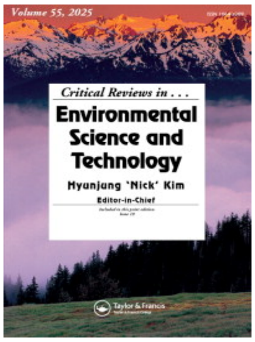

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Municipal solid waste incineration (MSWI) bottom ash-blended cementitious materials: Performance, challenges, and potential solutions

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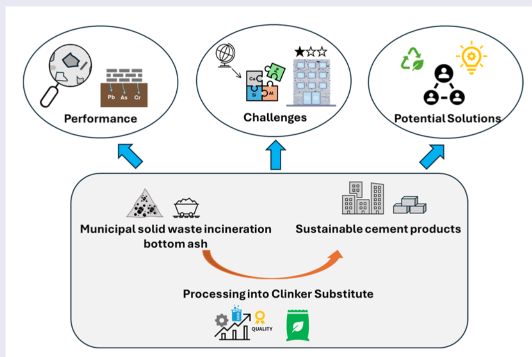
ABSTRACT

The recycling of municipal solid waste incineration (MSWI) bottom ash as a supplementary cementitious material (SCM) has attracted global attention, driven by the increasing availability of this by-product and the demand for sustainable SCMs to lower CO_2 emissions from cement production. Currently, the widespread use of MSWI bottom ash in the cement industry is hindered by the lack of guidelines to regulate material composition, optimize pretreatment processes, and specify mix design requirements. This review compiles and analyzes literature data on mix design, microstructural evolution, fresh properties, mechanical properties, durability, leaching risks, and environmental impacts of MSWI bottom ash-blended cement pastes, mortars, and concretes. The analysis aims to assess the influence of the pretreatment and physicochemical properties of bottom ash[1] on the microstructure and performance of blended cementitious materials.[2] The Ash Impact Strength Index (AISI) is introduced to quantify the effects of various factors on compressive strength, enabling direct comparison across different studies. Based on the statistical analysis of the 28-day AISI, the key quality requirements for MSWI bottom ash as an SCM are proposed, along with the optimal mix design. This work provides valuable insights and practical guidance to support the integration of bottom ash into the cement industry.



HIGHLIGHTS

- Effective pretreatment methods for converting MSWI bottom ash into SCM are identified.
- Mix design datasets for cement incorporating MSWI bottom ash as SCM are summarized.
- Microstructural evolution in MSWI bottom ash blended cement systems is analyzed.

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- The engineering performance of MSWI bottom ash blended cement products is evaluated.
- Strategies to advance the adoption of MSWI bottom ash as SCM are recommended.

KEYWORDS Ash Impact Strength Index (AISI); blended cementitious materials; microstructure and performance; municipal solid waste incineration bottom ash; supplementary cementitious material

HANDLING EDITOR Prof. Eric van Hullebusch

1. Introduction

The generation of municipal solid waste is projected to reach 3.40 billion tons in 2050 due to population growth and economic expansion. This represents a 69% increase compared to the 2.01 billion tons generated in 2016 (Kaza et al., 2018). Traditional waste disposal methods such as landfilling and open dumping often lead to significant pollution of water, soil, and air (Eurostat, 2023; Ferronato & Torretta, 2019; Grand View Research, 2019; International Renewable Energy Agency (IRENA), 2022; National Bureau of Statistics of China [NBS], 2022; United States Environmental Protection Agency [US EPA], 2022, 2024). In contrast, converting waste into energy not only reduces the volume of waste designated for landfills but also produces electricity and heat (Bunge, 2016; Kim et al., 2015; Tozlu et al., 2016). In Europe alone, current waste-to-energy plants can generate 39 TWh of electricity and 90 TWh of heat annually. If this energy were generated using fossil fuels, an additional 50 million tons of CO_2 would be emitted (Atstaja et al., 2024). There is a global trend favoring waste-to-energy incineration as a more sustainable alternative to traditional waste management methods. With the shift toward incineration, effective management of residues from municipal solid waste incineration (MSWI) is gaining increasing recognition worldwide.

As illustrated in Fig. 1(a), the residues discharged from municipal solid waste incineration (MSWI) include bottom ash, boiler and economizer ash, fly ash, and air pollution control residues (Phua et al., 2019; Sabbas et al., 2003). These residues account for approximately 20–40% of the total input waste mass and are characterized by concentrated levels of heavy metals, salts, and organic micropollutants (Sabbas et al., 2003). Among these residues, bottom ash is the most abundant (80–90 wt.%) and is usually classified as non-hazardous waste (M. Li et al., 2004; Margallo et al., 2015; Phua et al., 2019; Sabbas et al., 2003). The global generation of MSWI bottom ash is notably high, with approximately 9 million tons in the United States (2017) (V. Kumar & Garg, 2022), around 20 million tons annually from European incineration plants (Šyc et al., 2020), and over 13 million tons each year in China (Mainland) (Xia et al., 2017). The valorization of this residue is preferable to landfill, as it enables resource recovery (e.g., metals and minerals) (B. Chen, Perumal, et al., 2023), contributing to resource efficiency and environmental sustainability.

The bottom ash generated by waste-to-energy plants can be fully consumed within the construction industry. Conventionally, bottom ash is used to replace natural aggregates in road and embankment construction (Oehmig et al., 2015). However, this low-value application faces competition from other secondary materials, especially recycled concrete aggregates (B. Wang et al., 2021). This competition in the market has highlighted the need to explore higher-value applications for bottom ash to promote its sustained utilization. Previous research has shown that bottom ash is well-suited for use as a supplementary cementitious material (SCM) in blended cement binders (B. Chen, Perumal, et al., 2023) or as a precursor in alkali-activated binders (B. Chen, Perumal, et al., 2024; B. Chen & Ye, 2025). It can also be used as a raw material in high-temperature processes, primarily in the production of cement clinker (Clavier et al., 2021; Kleib et al., 2021; Lam et al., 2010; Y.-M. Li et al., 2020) or ceramics (Appendino et al., 2004; Y. M. Li et al., 2020; Monteiro et al., 2006; Rambaldi et al., 2010; Taurino et al., 2017; Z. Zhang et al., 2020). Among these applications of bottom ash, its use as a pozzolanic material is

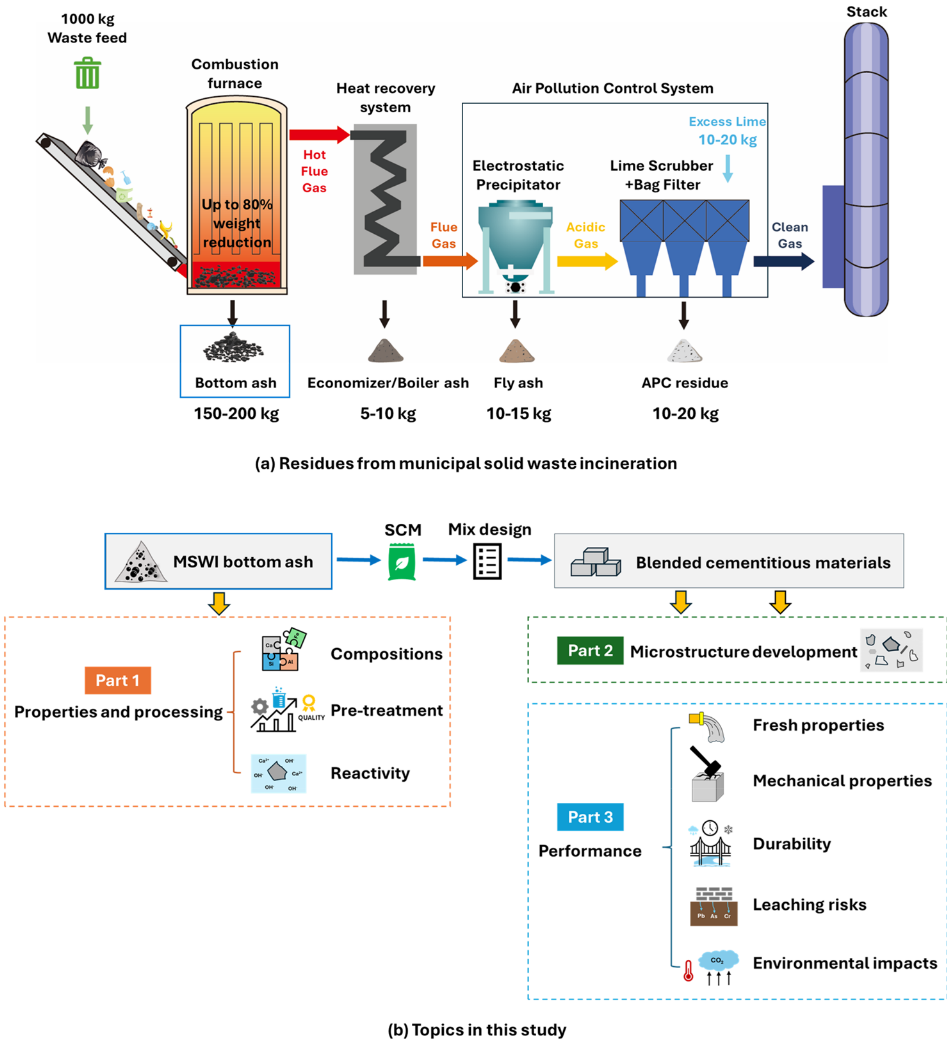


Figure 1. (a) An overview of residues discharged after municipal solid waste incineration. This figure is modified and reprinted from Phua et al. (2019). (b) Schematic overview of main topics in this study.

considered highly promising. This preference stems from the widespread acceptance of SCM in the construction industry, facilitated by its seamless integration with conventional cement and concrete production processes (Lothenbach et al., 2011).

Concrete made with Portland cement is the most commonly used construction material worldwide (Hewlett & Liska, 2019). The cement industry accounts for approximately 8% of global CO_2 emissions from human activities (Andrew, 2018). Reducing clinker content in cement is an effective way to lower its carbon footprint (World Business Council for Sustainable Development (WBCSD), 2009). In blended cement, between 10% and 90% of the clinker is typically replaced with SCMs, among which blast furnace slag, coal fly ash, and limestone are the most widely used (World Business Council for Sustainable Development (WBCSD), 2009). However, the supply of blast furnace slag and coal fly ash is expected to decline over the next 30 years due to the sustainability transitions in industries such as steel production and coal-fired power generation (International Energy Agency (IEA), 2009). This decline highlights the urgency of identifying new SCMs to support the low-carbon transition in the cement industry (Internal Energy Agency (IEA), 2018). The anticipated global availability of MSWI bottom ash (about one gigaton per year (Snellings et al., 2023)) has sparked growing interest in its use as an SCM.

Research on the use of MSWI bottom ash in cementitious materials has expanded in recent years, leading to an increasing number of publications. Numerous researchers have conducted literature reviews on these studies. Table S1 provides a summary of these review articles, highlighting their main contributions. As shown in this table, previous reviews mainly concentrated on the compositional characteristics and pretreatment techniques of MSWI bottom ash, with scant attention given to the performance aspects of cementitious materials blended with this ash. There has been scarcely any systematic discussion concerning the quality of treated bottom ash and the mix design of blended cement containing this ash. These aspects greatly influence the formation of microstructure, which determines the mechanical properties and durability of the resulting cementitious materials.

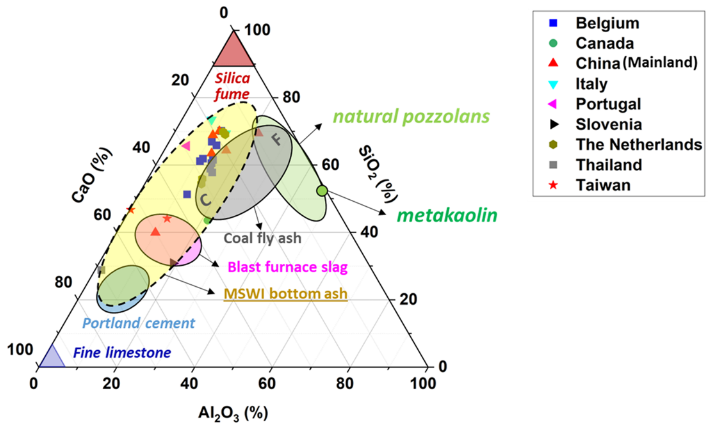
This review aims to provide a comprehensive assessment of MSWI bottom ash as an SCM, with a focus on its influence on the microstructure development and performance of blended cementitious materials. It identifies key challenges associated with its utilization and defines quality requirements for treated bottom ash. Practical insights and potential solutions are also provided to facilitate its adoption in the cement industry. As shown in Fig. 1(b), this review consists of three parts. The first part provides an overview of the properties and processing of MSWI bottom ash, highlighting recent findings on its compositional characteristics, pretreatment methods, and pozzolanic reactivity. The mix designs proposed by previous researchers are summarized and serve as the basis for the discussion in the second and third parts. The second part investigates the influence of MSWI bottom ash on the microstructure development of blended cement pastes. The third part analyzes the factors affecting the fresh properties, mechanical properties, long-term performance, heavy metal leaching, and environmental impacts of blended cementitious materials.

2. Properties and processing of MSWI bottom ash

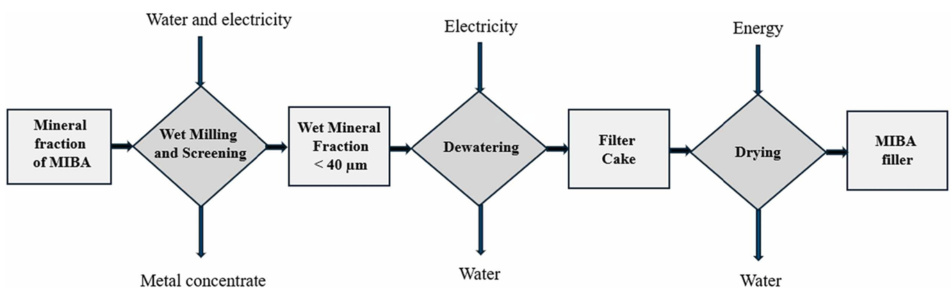
2.1. Chemical composition

This section discusses the compositional differences between MSWI bottom ash and other commonly used SCMs. The relative proportions of the major components in these materials are shown on a CaO-SiO_2-Al_2O_3 ternary diagram (see Fig. 2(a)). The composition data of bottom ash used as an SCM in previous studies can be found in Table S2. Figure 2(a) shows that the chemical composition of MSWI bottom ash covers a broad range on the ternary diagram. This variability arises from differences in waste input composition and the operational conditions of incinerators. Most data points for bottom ash cluster near the region associated with coal fly ash. In only two rare instances where bottom ash is enriched in CaO, its composition falls within the blast furnace slag region. Despite these compositional variations, previous studies have indicated that the potential of bottom ash as an SCM is comparable to that of coal fly ash (Class F) (B. Chen, Perumal, et al., 2023).

While MSWI bottom ash shares certain compositional similarities with coal fly ash, it typically contains higher levels of chloride, Na_2O, K_2O, and SO_3, often exceeding the standard limits established for cement clinker (B. Chen, Perumal, et al., 2023). A higher content of these soluble salts in Portland cement concrete may accelerate steel rebar corrosion, worsen alkali-silica reaction-induced damage, and cause expansion and cracking through late ettringite formation (Hewlett & Liska, 2019). Previous review articles have extensively discussed the presence of these undesirable components, along with pretreatment techniques to lower their contents and mitigate their adverse effects on the performance of bottom ash-blended cementitious materials (B. Chen, Perumal, et al., 2023; D. Chen et al., 2022; Cho et al., 2020; Devahi et al., 2022; Joseph et al., 2018; S. Kumar & Singh, 2021; J.-W. Lu et al., 2017; Silva et al., 2019; Snellings et al., 2023; Verbinnen et al., 2017). Therefore, this review does not examine this issue in detail.



(a) Relative proportions of CaO, Al_2O_3, and SiO_2 in MSWI bottom ash and other SCMs.



(b) Pilot-scale processing steps for producing MSWI bottom ash filler.

Figure 2. (a) CaO-Al_2O_3-SiO_2 ternary diagram illustrating the relative proportion of these three components in supplementary cementitious materials (SCMs). The dots indicate the chemical compositions of MSWI bottom ash collected from Belgium, Canada, China (Mainland), Italy, Portugal, Slovenia, the Netherlands, Thailand, and Taiwan (Alderete et al., 2021; Bertolini et al., 2004; Carsana et al., 2016; B. Chen & Ye, 2024; Y. Cheng et al., 2019; Gong et al., 2022; Joseph et al., 2020; Jurič et al., 2006; X. G. Li et al., 2012; Lin et al., 2008; Lin & Lin, 2006; Y. Liu et al., 2018; Lo et al., 2020; Loginova et al., 2021; Simões et al., 2020; Sun et al., 2024; P Tang et al., 2016; Pei Tang et al., 2020; Wongsa et al., 2017; Yang, Ji, et al., 2018; Yang, Tian, et al., 2018; S. Zhang et al., 2021). These compositions were measured through XRF analysis. The remaining shaded regions denote the composition ranges for silica fume, coal fly ash, natural pozzolans, metakaolin, blast furnace slag, fine limestone, and Portland cement. Data for these SCMs were sourced from the paper authored by Lothenbach et al. (2011). (b) Flowchart illustrating the pilot-scale pretreatment process for producing MSWI bottom ash filler with enhanced reactivity (Bakker et al., 2025). The term "MIBA" in the figure refers to the same material described as "MSWI bottom ash" in the text.

2.2. Pretreatment techniques

Most of the proposed methods for converting MSWI bottom ash into SCM have been tested at the lab scale and require upscaling (B. Chen, Perumal, et al., 2023, 2024). Among these treatments, two methods are considered the most suitable and hold the greatest potential for future development: wet milling (Bertolini et al., 2004) or dry milling followed by water immersion (B. Chen & Ye, 2024; Joseph et al., 2020). Currently, the only reported pilot-scale facility dedicated to improving the quality of MSWI bottom ash as an SCM is located in the Netherlands, operating at a capacity of 0.65 tons per hour. This facility employs advanced processing techniques, including wet milling, screening, dewatering, and drying (see Fig. 2(b)). Wet milling plays a critical role by reducing particle size, removing water-soluble contaminants, and increasing the amorphous content. The resulting fine powder, designated as "MIBA filler", has a median particle size (d_{50}) of 8–10 μm. To date, this pilot-scale operation has produced over 1000 tons of MIBA filler. Although referred to as "filler", the bottom ash powder contains a significant fraction (~66 wt%) of amorphous glassy material, indicating potential pozzolanic reactivity (Bakker et al., 2025).

The European Assessment Document (EAD) provides technical guidelines for the use of MSWI bottom ash as a Type II SCM. Specifically, EAD 260009-00-0301 (European Organisation for Technical Assessment [EOTA], 2018) defines the essential criteria, including composition, activity index, fineness, and other performance parameters, to evaluate its suitability for use in concrete or mortar. However, it is important to note that these criteria are primarily derived from existing European standards, such as EN 206 (NEN-EN 206, 2021) for concrete specifications and EN 450-1 (European Committee for Standardization [CEN], 2012) for siliceous fly ash, which do not fully address the unique properties of MSWI bottom ash.

3. Microstructure formation of MSWI bottom ash-blended cement pastes

3.1. Reaction kinetics

3.1.1. Early-age hydration

The effect of MSWI bottom ash on the early-age hydration of Portland cement is usually studied by measuring the heat flow with isothermal calorimetry. Figure 3(a,b) illustrates a schematic of the heat evolution patterns for Portland cement paste and cement pastes containing MSWI bottom ash over the initial 3 days of hydration. These curves are derived from the calorimetry results reported in the literature (B. Chen & Ye, 2024; Z. Chen & Yang, 2017; Joseph et al., 2020; Loginova et al., 2021; Sun et al., 2024; P Tang et al., 2016; Pei Tang et al., 2020; S. Zhang et al., 2021). As shown in Fig. 3(a), replacing a portion of Portland cement with bottom ash typically reduces cumulative heat release. The hydration process of bottom ash-blended cement paste, similar to that of pure cement, can be divided into five stages: initiation (Stage I), induction (Stage II), acceleration (Stage III), deceleration (Stage IV), and slow reaction (Stage V), as illustrated in Fig. 3(b). In each stage, the heat flow in bottom ash-blended cement pastes is lower than that of Portland cement paste. The reduction in reaction heat is primarily caused by the considerably lower reactivity of bottom ash compared to Portland cement (B. Chen & Ye, 2024; Filipponi et al., 2003; Joseph et al., 2019; Saikia et al., 2008; Simões et al., 2020).

MSWI bottom ash plays a role in heat release during the initiation (I) and deceleration (IV) stages. Since bottom ash contains soluble salts and metallic aluminum, a portion of the heat released during the initiation stage can be attributed to the dissolution of the salts (Z. Chen & Yang, 2017) and the oxidation of the metal (B. Chen, Zuo, et al., 2023; Joseph et al., 2020). The shoulder peak observed in stage IV corresponds to the hydration of tricalcium aluminate (C_3A) in the cement paste. This shoulder peak is broader and often found in the calorimetric curve of the cement pastes incorporating bottom ash (B. Chen & Ye, 2024; Z. Chen & Yang, 2017; Joseph et al., 2020; P Tang et al., 2016). The SO_4^{2-} supplied by bottom ash increases the sulfate levels in the pore solution of blended cement pastes (B. Chen & Ye, 2024). This rise in sulfate concentration promotes the reaction of C_3A, leading to ettringite formation. Furthermore, in some cases, the anhydrite found in bottom ash also reacts with C_3A, promoting the generation of ettringite and monosulfate in stage IV (B. Chen & Ye, 2024; Z. Chen & Yang, 2017; P Tang et al., 2016; Taylor, 1997).

The incorporation of MSWI bottom ash mainly affects the reaction rate by slowing down cement hydration during stage II and stage III (B. Chen, Chen, et al., 2024; B. Chen & Ye, 2024; Z. Chen & Yang, 2017; X. G. Li et al., 2012; Lin & Lin, 2006; Loginova et al., 2021; Sun et al., 2024; P Tang et al., 2016). The delay already starts at a ash replacement level of 5 wt.%, but is often reported at replacement levels between 20 and 30 wt.% (B. Chen & Ye, 2024; Z. Chen & Yang, 2017; Joseph et al., 2020; Loginova et al., 2021; Sun et al., 2024; P Tang et al., 2016; Pei Tang et al., 2020; S. Zhang et al., 2021). The CaO content in bottom ash is a key factor influencing

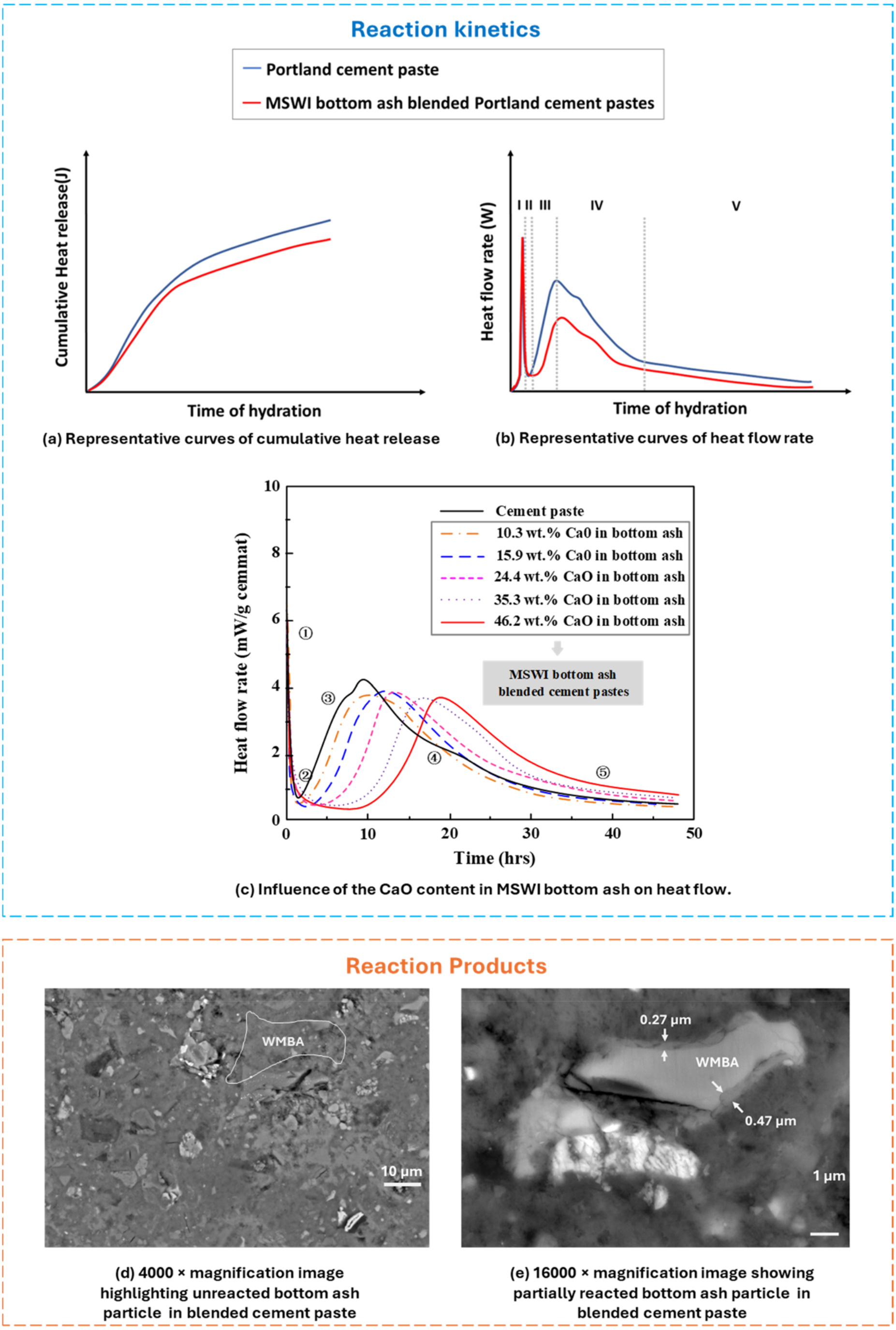


Figure 3. (a,b) Schematic representation of the heat evolution curves that describe cumulative heat release and heat flow rate of Portland cement paste and MSWI bottom ash-blended cement pastes during the first three days of reaction, derived from curves presented in the literature (B. Chen & Ye, 2024; Z. Chen & Yang, 2017; Joseph et al., 2020; Loginova et al., 2021; Sun et al., 2024; P Tang et al., 2016; Pei Tang et al., 2020; S. Zhang et al., 2021). (c) Heat flow curves for plain cement paste and cement pastes incorporating MSWI bottom ash with varying CaO content. The CaO content in the MSWI bottom ash was analyzed using XRF. All blended cement pastes contain 20 wt.% MSWI bottom ash, with a water-to-binder ratio of 0.5 (Z. Chen & Yang, 2017). (d,e) SEM-BSE image of a 90-day cement paste sample incorporating 25 wt.% MSWI bottom ash as a replacement for Portland cement. “WMBA” indicates MSWI bottom ash that has undergone water treatment (B. Chen & Ye, 2024).

the hydration rate of cement blended with this ash. Figure 3(c) shows that using bottom ash with higher CaO content as an SCM further prolongs the induction period. Upon contact with water, calcium-bearing compounds like anhydrite and lime release significant amounts of calcium and hydroxyl ions into the pore solution of blended cement pastes. This high concentration of calcium ions may inhibit the dissolution of alite (C_3S), which could partially explain the delayed hydration during the early stage (Z. Chen & Yang, 2017; Juilland & Gallucci, 2015; Nicoleau et al., 2013). If the onset of stage III is delayed, the shoulder peak also appears late in stage IV. However, Pei Tang et al. (2020) observed that the inclusion of MSWI bottom ash could also accelerate AFm formation in stage IV. This acceleration may result from a change in the calcium sulfate to C_3A ratio in the bottom ash-cement mixture compared to that in pure cement (Pei Tang et al., 2020). When this ratio is reduced, the formation of AFm can be accelerated (Quennoz, 2011).

3.1.2. Late-age hydration

The late-stage hydration of cement in mixtures containing MSWI bottom ash can be evaluated by measuring the degree of clinker hydration. With this method, B. Chen and Ye (2024) found that between 7 and 90 days, the clinker hydration degree in cement pastes with 25 wt.% bottom ash was higher than that in plain cement pastes. Li et al. (2012) reported that the C-S-H gel formation was more pronounced on the fracture surface of a 28-day cement mortar sample containing 30% bottom ash, compared to a plain cement mortar sample. The heterogeneous nucleation and dilution effect are key physical mechanisms that enhance hydration in bottom ash-blended cement (Berodier & Scrivener, 2014; Lawrence et al., 2003). The bottom ash particles introduce additional surfaces that serve as nucleation sites, promoting the formation of hydration products (Lawrence et al., 2003; Lothenbach et al., 2011). Partial replacement of Portland cement with bottom ash increases the effective water-to-cement ratio compared to plain cement, leading to greater spacing between particles (Bentz & Aitcin, 2008). This additional space allows hydrates to grow more freely, thereby enhancing the hydration of clinker (Hewlett & Liska, 2019).

3.2. Reaction products

In blended cement systems, the reactions of MSWI bottom ash primarily take place in the later stages, contributing to strength development as the reaction products fill small capillary pores. Some Portlandite formed during clinker hydration was consumed by bottom ash. Compared to the C-S-H gel in plain cement pastes, which has a Ca/Si molar ratio of 1.72, the gel formed in 90-day cement samples containing 25% bottom ash exhibits a lower Ca/Si molar ratio (1.57) and a higher (Na + K)/Ca ratio. The Al/Si ratio shows little difference between the C-S-H gel in plain cement paste and that in cement paste containing bottom ash (B. Chen & Ye, 2024).

Incorporating MSWI bottom ash as an SCM can result in the formation of additional hydrates, together with the development of C-S-H gel. Owing to the heterogeneous distribution of the mineral phases in MSWI bottom ash, not all particles exhibit reactivity. Figure 3(d,e) presents SEM-BSE images of a 90-day cement paste sample containing 25 wt.% MSWI bottom ash, where both the unreacted and partially reacted MSWI bottom ash can be observed. A layer of reaction products, most likely sodicgedrite ($Na_{0.55}(Ca_{0.04}Al_{1.37}Mg_{3.01}Fe_{2.57})(Si_{5.95}Al_{2.05})O_{22}(OH)_2$), was accumulated on the surface of partially reacted bottom ash particle (Fig. 3(e)) (B. Chen & Ye, 2024).

4. Performance of MSWI bottom ash-blended cementitious materials

4.1. Fresh properties

Fresh properties, such as setting time, workability, rheology, air content, and apparent density, are essential for the effective placement, consolidation, and finishing of cement paste, mortar, and concrete (Kovler & Roussel, 2011). Previous studies have primarily focused on setting time and workability, as these properties are significantly influenced by bottom ash and are key considerations when developing new cementitious materials with this ash.

4.1.1. Setting time

The setting time of cement pastes containing MSWI bottom ash depends primarily on factors such as the CaO content, organic content, and substitution rate of bottom ash. The Ca-bearing phases and organics in MSWI bottom ash can influence the setting time by hindering cement clinker hydration (as discussed in Section 3.1.1). Moreover, even when bottom ash with low CaO content (<15%) and minimal organic components (< 1%) is used to replace cement, increasing the substitution level of ash still extends the setting time of blended cement pastes (X. G. Li et al., 2012; Yang, Ji, et al., 2018). The extended setting time is due to the reduced amount of reactive phases when cement is replaced by bottom ash (Filipponi et al., 2003; Saikia et al., 2008; Simões et al., 2020; Van Zomeren & Comans, 2004).

4.1.2. Workability

The water demand of blended cement mixtures is influenced by the porosity and specific surface area of MSWI bottom ash. Additional water is required in cases where blended cement mixtures contain porous particles from the fine fraction of bottom ash (<3 mm) (Loginova et al., 2021; Sun et al., 2024) or finely ground bottom ash particles (D_{50} < 6 μm) with high specific surface area (Bertolini et al., 2004; Carsana et al., 2016; Wongsa et al., 2017). The porous bottom ash particles are usually rich in chlorides, sulfates, and heavy metals (Alam et al., 2019, 2020; P Tang et al., 2016). Superplasticizers are used to improve the workability of the bottom ash-blended cement without changing the water-to-binder (w/b) ratio (Bertolini et al., 2004; Carsana et al., 2016; Y. Liu et al., 2018). The required amount of superplasticizer increases with higher replacement levels of cement by bottom ash (Carsana et al., 2016).

4.2. Mechanical properties

In previous research, compressive strength was the primary indicator used to assess the mechanical performance of MSWI bottom ash-blended cementitious materials. According to the data compiled in Table S2, there is a wide variety in the mix design of bottom ash-blended cementitious materials. The analysis of this data indicates that compressive strength is mainly influenced by the properties of bottom ash, its replacement level, and the water-to-binder ratio. The properties of bottom ash include the metallic aluminum content, pozzolanic reactivity, and particle size.

4.2.1. Ash Impact Strength Index (AISI)

The Ash Impact Strength Index (AISI) is introduced in this work to quantify the effect of incorporating MSWI bottom ash on the compressive strength of cementitious materials. This index is calculated for each study using Eq. (1). The idea of AISI is to use the reference sample as a baseline to compare against the bottom ash sample under identical conditions within the same study. By using AISI, it is possible to compare the strength measurement results across different studies without the need to account for variations in mixture design, curing conditions, or ash composition. This approach enables statistical analysis of factors affecting compressive strength and simplifies the assessment of their effects. As a complement to Table S2, Table S3 provides detailed compressive strength data for cement samples at 28 and 90 days, including those with MSWI bottom ash as an SCM and the reference samples without bottom ash. The calculated 28-day AISI and 90-day AISI can also be found in Table S3.

$$\text{AISI} = \frac{\text{Compressive strength of sample containining MSWI bottom ash}}{\text{Compressive strength of reference sample without MSWI bottom ash}} \tag{1}$$

If the AISI exceeds one, it indicates that using bottom ash as an SCM enhances the compressive strength. Conversely, an AISI below one suggests that incorporating bottom ash in cement reduces compressive strength. An AISI of exactly one implies that using bottom ash as a partial replacement for cement does not affect the compressive strength. It is important to note that in most cases, the relative AISI – whether higher or lower at 28 days – remains consistent at 90 days (see Table S3). This stability justifies the use of 28-day AISI for the analysis in the following section, as it effectively captures trends that persist over extended curing periods. Additionally, the 28-day AISI data are more widely available in the literature compared to the 90-day data, making it more suitable for comparison and statistical analysis. Based on the 28-day AISI, the following sections present a comprehensive evaluation of the factors influencing compressive strength.

4.2.2. Influence of metallic aluminum content

Figure 4(a) shows the correlation between the metallic aluminum content in MSWI bottom ash and the 28-day AISI for cement pastes, mortars, and concrete incorporating this ash. Most of the 28-day AISI values presented in this figure are below one, indicating the detrimental effects of metallic aluminum on strength development. The only case with a 28-day AISI above 1 is for the mixture containing MSWI bottom ash with 0.06 wt.% metallic aluminum (S. Zhang et al., 2021). Recommendations regarding the acceptable metallic aluminum content for blended cement pastes, mortars, and concrete can be found in the literature. Table S4 indicates that metallic aluminum content should generally be kept below 0.2 wt.% to minimize the risk of volume expansion and cracking.

Table S4 shows that in studies using MSWI bottom ash with a similar metallic aluminum content, their 28-day AISI values are not necessarily the same. In addition to metallic aluminum, other factors also influence the compressive strength. The maximum allowable substitution level of bottom ash is typically determined by its metallic aluminum content, as excessive aluminum can lead to expansive cracking (B. Chen & Ye, 2024). The severity of metallic aluminum's negative effect on strength also depends on the water-to-binder ratio. As shown in Table S4, the dry-cast sample ($w/b = 0.35$) can tolerate slightly higher levels of metallic aluminum, as its negative impact on strength is less significant compared to the wet-cast sample ($w/b = 0.484$) (Y. Liu et al., 2018; S. Zhang et al., 2021). Additionally, the negative effect of metallic aluminum on strength is less pronounced in concrete than in paste and mortar (Alderete et al., 2021; B. Chen, Chen, et al., 2024; B. Chen & Ye, 2024).

4.2.3. Influence of replacement level and reactivity

Figure 4(b) demonstrates the relationship between the 28-day AISI and replacement levels, ranging from 10% to 50%. The blue lines in the figure have a similar slope, indicating a consistent trend of decreasing compressive strength with increasing bottom ash replacement levels. A linear fit applied to these lines shows a slope of approximately −0.8. This indicates that the 28-day AISI decreases by about 0.08 for every 10% increase in the ash replacement level. A decrease of 0.08 in the AISI means that the compressive strength of the sample with bottom ash becomes 8% lower relative to the reference sample without bottom ash.

However, there are two exceptions to the decreasing trend. The first case, reported in Carsana et al. (2016) and shown by the orange line in Fig. 4(b), demonstrates an increase in strength resulting from the enhanced reactivity of MSWI bottom ash after particle size reduction through pretreatment. The second case, reported in Kim et al. (2016) and shown by the green line in Fig. 4(b), indicates that increasing the replacement level of bottom ash from 10% to 20% improves compressive strength, whereas a replacement level of 30% causes a reduction in strength. The strength improvement is attributed to the filler effect of small bottom ash particles, while the subsequent reduction is due to gas generation caused by residual metallic aluminum. The dominant factor affecting compressive strength changes with the replacement level.

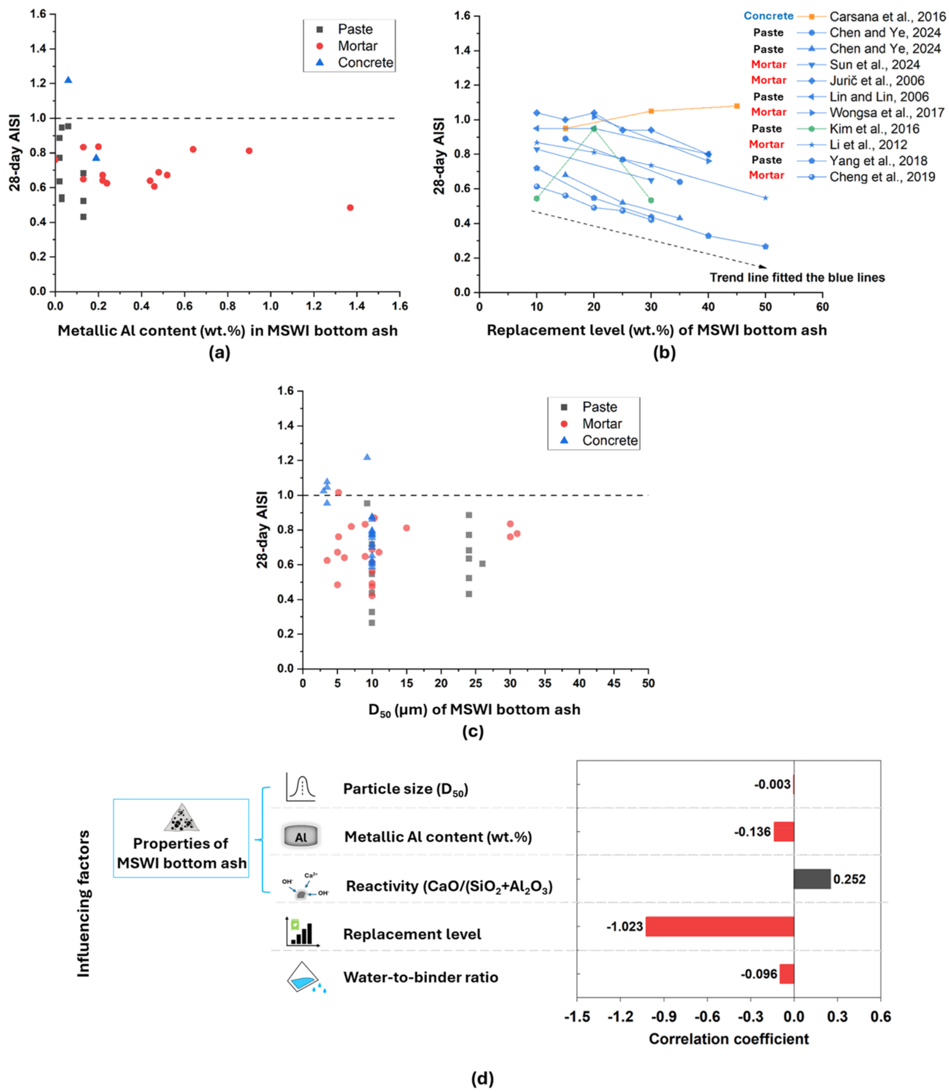


Figure 4. (a–c) Relationship between the 28-day Ash Impact Strength Index (AISI) of blended cementitious materials and three key influencing factors: metallic aluminum (Al) content (Alderete et al., 2021; B. Chen & Ye, 2024; Joseph et al., 2020; Kim et al., 2016; Sun et al., 2024; P Tang et al., 2016; S. Zhang et al., 2021), replacement level (Carsana et al., 2016; B. Chen & Ye, 2024; Y. Cheng et al., 2019; Jurič et al., 2006; Kim et al., 2016; X. G. Li et al., 2012; Lin & Lin, 2006; Sun et al., 2024; Wongsa et al., 2017; Yang, Ji, et al., 2018), and particle size of MSWI bottom ash (Alderete et al., 2021; Bertolini et al., 2004; Carsana et al., 2016; B. Chen & Ye, 2024; Y. Cheng et al., 2019; Joseph et al., 2020; Jurič et al., 2006; Kim et al., 2016; X. G. Li et al., 2012; Lin & Lin, 2006; Y. Liu et al., 2018; Loginova et al., 2021; Sun et al., 2024; P Tang et al., 2016; Pei Tang et al., 2020; Wongsa et al., 2017; Yang, Ji, et al., 2018; Yang, Tian, et al., 2018; S. Zhang et al., 2021). (d) Correlation coefficients between each influencing factor and 28-day AISI.

The high replacement level of MSWI bottom ash usually results in a dramatic reduction in early-age strength, as the incorporation of this ash slows down cement hydration. Li et al. (2012) found that the 3-day compressive strength of mortars decreased by 54.7% after replacing 50 wt.% cement with bottom ash. Most previous researchers used no more than 30 wt.% of bottom ash as cement replacement (see Table S2). These studies also provide compositional and strength data, allowing for an analysis of the combined effects of replacement level and reactivity.

The influence of reactivity and replacement levels was studied by plotting ternary diagrams to demonstrate the correlation between the chemical composition of MSWI bottom ash and the 28-day AISI. The reactivity of MSWI bottom ash is closely linked to its composition, especially the contents of CaO, Al_2O_3, and SiO_2. Figure 5 presents CaO-Al_2O_3-SiO_2 ternary diagrams, illustrating the relative proportions of these components in MSWI bottom ash. These diagrams were constructed using the contents of CaO, Al_2O_3, and SiO_2 determined by X-ray Fluorescence (XRF) analysis. The resulting plots were color-coded to reflect the 28-day AISI, with areas indicating higher AISI values colored in red and those with lower values in blue. Additionally, to visualize the influence of MSWI bottom ash replacement levels, each specific level (such as 20%, 25%, and 30%) is depicted in a corresponding ternary diagram.

In the ternary diagrams shown in Fig. 5, the highest 28-day AISI was typically noted in regions where the CaO/(Al_2O_3 + SiO_2) ratio is approximately one regardless of replacement level, highlighting that the high CaO content in MSWI bottom ash has a positive effect on strength development after 28 days of curing. It is worth noting that in Fig. 5(c), the samples prepared with bottom ash characterized by high SiO_2 content and low CaO content also exhibit high AISI values. These high values are primarily attributed to the fine particle size of the MSWI bottom ash (Bertolini et al., 2004; Carsana et al., 2016). A comparison of Fig. 5(a–c)

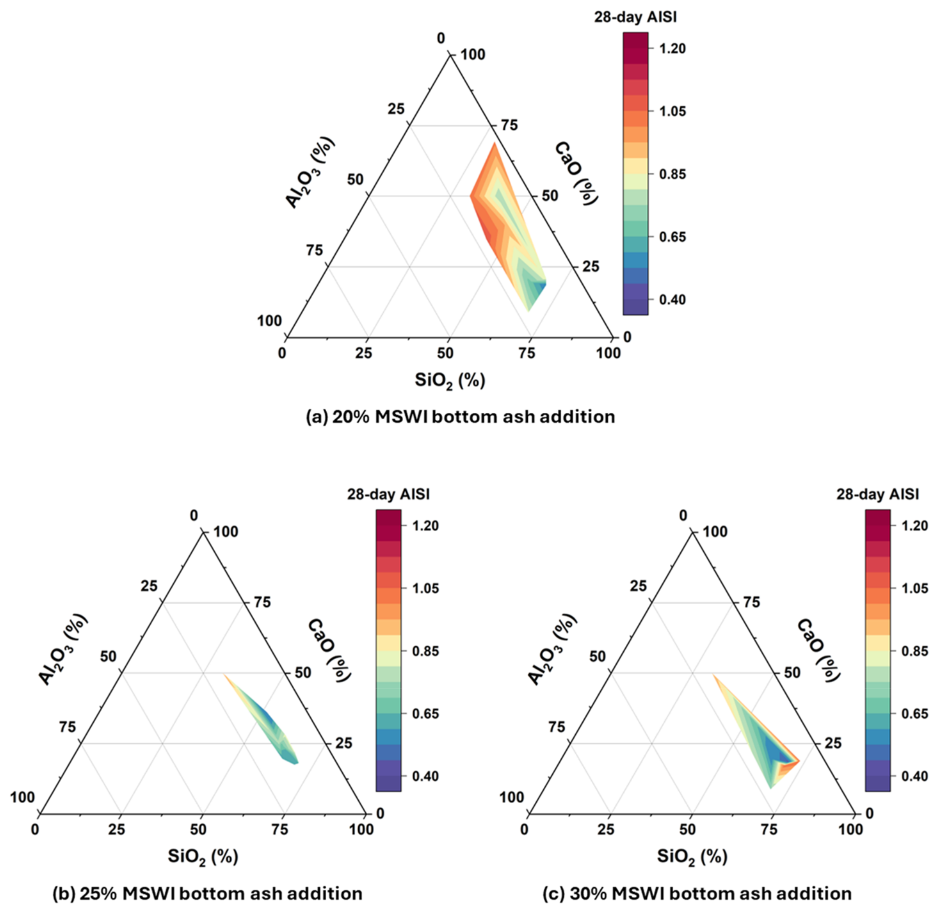


Figure 5. Ternary diagrams illustrating the relative proportion of CaO, Al_2O_3, and SiO_2 in MSWI bottom ash, shaded according to the value of 28-day Ash Impact Strength Index (AISI). These plots show the AISI for cementitious materials prepared with MSWI bottom ash at replacement levels of (a) 20% (Y. Cheng et al., 2019; Jurič et al., 2006; Kim et al., 2016; X. G. Li et al., 2012; Lin & Lin, 2006; Y. Liu et al., 2018; Pei Tang et al., 2020; Wongsa et al., 2017; Yang, Ji, et al., 2018; S. Zhang et al., 2021), (b) 25% (Alderete et al., 2021; B. Chen & Ye, 2024; Y. Cheng et al., 2019; Joseph et al., 2020; Jurič et al., 2006), and (c) 30% (Bertolini et al., 2004; Carsana et al., 2016; Y. Cheng et al., 2019; Kim et al., 2016; X. G. Li et al., 2012; Sun et al., 2024; P Tang et al., 2016; Yang, Ji, et al., 2018). The color gradient on the right serves as a scale, indicating the range of AISI values from lowest to highest.

reveals a gradual color transition in the plots from red to blue. This transition indicates that the 28-day AISI generally decreases as the substitution level of MSWI bottom ash increases from 20% to 30%.

4.2.4. Influence of particle size and water-to-binder ratio

As shown in Fig. 4(c), the 28-day AISI is influenced by the particle size of MSWI bottom ash. The ash used as an SCM typically has a particle size smaller than 35 μm. Among the particle sizes tested, only those equal to or smaller than 10 μm resulted in strength comparable to or higher than samples without MSWI bottom ash, as indicated by the 28-day AISI being close to or higher than 1. In the example with the highest 28-day AISI (1.22), the strength increase was achieved by grinding MSWI bottom ash to a D_{50} of around 9.3 μm (S. Zhang et al., 2021). This research focused on a dry-cast concrete mixture, so the increased water demand due to particle size reduction was not a concern. Another notable example is the reduction of bottom ash particle size to around 3 μm, resulting in a 28-day AISI ranging from 1.0 to 1.1 (Bertolini et al., 2004; Carsana et al., 2016). As this concrete was prepared using conventional methods, the workability issues caused by particle size reduction needed to be addressed. A superplasticizer was used to maintain the water-to-binder ratio of the MSWI bottom ash-containing concrete mixture at the same level as that of the reference concrete.

4.2.5. Sensitivity of compressive strength to each influencing factor

As discussed above, compressive strength is not determined by a single factor alone. Instead, it is influenced by the combined effects of multiple factors. Therefore, it is essential to identify which factor has the most significant influence. This section utilizes multiple linear regression analysis to derive correlation coefficients, quantifying the influence of each factor on the 28-day AISI. Multiple linear regression is a method particularly suitable for studies where multiple variables are believed to contribute to a single outcome, as it helps in understanding the individual contribution of each factor while accounting for the presence of other influencing variables.

In the multiple linear regression analysis, the dependent variable is designated as the 28-day AISI (see Table S3). The independent variables are the factors that influence compressive strength (see Fig. 4(d)). The data on influencing factors, including particle size, metallic aluminum content, replacement level, and water-to-binder ratio for each research paper, are detailed in Table S2. The particle size used in the analysis is the D_{50} value of MSWI bottom ash powder used for sample preparation. The reactivity of MSWI bottom ash is represented by the $CaO/(SiO_2 + Al_2O_3)$ mass ratio, with a higher value of this ratio indicating increased reactivity. The weight percentages of these three components are measured by XRF (see Table S2). Our dataset consisted of 21 observations with no missing values, ensuring a robust analysis. Initial exploratory data analysis confirmed no apparent outliers, allowing us to proceed without data imputation or anomaly correction.

The correlation coefficients displayed in Fig. 4(d) reveal how sensitive the 28-day compressive strength is to changes in each factor. The value of a correlation coefficient indicates the strength and direction of a relationship between two variables, where values closer to 1 or −1 indicate a strong positive or negative correlation, respectively, while values close to 0 suggest a weak or nonexistent correlation. Among these factors, only reactivity demonstrated a positive correlation of 0.252, suggesting that an increase in the reactivity of bottom ash correlates with a higher compressive strength. The replacement level exhibited the most significant negative correlation of −1.023, indicating that higher MSWI bottom ash replacement levels could significantly reduce compressive strength. The other factors (metallic aluminum content, water-to-binder ratio, and particle size) have minor or negligible negative correlations, demonstrating less influence on compressive strength relative to the replacement level and reactivity.

4.3. Durability properties

A comprehensive assessment of the durability properties of MSWI bottom ash-blended cementitious materials is essential for broadening their potential application in civil engineering. The durability of cementitious materials is determined by their ability to resist various forms of degradation while preserving structural integrity and appearance over their expected lifespan within a given environment. The durability properties evaluated in previous studies include resistance to chloride ingress, carbonation, sulfate attack, and freeze-thaw cycles. Figure 6 presents the key factors influencing the long-term performance of cementitious materials blended with MSWI bottom ash. It also outlines the underlying mechanisms driving these effects, providing a concise summary of current knowledge in this area. The ensuing sections provide a more detailed discussion of each property.

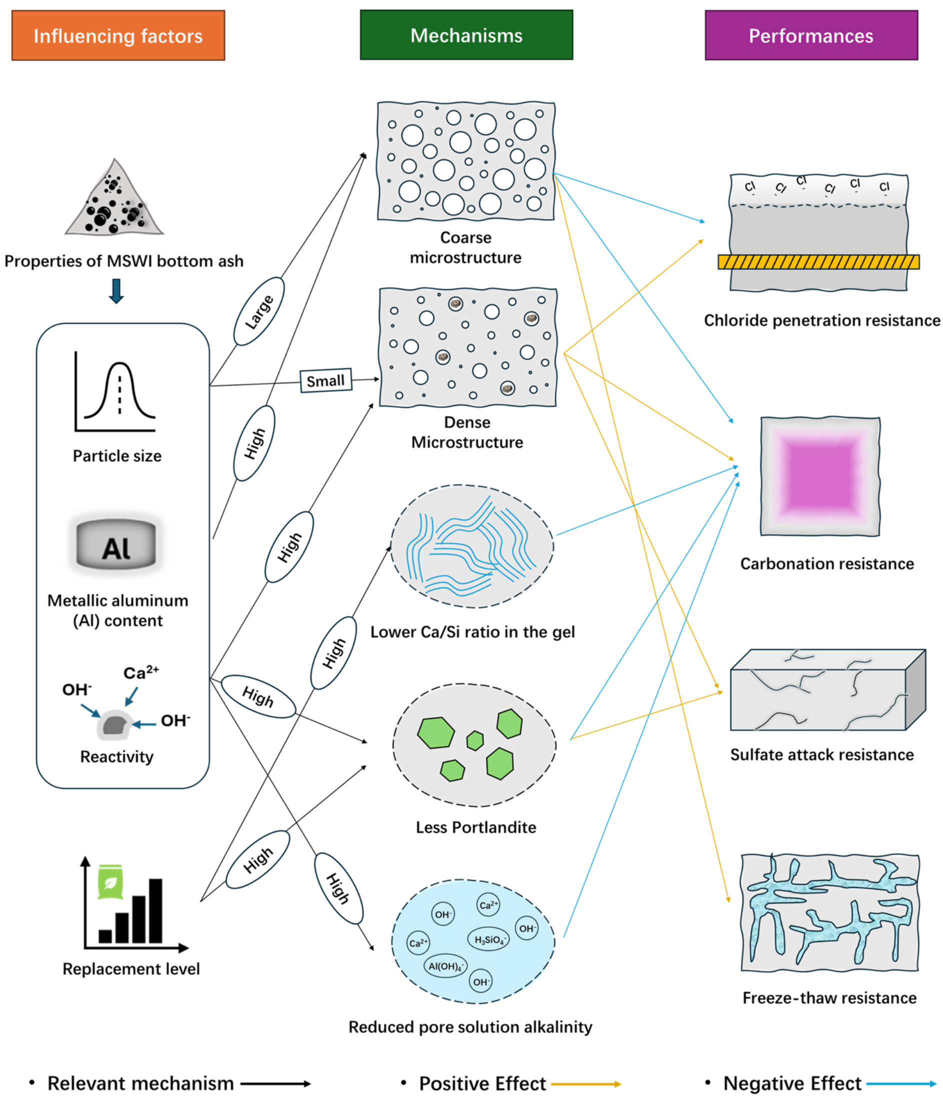


Figure 6. Influencing factors, associated mechanisms, and combined effects on the long-term performances of cementitious materials blended with MSWI bottom ash. The labels “large”, “small”, “low” and “high” in the figure refer to the magnitude of factors. For example, in the case of particle size, “large” refers to a larger particle size, while “small” refers to a smaller particle size.

4.3.1. Chloride penetration resistance

When MSWI bottom ash is incorporated into the reinforced concrete mix for marine environments or areas exposed to deicing salts, the investigation of chloride transport properties within the concrete becomes essential. Chloride exposure poses a significant risk of corrosion to the reinforcing steel, potentially compromising the structural integrity of the reinforced concrete (Mehta & Monteiro, 2014). The chloride penetration resistance of hardened cementitious materials is mainly influenced by the microstructure of the matrix and the capacity of hydrates to physically adsorb and chemically bind chloride ions (Georget et al., 2022; C. Liu et al., 2021; Osio-Norgaard et al., 2018; Weerdt et al., 2023; J. Zhang et al., 2019).

The metallic aluminum content and particle size of bottom ash are factors that influence the chloride resistance of blended cementitious materials by altering the pore structure. When MSWI bottom ash containing metallic aluminum was used as an SCM in blended cement concrete, the chloride diffusion coefficient of concrete increased with the ash addition (Simões et al., 2020). This is because hydrogen gas released after the redox reaction of metallic aluminum leads to a dramatic increase in porosity (Simões et al., 2020). Carsana et al. (2016) reported an increased resistance of concrete to chloride penetration when cement was partially replaced by MSWI bottom ash milled in the presence of water. The particle size of wet-ground MSWI bottom ash was smaller than that of cement particles, which can refine the pore structure of the concrete and thus reduce the rate of chloride penetration (Bertolini et al., 2004; Carsana et al., 2016). It is worth noting that reducing the porosity of MSWI bottom ash-blended cement concrete by lowering the water-to-binder ratio was also effective in lowering the diffusion of chloride ions (Alderete et al., 2021).

A previous study demonstrated that the incorporation of MSWI bottom ash as a partial replacement for Portland cement reduced the content of monosulfate and C-S-H gels (B. Chen & Ye, 2024), which may negatively influence the chloride binding capacity of the system. The AFm phases (monosulfate and hydroxy-AFm) account for approximately 70% of the total chloride binding capacity of the cement paste (Balonis et al., 2010; Florea & Brouwers, 2012). The chloride ions are chemically bound by replacing sulfate or hydroxyl ions in AFm phases, forming Friedel's salt. The C-S-H contributes relatively consistently across different chloride concentrations, accounting for 25–28% of the total chloride binding capacity (Florea & Brouwers, 2012). The chloride ions are physically adsorbed onto the negatively charged surface of C-S-H gels (Wilson et al., 2022). Although the influence of bottom ash addition on chloride binding capacity can be inferred from the changes in the reaction products, further research is needed to confirm this inference.

4.3.2. Carbonation resistance

It is important to assess the resistance of concrete to carbonation when incorporating MSWI bottom ash as an SCM. Carbonation of cementitious materials is a major cause of steel reinforcement corrosion, which can potentially lead to structural failure (Anstice et al., 2005). The carbonation resistance of concrete is influenced by factors such as pore structure, hydration product composition, pore solution alkalinity, curing conditions, and exposure conditions (Xu et al., 2022). Previous studies primarily examine the effects of bottom ash addition on concrete carbonation resistance by analyzing changes in pore structure and pore solution alkalinity.

The porosity of cementitious materials containing MSWI bottom ash is strongly influenced by its metallic aluminum content and particle size. Reducing the metallic aluminum content, increasing the fineness of the bottom ash, or lowering the water-to-binder ratio can all reduce the porosity in cement pastes containing bottom ash (Alderete et al., 2021; Carsana et al., 2016). A denser pore structure generally enhances carbonation resistance by reducing the ingress of CO_2 into the material. Nevertheless, in some cases, although adding MSWI bottom ash reduces porosity, it still leads to a decrease in carbonation resistance (Carsana et al., 2016).

Current research links the reduced carbonation resistance of bottom ash-blended cementitious materials to the lower portlandite content (Carsana et al., 2016). The lower CaO/SiO_2 ratio in bottom ash compared to cement results in less portlandite when the ash is used as a cement replacement (B. Chen, Perumal, et al., 2023). The reaction of bottom ash also consumes portlandite (B. Chen & Ye, 2024). With less portlandite available to react with CO_2, it becomes more difficult to maintain the high pH necessary to protect embedded steel reinforcement from corrosion. It is worth noting that the incorporation of bottom ash in cement also decreases the Ca/Si ratio of C-S-H gel (B. Chen & Ye, 2024). The gel with a lower Ca/Si ratio is more susceptible to decalcification induced by carbonation, which leads to the formation of silica gels and significant carbonation shrinkage (C. Liu et al., 2024; B. Lu et al., 2023; Zajac et al., 2020). To date, no specific studies have focused on this aspect.

4.3.3. Sulfate attack resistance

Sulfate attack is a crucial concern when MSWI bottom ash-blended cementitious materials are used in foundations, underground structures, marine environments, or any structures exposed to sulfate-rich industrial waste (Santhanam et al., 2001). Sulfate ions can penetrate the concrete and react with calcium hydroxide, AFm, or unreacted C_3A to form ettringite. The formation of this delayed ettringite is accompanied by volume expansion, which can cause extensive cracking and even structural failure of the concrete (Cohen, 1983). Besides, sulfate ions also react with $Ca(OH)_2$ to form gypsum, leading to the softening and spalling of the concrete surface (Santhanam et al., 2001; Tian & Cohen, 2000).

Using MSWI bottom ash as a partial replacement for cement can enhance the resistance of concrete against sulfate attack (Y. Cheng et al., 2019). On the one hand, the incorporation of bottom ash reduces the content of C_3A and $Ca(OH)_2$ in the system, thereby limiting the formation of ettringite at later ages (Y. Cheng et al., 2019). On the other hand, the finer particle size of bottom ash compared to cement particles allows it to fill voids between larger particles, improving packing density and contributing to a reduction in porosity. This reduction in porosity enhances the sulfate resistance of blended cementitious materials (Y. Cheng et al., 2019).

4.3.4. Freeze-thaw resistance

The freeze-thaw resistance is an important property for MSWI bottom ash-blended cementitious materials serving in cold climates. The degradation mechanisms behind the freeze-thaw cycles have not reached a consensus, but a widely accepted explanation is the formation and growth of ice crystals within the pores of the material. When water in these pores freezes, it expands and exerts pressure on the surrounding material (Powers & Willis, 1949). Repeated freezing and thawing cycles lead to the gradual development of micro-cracks, eventually compromising the durability and structural integrity of the concrete (L. Liu et al., 2011). The freeze-thaw resistance of concrete is mainly influenced by pore structure, water absorption capacity, and ability to resist cracking (R. Wang et al., 2022).

Existing research primarily focuses on how pore structure influences the freeze-thaw resistance of MSWI bottom ash-blended cement concrete. S. Zhang et al. (2021) reported that the metallic aluminum in bottom ash contributes to improved freeze-thaw resistance of concrete. The porous structure formed from the reaction between metallic aluminum and calcium hydroxide facilitates the even distribution of stress induced by freezing and thawing cycles, reducing the maximum stress imposed on the concrete (Ziaei-Nia et al., 2018). As a result, the damage caused by freeze-thaw cycles is mitigated.

4.4. Leaching of contaminants

The leaching potential of contaminants from MSWI bottom ash-blended cementitious materials must be assessed before their application. This concern arises from the presence of heavy metals (such as Cu, Zn, Pb, and Cr) and soluble salts (including Cl^- and SO_4^{2-}) in the ash, which may leach into aquatic and terrestrial environments, posing risks to both ecosystems and human health. Previous research has shown that with bottom ash replacement levels between 5 and 30 wt.%, the concentrations of contaminants in leachates from blended cement pastes, mortars, and concretes are generally below local regulatory limits (Gong et al., 2022; X. G. Li et al., 2012; Lin et al., 2008; Lin & Lin, 2006; Lo et al., 2020; Loginova et al., 2021; P Tang et al., 2016; Yang, Ji, et al., 2018; Yang, Tian, et al., 2018). However, due to significant regional variations in these threshold values, products considered compliant in one area may not satisfy the requirements of another. The following sections examine the differences in regulatory limits and highlight potential deficiencies in the standards. Additionally, the leaching behavior of bottom ash-blended cementitious materials and the influencing factors are discussed.

4.4.1. Threshold values for leaching assessment

The regulatory thresholds used to evaluate the environmental risk associated with leaching from MSWI bottom ash-blended cementitious materials are summarized in Table S5. These values are specified in regulatory standards collected from China (Mainland) (Gong et al., 2022; X. G. Li et al., 2012; Yang, Ji, et al., 2018; Yang, Tian, et al., 2018), Taiwan (Lo et al., 2020), USA (Gong et al., 2022), Singapore (Gong et al., 2022), the Netherlands (Loginova et al., 2021; P Tang et al., 2016), Slovenia (Republic of Slovenia, 2022), Belgium (Vlaamse overheid, 2024), Austria (Republic of Austria, 2024), and Denmark (Kingdom of Denmark, 2016). All the threshold values are plotted in Fig. 7(a). Among these regions, only the Netherlands has established specific leaching standards for building materials (Keulen et al., 2016). In other regions, where specific leaching threshold values for building materials are not established, researchers have applied the most relevant standards to evaluate the leaching risks of MSWI bottom ash-blended cementitious materials. The upper limits for each contaminant vary significantly across regions and differences in test methods make direct comparisons difficult. It is unclear whether some regions impose stricter leaching thresholds or if the standards are generally comparable.

In the Netherlands, leaching tests can be conducted on crushed pastes, mortars, and concretes, which typically fall under the category of "unshaped material". Previous researchers in the Netherlands primarily conducted leaching tests on crushed samples to represent end-of-life conditions for bottom ash-blended cementitious materials (Loginova et al., 2021; P Tang et al., 2016). The threshold value prescribed for "unshaped material" is also utilized to evaluate the leaching of bottom ash as a raw material (Loginova et al., 2021; P Tang et al., 2016). Cylinders drilled from hardened cementitious materials, termed "monolithic material", are also used in the leaching tests. The threshold values set for "unshaped material" and "monolithic material" are listed in Table S5. When comparing threshold values for these two categories, the allowable concentrations of most heavy metals are higher in "monolithic materials" than in 'unshaped materials" (see Figure 7(a)).

4.4.2. Factors influencing leaching risks

The leaching risks of MSWI bottom ash-blended cementitious materials are influenced by factors such as the leaching resistance of the ash, the ash replacement level, the alkalinity of the pore solution, and the composition of hydration products. Previous research has primarily focused on minimizing environmental risks related to bottom ash leaching while optimizing its replacement level to meet regulatory requirements.

4.4.2.1. Leaching resistance of MSWI bottom ash. MSWI bottom ash contains toxic elements of environmental concern, including As, Zn, Pb, Cu, Cr, Ni, Se, and Cd (Crillesen et al., 2006; Dou et al., 2017; Hjelmar et al., 2022). Dou et al. (2017) reviewed the leaching characteristics of MSWI bottom ash, highlighting the behavior of heavy metals and alkali salts under various environmental

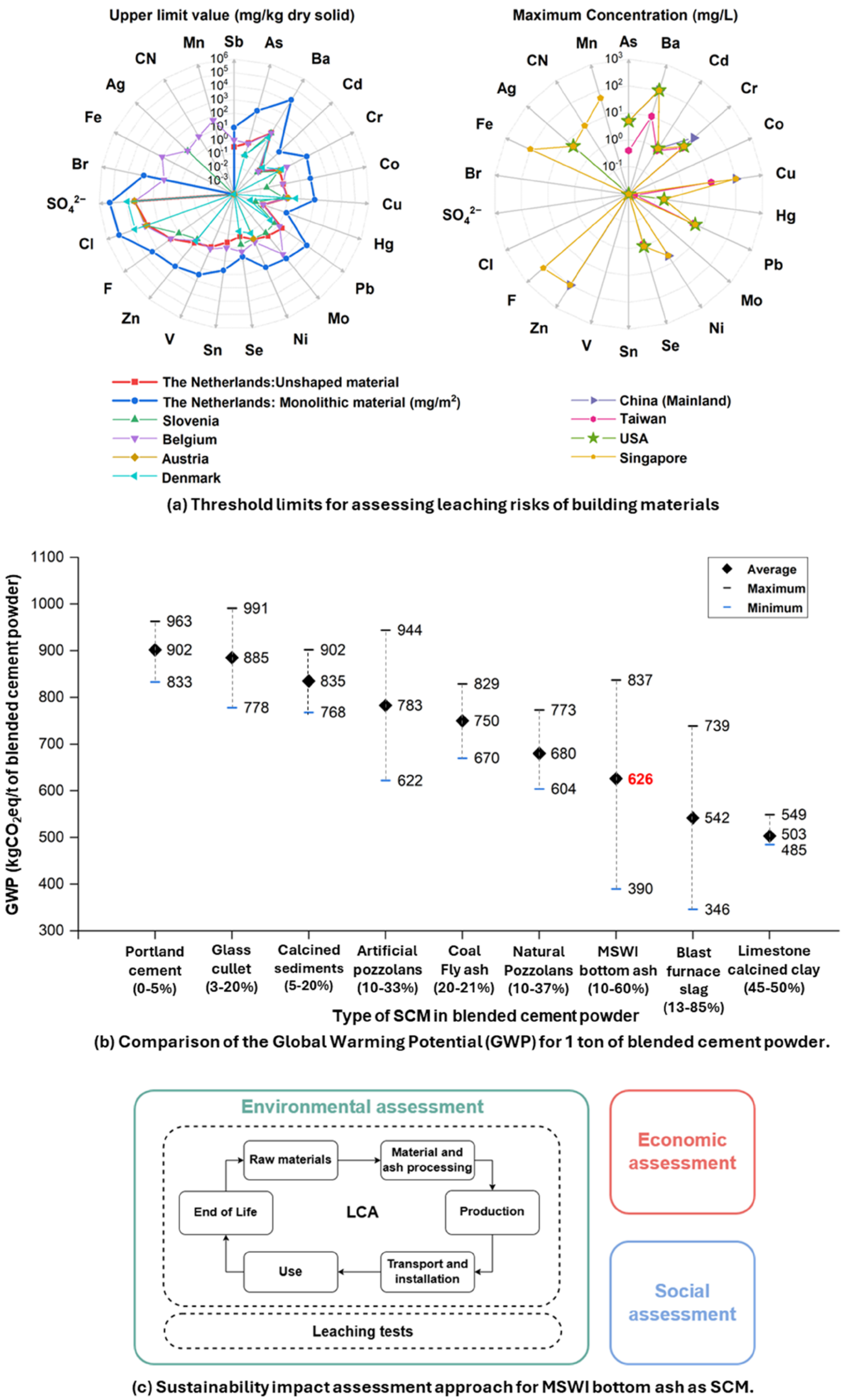


Figure 7. (a) Threshold limits from the most relevant standards across different regions used to assess the leaching risks of building materials. This figure is based on data provided in Table S5. (b)The global warming potential of 1 ton of blended cement powder, which consists of clinker and various supplementary cementitious materials (SCMs). The data for MSWI bottom ash-blended cement powder were calculated based on the information presented in (Alderete et al., 2021; L. Cheng et al., 2024), while the other blended cement data were obtained from (Rhaouti et al., 2023). The percentages in this figure represent the replacement levels of SCMs for clinker (c) A schematic presentation of the sustainability impact assessment approach for the use of MSWI bottom ash as a supplementary cementitious material (SCM) in blended cement paste, mortar, and concrete.

conditions. The extent of heavy metal leaching is strongly influenced by pH. Typically, less than 10% of the total heavy metals can be released by MSWI bottom ash. In contrast, most of the alkali salts (e.g., Na, K, Cl^-, and SO_4^{2-}) present in the bottom ash are highly leachable, as their release occurs regardless of pH (Wiles, 1996). The improvement of leaching resistance in MSWI bottom ash can be achieved through processes such as weathering and water-washing at the plant scale (Chimenos et al., 2000, 2003; Gori et al., 2011; Meima & Comans, 1999; Saffarzadeh et al., 2011; Santos et al., 2013; Speiser et al., 2000, 2001) or through thermal treatments at the lab scale (Lin & Lin, 2006; Stabile et al., 2019; Xiao et al., 2008). If the concentration of heavy metals in the leachate from treated bottom ash is below the threshold values set by standards, this material can be used as an SCM without concerns about the heavy metal release (X. G. Li et al., 2012; Lin et al., 2008; Lin & Lin, 2006; Lo et al., 2020; Yang, Ji, et al., 2018).

4.4.2.2. Replacement level of MSWI bottom ash. For treated MSWI bottom ash with contaminants still above the legislative upper limit, it is necessary to control its replacement level to avoid the risk of excessive leaching. Loginova et al. (2021) performed mechanical treatments on MSWI bottom ash (<3 mm size fraction) and found that the leaching of chloride, sulfate, and antimony was beyond the regulatory threshold value. In this case, a replacement level of 5 wt.% was recommended. Similarly, P Tang et al. (2016) did mechanical and thermal treatments on MSWI bottom ash (<2 mm size fraction) and found that the leaching of chloride, sulfate, and molybdenum still exceeded the upper limits. The replacement level was limited to 30 wt.%.

4.4.2.3. Pore solution and hydration products. The pH of the pore solution in cementitious materials plays a critical role in the immobilization of heavy metals, as it affects the solubility and precipitation of heavy metal compounds like hydroxides, carbonates, and silicates (Q. Y. Chen et al., 2009). The hydration products of cement, such as C-S-H, AFt, and AFm, contribute to immobilization through sorption and precipitation mechanisms (Q. Y. Chen et al., 2009; Gougar et al., 1996; Hong & Glasser, 2002). The incorporation of MSWI bottom ash as an SCM results in changes in the pH of the pore solution, the proportions of hydration products, and the Ca/Si ratio of the C-S-H gel (B. Chen & Ye, 2024). These changes are expected to influence the immobilization of heavy metals, but their precise impact remains underexplored and requires further investigation.

4.5. Environmental impacts

Previous life cycle assessments (LCA) indicate that incorporating MSWI bottom ash as an SCM has environmental benefits. Alderete et al. (2021) reported that replacing 20 wt.% of Portland cement with MSWI bottom ash in concrete reduced its environmental impacts across all assessed categories. It is important to note that (semi-)industrial-scale treatments were applied to convert MSWI bottom ash into a qualified SCM, but the environmental impacts of these treatments were not considered during the LCA (Alderete et al., 2021). L. Cheng et al. (2024) conducted an LCA on substituting 10–60% of Portland cement with MSWI bottom ash in concrete, observing a 7.5–44.1% reduction in environmental impacts compared to Portland cement concrete. A 30% replacement level was proposed as optimal for balancing environmental benefits with concrete performance. Global warming potential (GWP) and eutrophication potential (EP) were identified as the primary environmental contributors (L. Cheng et al., 2024).

The GWP is widely used to communicate environmental impacts and is readily accessible in the literature. Figure 7(b) compares the GWP of 1 ton of unreacted blended cement powder consisting of clinker and SCMs. The data for MSWI bottom ash-blended cement powder (Alderete et al., 2021; L. Cheng et al., 2024) were converted to align with the same evaluation method as the data presented in Rhaouti et al. (2023), ensuring consistency for comparison. MSWI bottom ash-blended cement powder exhibits an average GWP of 626 $kgCO_2eq/t$, which is lower than that of coal fly ash-blended cement powder and slightly higher than blast furnace slag-blended cement powder. However, the GWP values vary significantly with replacement levels, ranging from 390 to 837 $kgCO_2eq/t$. These results highlight the potential of MSWI bottom ash as an SCM to reduce GWP, especially when used at optimized replacement levels.

Notably, current LCA studies on the use of MSWI bottom ash as SCM remain scarce and are often constrained by narrow system boundaries. To provide a more comprehensive environmental evaluation, these studies should adopt cradle-to-cradle approaches aligned with circular economy principles (see Fig. 7(c)). Key improvements include addressing leaching risk, ensuring high-quality and consistent datasets, and conducting sensitivity and uncertainty analyses to enhance methodological robustness (Allegrini et al., 2015). Additionally, integrating environmental, economic, and social dimensions through a life cycle sustainability assessment framework is crucial. This multidisciplinary approach is essential to fully quantify the sustainability potential of MSWI bottom ash as an SCM.

5. Conclusions and recommendations

This review provides a comprehensive analysis of the potential of MSWI bottom ash as a SCM and underscores the need for continued efforts to overcome its challenges and facilitate its broader application in the cement industry. The detailed conclusions and recommendations derived from this review are presented below.

- The compositional variations in MSWI bottom ash, resulting from differences in waste inputs and incineration conditions, present significant challenges for quality control and standardization. Although the current pilot-scale method for producing SCM shows promise, its application must be further validated and adapted to address regional differences in ash properties. The mix designs of MSWI bottom ash-blended cementitious materials often need to be modified to accommodate the specific characteristics of the ash. Achieving reliable use of MSWI bottom ash as an SCM will require localized research, customized treatments, and large-scale collaborative testing.
- Intensive studies have examined the pozzolanic reactivity of MSWI bottom ash and its effects on the microstructure of cementitious materials. However, previous research primarily focused on changes in pore structure and reaction products. The pozzolanic reaction of bottom ash results in the formation of new phases, including sodicgedrite and C-S-H gel with a low Ca/Si ratio. Future research should explore the intrinsic properties of these products, which critically impact the strength, stability, and durability of blended cementitious materials
- Compressive strength is widely regarded as the key indicator of mechanical performance of MSWI bottom ash-blended cementitious materials with extensive data documented in previous studies. In contrast, data on other strength properties, such as tensile strength, flexural strength, and splitting tensile strength, are rarely reported in the literature. Research on the fresh properties and long-term performance of MSWI bottom ash-blended cementitious materials is still at an early stage. Using bottom ash as an SCM delays the setting time and reduces workability. Incorporating MSWI bottom ash into concrete has been shown to enhance resistance to chloride penetration, sulfate attack, and freeze-thaw cycles, but compromise carbonation resistance. Despite these observed effects, the mechanisms underlying these durability behaviors remain poorly understood.
- The AISI introduced in this study facilitates a direct comparison of the effects of various factors on compressive strength across different study conditions. The statistical analysis of 28-day AISI indicates that to achieve a high compressive strength of blended cementitious materials, the bottom ash used as an SCM should meet the following criteria: minimal metallic aluminum content (preferably zero), high reactivity with a $CaO/(Al_2O_3 + SiO_2)$ ratio close to 1, and a particle size no greater than 10 μm. Additionally, the mixture design

should be tailored to limit the replacement level to less than 30 wt.% and ensure an appropriate water-to-binder ratio, with the optional use of a superplasticizer.

- According to previous research, when the substitution rate of bottom ash ranges from 5 to 30 wt.%, concentrations of heavy metals in leachates from blended cementitious materials generally remain below regulatory limits. However, significant variations in leaching standards and test methods highlight the need for tests simulating real environmental scenarios. Although current studies mainly use leaching as a quality control measure, the mechanisms by which bottom ash immobilizes heavy metals remain unclear. Moreover, industry concerns persist that once bottom ash-blended cement products are widely adopted, residual heavy metals from the bottom ash may complicate recycling at the end of their service life. Thus, future research could explore efficient heavy-metal recovery methods to produce cleaner bottom ash with economic value, while minimizing negative effects on bottom ash reactivity.
- Previous LCA suggest that using MSWI bottom ash as an SCM demonstrates sustainability comparable to that of coal fly ash and blast furnace slag. However, comprehensive investigations in this field remain scarce. Most assessments neglect the environmental impacts of pretreatment, heavy metal leaching, and other critical factors necessary for a holistic evaluation.
- A systematic approach is recommended for the incorporation of MSWI bottom ash into blended cementitious materials. As illustrated in Fig. 8, the process begins with a quality assessment to determine whether the ash meets the required standards for use. If the criteria are met, the material can proceed directly to mix design. Otherwise, pretreatment is necessary, along with an evaluation of its environmental impact. The next step involves defining the target application and developing a suitable mix design. This is followed by a thorough performance evaluation, focusing on mechanical strength, volume stability, and durability, with design adjustments made as needed. Continuous monitoring of leaching risks throughout the life cycle is crucial to manage potential environmental risks. Finally, a LCA is conducted to evaluate the overall environmental impact, ensuring the sustainability of the entire process.

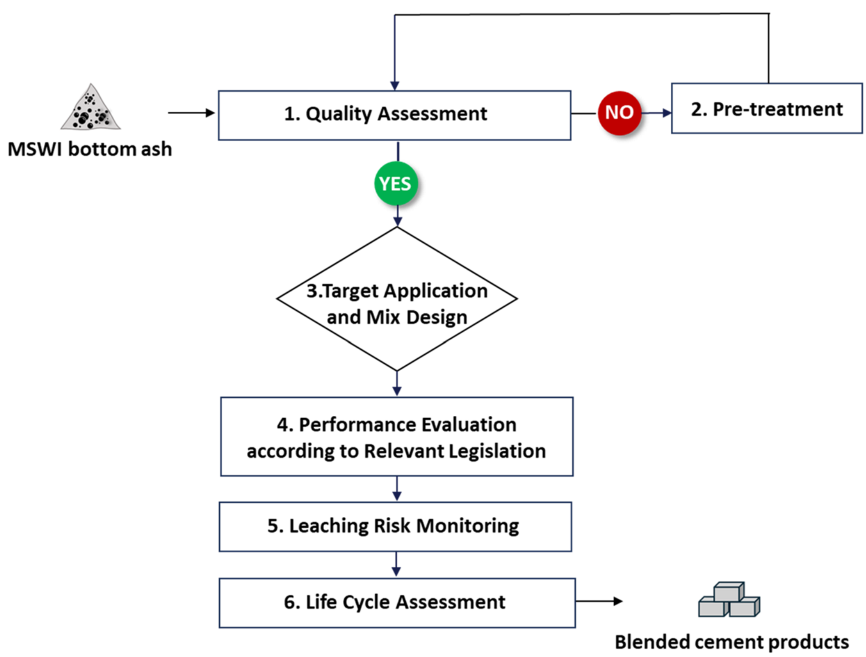


Figure 8. A systematic approach to produce blended cement paste, mortar, and concrete using MSWI bottom ash as a supplementary cementitious material (SCM).

Notes

1. In this article, the terms "bottom ash" and "ash" are used interchangeably and specifically refer to "MSWI bottom ash".
2. In this paper, the term "cementitious materials" encompasses cement paste, mortar, and concrete collectively, as distinct from supplementary cementitious materials (SCMs), which are additives used to partially replace cement.

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