, the reactive CaO in MSWI bottom ash was 12.7 wt%, less than half of its content in blast furnace slag (33.6 wt%). The MSWI bottom ash had 12.2 wt% reactive Al_2O_3, slightly lower than that in blast furnace slag (18.4 wt%).

The chemical attack test is proposed by previous researchers for determining the amount of reactive SiO_2 and Al_2O_3 in MSWI bottom ash that could participate in the AAM formation [58,164]. This test method has not been standardized yet. The chemical attack test is conducted by dissolving 1 g of MSWI bottom ash in 100 ml solution of hydrofluoric acid (HF) or NaOH. The attack with HF solution is usually performed at room temperature to quantify the amount of amorphous SiO_2 in MSWI bottom ash. The attack with NaOH solution is conducted at 80 °C and is used to determine the amount of SiO_2 and Al_2O_3 released from MSWI bottom ash [58,164,166].

Maldonado-Alameda et al. [58] evaluated the potential of weathered MSWI bottom ash as AAM precursor using the chemical attack test. The MSWI bottom ash went through metal extraction and weathering treatments in a Spanish waste valorization plant. Before reactivity measurement, MSWI bottom ash was ground into fine powder. The results of the attack with HF solution showed that the attack with NaOH solution could only dissolve a small fraction of the amorphous SiO_2. The results of the attack with NaOH solution

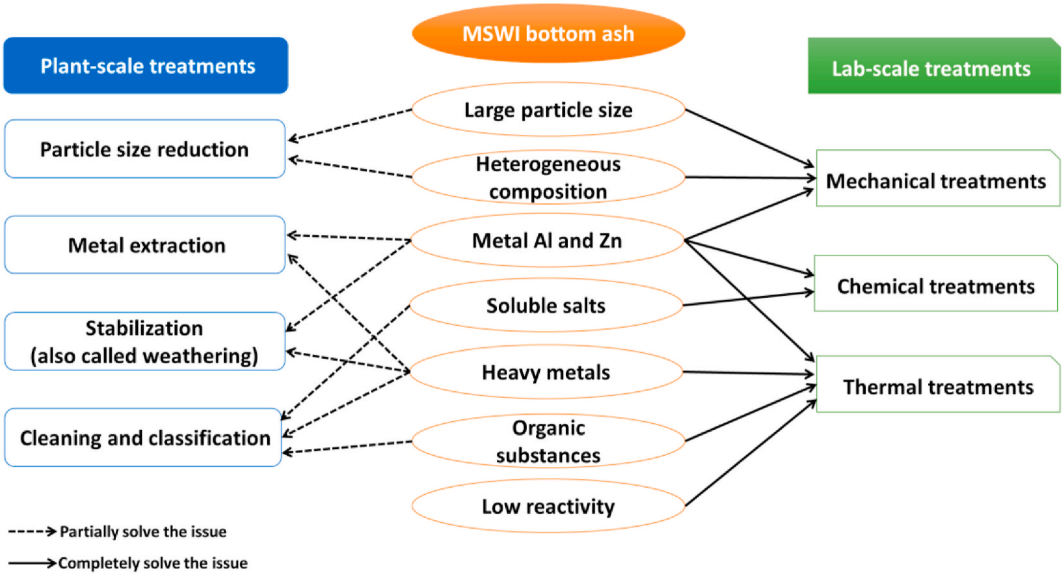


Fig. 5. Issues and corresponding solutions of using MSWI bottom ash as SCMs and AAM precursors.

indicated that more SiO_2 and Al_2O_3 was dissolved from MSWI bottom ash when the concentration of NaOH solution increased from 2 M to 8 M. The molar ratio between dissolved Si and Al was much higher than two [58]. Given that the strength of alkali-activated metakaolin was maximized when the molar ratio between Si and Al in the mixture of metakaolin and activator was 1.9 [167], Maldonado-Alameda et al. [58] recommended introducing additional sources of reactive Al_2O_3 or SiO_2 to modify the Si/Al molar ratio when MSWI bottom ash was used for the preparation of AAM.

7. Conclusions

The utilization of municipal solid waste incineration (MSWI) bottom ash as supplementary cementitious material (SCM) and precursor for alkali-activated materials (AAM) promotes the value-added application of this industrial by-product. This review discussed the composition diversity, the plant-scale and lab-scale quality-upgrade treatments, and the reactivity of MSWI bottom ash. The conclusions are presented below.

- The freshly produced MSWI bottom ash, due to its heterogeneous composition and high risk of excessive leaching, is unsuitable for being used as a mineral resource to produce construction materials. Quality-upgrade treatments, such as plant-scale treatments and lab-scale treatments, are performed on fresh MSWI bottom ash to make it suitable for application as SCM and AAM precursor. As summarized in Fig. 5, the issues considered in the quality upgrade treatments are coarse particle size, heterogeneous composition, hazardous components (such as heavy metals, organics, and soluble salts), and low reactivity.

- Compared with fresh MSWI bottom ash, weathered MSWI bottom ash obtained after plant-scale treatments usually has a more stable mineralogical composition and lower leaching of contaminants into the environment. Weathered MSWI bottom ash produced in different regions shows common features. The chemical composition of weathered MSWI bottom ash varies within the same range as that of coal fly ash. The crystalline phases fall within 11 mineral groups. In most weathered MSWI bottom ash, the amorphous phase accounts for more than 50 wt%.
- Most of the MSWI bottom ash sent to the laboratory is produced after plant-scale treatments of fresh MSWI bottom ash. The lab-scale treatments include mechanical treatments, chemical treatments, and thermal treatments (see Fig. 5). All these methods can be used to reduce the metallic Al content in MSWI bottom ash. In addition to the reduction of metallic Al content, mechanical treatments can also reduce the particle size of MSWI bottom ash. Thermal treatments can increase the reactivity of MSWI bottom ash and reduce the content of organics.
- At present, different standardized methods have been used to measure the pozzolanic reactivity of MSWI bottom ash. However, there is no standardized method that can be used to measure the reactivity of MSWI bottom ash as AAM precursor. Current test results indicate that the reactivity of MSWI bottom ash as SCM and AAM precursor can be similar to that of Class F coal fly ash. The use of MSWI bottom ash as an alternative to Class F coal fly ash is promising.

8. Outlooks

Based on the current state of the art, the following aspects may require more attention and research to promote the commercial application of MSWI bottom ash as a mineral resource for construction materials.

- There is still a need to establish a standardized procedure to assess the reactivity of MSWI bottom ash, especially as AAM precursor. The content of the amorphous phase has been quantified in previous work, but the chemical composition of the amorphous phase has not been determined. The amorphous phase is regarded as the primary reactive phase in MSWI bottom ash. The relationship between the chemical composition of the amorphous phase and the reactivity of MSWI bottom ash has not been fully understood.
- The prerequisite for using a high dosage of MSWI bottom ash in blended cement pastes and alkali-activated pastes is to improve the quality of MSWI bottom ash through pre-treatments. Although different methods have been proposed to improve the quality of MSWI bottom ash, there is no systematic guidance for the selection of quality-upgrade treatments. The quality requirements need to be specified based on the targeted engineering properties of MSWI bottom ash-based construction materials. The quality-upgrade treatment can combine two or more techniques, but it should be tailored according to the issues of each type of MSWI bottom ash.
- Cost is rarely a consideration when developing lab-scale quality-upgrade treatments. The high cost of quality-upgrade treatments may discourage the construction industry from using MSWI bottom ash as SCM or AAM precursor. There is a need to develop environmentally friendly and cost-effective plant-scale treatment techniques on top of current lab-scale treatments. Besides, a high dosage of MSWI bottom ash should not be realized at the expense of unexpected damage to the environment. The environmental impacts of MSWI bottom ash-containing construction materials should be evaluated prior to their industrial application.
- It is recommended to build a database about the chemical and physical properties of MSWI bottom ash produced in the world. The database should include information such as the particle size, composition, reactivity, and leaching potential of MSWI bottom ash. Based on this database, a classification system can be made for MSWI bottom ash. The classification system of cement can be used as a reference for classifying MSWI bottom ash. Recommended treatment techniques should also be provided for MSWI bottom ash that requires quality upgrades. Establishing a database could help promote the commercial application of MSWI bottom ash in concrete.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix

Appendix Table 1
Mineralogical compositions of weathered MSWI bottom ash determined by QXRD analysis.

Mineral Types	Minerals (wt.%)	Particle size (mm) of weathered MSWI bottom ash											
		<0.6 [122]		0 - 8 [168]	8 - 30 [168]	≤4 [80]	4 - 12 [60]	Unknown [61]	Not separated [20]	0 - 2 [120]	Unknown [133]	0 - 8 [59]	
		Thailand		UK		The Netherlands			Germany	Spain	Canada	Belgium	
SiO_2	Quartz	13.5	22.6	7.2	7.6	12.5	5.4	14.4	9.4	10.9	4.7	12	21
	Cristobalite								0.3			0.6	1.1
FeO_x	Hematite	0.8	1.5			3.8	0.4	0.9	1.8	0.9	1.6	1	2.4
	Magnetite	1.8	2.9			8.9	0.2		1.8	1.7		2.5	0.8
	Wustite					1.5			0.6			0.6	
	Magnesioferrite			0.9	0.7								
Silicates	**Melilite group**												
	Melilite			2.1	1.2	4.7	2		2.1				
	Gehlenite		11.3					2.2				4.5	0.7
	Feldspar group												
	Alkali Feldspar											1.8	2.2
	Sanidine			1.1	2.0								
	Microcline	3.5	3.3							1.4			
	Albite	4.5	1.2	3.0	6.7		4.3			2.3			
	Plagioclase Feldspar					5.7			1.7		5.1		
	Anorthite							0.6					
	Pyroxene group												
	Pyroxene					4.2						1	
	Diopside						1.8		1.4				
	Wollastonite											1.8	1.6
	Augite								1.1				
	Clinopyroxene							9.3					
	Other silicates												
	Mullite	12.1											
	Mg-chloritoid	2.3											
	Margarite			0.3	1.3								
	Muscovite								2.8	0.9			
	Zeolite					0.1							
	Chabazite								0.8				
	Amphibole								3.7				
Carbonates	Calcite	2.7		0.9	0.8	13.5	2.9	3.4	4.7	11.4	22.7	7.5	1.9
	Dolomite						1.2						
	Potassium carbonate								2.1				
Sulfates	Ettringite					0.2			6.5				
	Gypsum					0.2						0.7	0.4
	Anhydrite								1.7		4.2	0.3	4.1
	Vishnevite			0.3	0.8								
	Rozenite				0.8								

(*continued on next page*)

Appendix Table 1 (*continued*)

Mineral Types	Minerals (wt.%)	Particle size (mm) of weathered MSWI bottom ash											
		<0.6 [122]		0 - 8 [168]	8 - 30 [168]	≤4 [80]	4 - 12 [60]	Unknown [61]	Not separated [20]	0 - 2 [120]	Unknown [133]	0 - 8 [59]	
		Thailand		UK		The Netherlands			Germany	Spain	Canada	Belgium	
	Alunite								0.7				
	Baryte								0.2				
Chloride Salts	Halite					0.8	0.5				2.4		
Phosphates	Apatite					6.5				1.1			7.7
Non-ferrous metal oxides	Corundum								4.4				
	Periclase								0.5				
	Rutile					1.3			0.9		2.2		
Hydroxides	Hydrocalumite								15.4	6.7			
	Hydroxilapatite									2.1			
	Rosenhahnite								1.5				
	Gibbsite								0.4				
	Lepidocrocite								0.6				
	Tobermorite								0.6				
Sulfides	Covellite								0.8				
Other minerals	Hercynite								0.8				
	Graphite			1.7	2.4								
	Silicon								0.3				
Amorphous		58.8	59.3	81.3	75.4	36.1	81.2	69.2	30.8	60.1	57.1	65	56

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