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A REVIEW OF CHEMICAL AND PHYSICAL PROPERTIES OF MUNICIPAL SOLID WASTE INCINERATION BOTTOM ASH AND ITS IMPACT ON CONCRETE PRODUCTION

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Abstract – *This research assesses the physical, chemical, and mineral characteristics of bottom ash from municipal solid waste incinerators and its effects when used in place of traditional aggregates in concrete. Data was collected from scopus.com during the period 2010–2024 using a qualitative study approach and then united using the WOSviewer tool to supply orderly illustration maps proving the need for the research. A review of these investigations disclosed essential tendencies in the domain, accentuating the capability of bottom ash as a valuable difference from customary aggregates. As stated by the review's discoveries, concrete's properties, including compressive strength, shrinkage, porosity, water permeability, expansion, and shrinkage, vary notably when bottom ash replacements standard particles. Though initially concerning, these changes can be mitigated by applying various treatment techniques. Removing bottom ash using mechanical, chemical, and thermal techniques increases its use rate in concrete while preserving its necessary characteristics, such as durability and structural integrity. Additionally, the study emphasizes the potential for improving bottom ash's properties to meet construction industry standards. Reusing bottom ash in buildings reduces the disapproving environmental impact and significantly enhances natural aggregate resources. This, in turn, mitigates dependence on newly obtained materials, reducing the environmental footprint of traditional aggregate extraction. As a result, this research supports auxiliary sustainable development in the building field, contributing to environmental preservation and resource optimization in the long run.*

Keywords: concrete performance, impact of MSWI bottom ash in concrete, municipal solid waste incineration bottom ash.

I. INTRODUCTION

As the world population and economic system continue to expand, the amount of municipal solid waste (MSW) created across the globe will rise considerably, reaching 3.4 billion tons by 2050 [1]. By transforming rubbish into thermal energy, waste incineration infrastructure offers a viable method for dealing with MSW that is complex to biodegrade or recycle [2–4]. The release of atmospheric contaminants and the creation of remnants are the main ecological issues of waste-to-energy processes [5]. The problem of atmospheric contamination can be alleviated by implementing an efficient pollution control system in waste-to-energy plants [1, 6]. Nonetheless, the disposal of incineration by-products continues to be a challenge that must be addressed efficiently. The method of incineration significantly impacts the quantity of residues produced. Research indicates that the by-products generated after incinerating MSW can constitute approximately 20% of the input waste [7, 8]. Depending on the incineration method, waste incineration processes produce three kinds of by-products: fly ash, bottom ash (boiler ash/including economizer), and atmospheric pollution residues [8]. Of these by-products, only bottom ash is regarded as non-hazardous waste [9]. Bottom ash from

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municipal solid waste incineration (MSWI) is typically gathered at the base of the combustion chamber and can make up 80–90 wt% of the total incineration remnants [10, 11]. In Vietnam, the swift inhabitant growth and urban development have led to a rise in MSW, resulting in environmental infection and influencing human health. Thus, many MSWI plants have been built and are functioning, producing a large amount of bottom ash that is currently being landfilled. Figures show that the overall volume of MSW created nationally in 2019 was 64,658 tons per day. The country is building waste incineration plants with diverse techniques, producing a substantial ash source.

Using bottom ash from MSWI for productive materials in the construction industry is becoming essential. Globally, the mineral components found in bottom ash from MSWI can be utilized in ceramics production [12–17] and in other construction materials such as cement clinker, aggregates, and binding agents [18–24]. Bottom ash from MSWI is widely used as a landfill for building highways and levees [25]. In Vietnam, although there are regulations and standards for using a portion of bottom ash in the construction sector, its application remains limited, and there are very few studies on using bottom ash in concrete production. Research on optimizing the use of bottom ash and creating environmentally friendly concrete is still scarce. However, employing bottom ash from MSWI as an additional cementitious component or a precursor for alkali-activated materials presents considerable challenges because of its diverse and complex composition. The chemical and physical and chemical characteristics of bottom ash from MSWI are greatly influenced by the composition of the input materials, the combustion process, and the processing methods applied, which necessitate extensive research and development to enhance its application in concrete production.

Using energy-dispersive X-ray (EDX) and X-ray emission spectroscopy, the present work investigates bottom ash's chemical and physical properties from MSWI to identify Ca, Si, Al, Fe, and Mg, among others. The interaction of bottom ash with cement and the hydration process is much influenced by its abundance of minerals, including quartz, calcite, and iron oxide, as well as physical properties, including porosity, particle size, and mineral phase distribution. The work investigates how MSWI bottom ash affects concrete properties, including compressive strength and durability. Changing a component of traditional aggregate with MSWI bottom ash changes the compressive strength of concrete. Notably, substituting 30% can diminish compressive strength; a smaller proportion (10%) may only marginally weaken or even raise the compressive strength in particular cases. Particularly about controlling the growth of ettringite crystals from the sulfate and alumina phases, further research is needed to identify the exact factors influencing the expansion and contraction of concrete with bottom ash. A review of the studies on bottom ash in Vietnam exposes the possibilities and challenges of employing this waste substance in manufacturing concrete, opening new paths for the building sector and environmental preservation.

II. RESEARCH METHODS

The bibliometric analysis method is applied in this study to determine research trends regarding the physical and chemical characteristics of MSWI bottom ash and how they affect concrete production. The credibility and inclusiveness of the information source are confirmed by the fact that the data was compiled from the Scopus database, a prestigious system for research-based document repositories. To ensure the exactness. The applicability of the data, the search procedure, and data collecting are carried out according to set standards. The years 2010–2024 are included in the requirements. Journal articles, conference papers, and review articles are among the documents that need to be collected. The documentation needs to be written in English. The terms 'MSWI', 'concrete', 'treatment', 'bottom ash', and 'cement', coupled with logical operators like OR, AND, and NOT are used in the search process to maximize results. Lastly, duplicate articles that are unnecessary or lack essential information will be eliminated by filtering the gathered data.

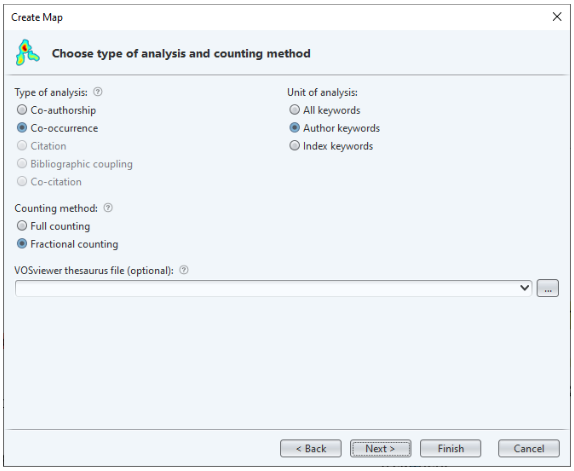
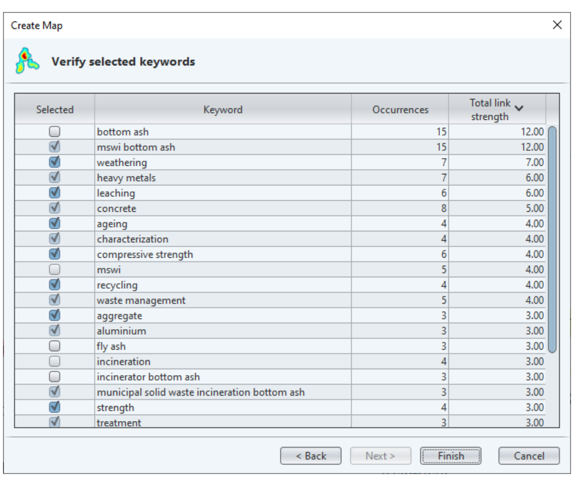


Fig. 1: Choosing the type of analysis and counting method for map creation



Selected	Keyword	Occurrences	Total link strength
☐	bottom ash	15	12.00
☑	mswi bottom ash	15	12.00
☑	weathering	7	7.00
☑	heavy metals	7	6.00
☑	leaching	6	6.00
☑	concrete	8	5.00
☑	ageing	4	4.00
☑	characterization	4	4.00
☑	compressive strength	6	4.00
☐	mswi	5	4.00
☑	recycling	4	4.00
☑	waste management	5	4.00
☑	aggregate	3	3.00
☑	aluminium	3	3.00
☐	fly ash	3	3.00
☐	incineration	4	3.00
☐	incinerator bottom ash	3	3.00
☑	municipal solid waste incineration bottom ash	3	3.00
☑	strength	4	3.00
☑	treatment	3	3.00

Fig. 2: Verifying selected keywords for map creation

Upon data collection, a comma-separated values file is loaded into WOSviewer as the research method of Van et al. [26] to generate visual maps of the keyword co-occurrence network, facilitating the identification of primary research subjects. The process commences with selecting the data type, wherein the user opts for 'Create a map based on bibliographic data' followed by extracting data from bibliographic database files from Scopus. Subsequently, it employs many accessible analytical techniques (Figure 1). Keyword co-occurrence analysis is the principal method used to discern the fundamental issues, utilizing the author's keywords as the analytical unit (Figure 2). A minimal criterion for the frequency of keyword occurrences is established. Subsequently, to facilitate the visualization of the linkages across study topics, only the keywords that satisfy the requirements are chosen to construct the map (Figure 3).

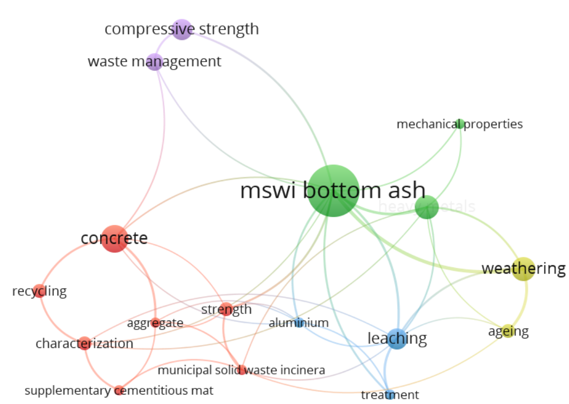


Fig. 3: Network of MSWI bottom ash

III. RESULTS AND DISCUSSION

This section analyzes bottom ash's chemical and physical properties from the MSWI process and assesses its impact when applied to concrete production. First, the chemical characteristics of the bottom ash are presented based on X-ray fluorescence analysis results and the main oxide components, clarifying the potential of these components in the cement hydration process. The part on physical properties covers bottom ash's surface qualities and structure, influencing concrete's mechanical properties and lifetime. Next under examination are studies on compressive strength, water permeability, porosity, and concrete expansion, including bottom ash, to help define the effect of various replacement ratios. Lastly, treatment plans to maximize bottom ash before its concrete manufacturing use is covered to improve reuse possibilities and reduce environmental impact.

Chemical properties

In this portion, we revise and fuse existing studies on the chemical personal effects of MSWI bottom ash, drawing upon various trial data to highlight the initial elements present and their possible roles in concrete making.

A chemical composition analysis of bottom ash from MSWI was conducted using X-ray Fluorescence Spectroscopy. MSWI bottom ash holds significant amounts of Al_2O_3, SiO_2, and CaO [27], which are essential for the hydration process in cement. Significantly, the CaO content in disintegrate secondary than 0.125 mm is 38.41%, while SiO_2 and Al_2O_3 are 16.46% and 15.68% singly [28]. These concentrations vary depending on particle size, with SiO_2 increasing in more significant segments [29]. These are also the main components of the OPC [27].

The primary cation elements, besides Si, which is present at high concentrations (> 10,000 mg/kg), include Ca, Al, Na, and Fe. Environmentally concerning heavy metals are present at relatively high concentrations (> 100 mg/kg) and include Zn, Pb, Cr, and Cu [30].

Moreover, the average chemical composition of naturally cured bottom ash from MSWI is presented in Table 1, containing 49.38% SiO_2 and 14.68% CaO, along with other components [31].

Table 1: Average chemical composition of naturally weathered bottom ash from MSWI

Oxides	Bottom ash MSWI (%)
Cl	n.d.
SiO_2	49.38
CaO	14.68
Fe_2O_3	8.38
Na_2O	7.78
Al_2O_3	6.58
MgO	2.32
K_2O	1.41
CuO	1.26
SO_3	0.57
ZnO	0.38

In this table, the chlorine (Cl) value is listed as 'n.d.' which stands for 'not detected'. It indicates that the chlorine concentration in the naturally weathered bottom ash sample is too low to be measured or detected using the analytical method.

The first oxide components of MSWI are outlined in Table 1, with values aligning with previous research [32–34]. A comprehensive review of the principal oxide components in bottom ash from MSWI reveals that the primary components include SiO_2 (34.0%), CaO (28.4%), Al_2O_3 (8.3%), and other oxides. The secondary components of MSWI bottom ash also have a significant influence, with variations tied to the specific characteristics of MSWI and operating conditions like combustion heat. Earlier research has determined that treating salty and polyvinyl chloride waste has led to MSWI bottom ash with elevated chloride content [35]. In MSWI bottom ash, SiO_2 primarily exists as quartz, providing nucleation sites during the hydration process but limiting its contribution [32, 36]. Research by Loginova et al. [32] demonstrated that the Si proportion of coarse bottom ash from MSWI particles might reach double those of smaller particles, highlighting the importance of grinding the coarse particles [32]. For aluminum, most aluminum-bearing phases in bottom ash exist in their pure metallic state [34].

The most critical compounds for concrete products are Al, Pb, and Zn. Elevated aluminum concentrations can cause swelling in fresh concrete. Besides, the Pb and Zn content can delay concrete curing time [37, 38].

The results in Table 2 show that the heavy metal content is much lower than the limits set by QCVN 07:2009/BTNMT [39], indicating that MSWI bottom ash is non-hazardous solid waste. The chemical composition of the bottom ash was analyzed by wet chemistry (Table 3), showing that it mainly consists of common oxides.

Physical properties

This section examines the physical characteristics of MSWI bottom ash based on established research. By aggregating various studies, we aim

Table 2: Heavy metal composition in MSWI bottom ash

Parameter	Leaching Concentration (mg/L)	Absolute content (ppm)
Antimony	0.002	22.9
Arsenic (As)	0.009	10.7
Barium (Ba)	2.604	209.8
Silver (Ag)	< 0.001	37.2
Beryllium (Be)	< 0.001	0.14
Cadmium (Cd)	0.002	144.4
Lead (Pb)	0.170	774.6
Cobalt (Co)	0.009	4.3
Zinc (Zn)	0.279	1,476
Molybdenum (Mo)	0.075	2.4
Nickel (Ni)	0.013	15.8
Selenium (Se)	0.007	2.5
Thallium (Tl)	0.023	< 1
Mercury (Hg)	0.024	0.86
Vanadium (V)	<0.01	10.5
Chromium VI (Cr VI)	0.400	< 6
pH (alkalinity/acidity)		11.5

Table 3: Basic chemical composition of MSWI bottom ash

Chemical Formula	Name	Unit	Result
LOI	Loss on Ignition	%	5.73
SiO_2	Silicon Dioxide	%	52.84
Fe_2O_3	Iron Oxide	%	3.44
Al_2O_3	Aluminum Oxide	%	7.77
CaO	Calcium Oxide	%	19.32
MgO	Magnesium Oxide	%	2.02
SO_3	Sulfur Trioxide	%	0.75
K_2O	Potassium Oxide	%	1.64
Na_2O	Sodium Oxide	%	3.51
TiO_2	Titanium Dioxide	%	0.44
Cl-	Chloride Ion	%	1.33
	Soluble Silica Content	mMol/L	105
	Alkali Reduction	mMol/L	269

to provide a detailed understanding of how the material's physical attributes influence its concrete application.

The EDX spectra analysis of finely ground bottom ash particles has identified the presence of Al, Fe, Mg, and Si (Figures 4c, 4d, 4e), aligning with the primary oxide components identified by X-ray Fluorescence Spectroscopy and shown in Table 1. Titanium (seen in Figure 4c.z4) was likewise detected [40]. The EDX spectra reveal larger particles (Figure 4c.z1) that appear more abundant in silicon, oxygen, and sodium. A few small, bright particles contain iron and oxygen, likely iron oxide (Figure 4c.z5) [41].

As observed in Figure 4a, the crushed bottom ash particles, considered using Scanning Electron Microscopy (SEM), display an irregular and angular shape, and debris from fragmented material can be seen on the surfaces of some particles. Figure 4b shows these features are consistent with previous studies [20, 42, 43]. The surface characteristics of MSWI particles predominantly originate from buffer substances or waste-holding contaminants and intricate elements that can lead particles to clump together at high heat during burning [40]. Particles with a spongy structure, seen in Figure 4a.z3, might comprise mineral components, partially or fully molten, then become porous as trapped gases escape, as suggested by [34, 35].

SEM images (Figure 5) reveal that the ash particles have numerous gaps and voids, leading to a rough surface and a large surface area. It increases the water demand when mixed into the cement blend and offers better opportunities for chemical interaction during the hydration process [29]. The particle composition and physical properties of MS bottom ash were determined according to TCVN 7572:2006 [44]. The Los Angeles abrasion test was performed for particles larger than 5 mm. The hazardous components in MSWI bottom ash were determined using US EPA Method 1311 and SMEWW 3125B:2012. Bottom ash from MSWI is a suitable substitute for fine aggregate in concrete and concrete bricks due to its appropriate particle size and not overly complex manufacturing process. However, bottom ash contains easily soluble chloride salts and a small amount of heavy metals, requiring treatment to reduce Cl- ions and alkalis levels. The heavy metals in the ash can cause expansion and cracks in the concrete structure. The low melting temperature of bottom ash allows for manufacturing ceramic aggregates with good mechanical properties, but this is more costly. The porous particle structure of bottom ash increases the water demand for the concrete mix and the process of shaping concrete bricks.

Mineral constituents

This section presents a comprehensive review of the mineral constituents of MSWI bottom ash, summarizing key findings from various studies.

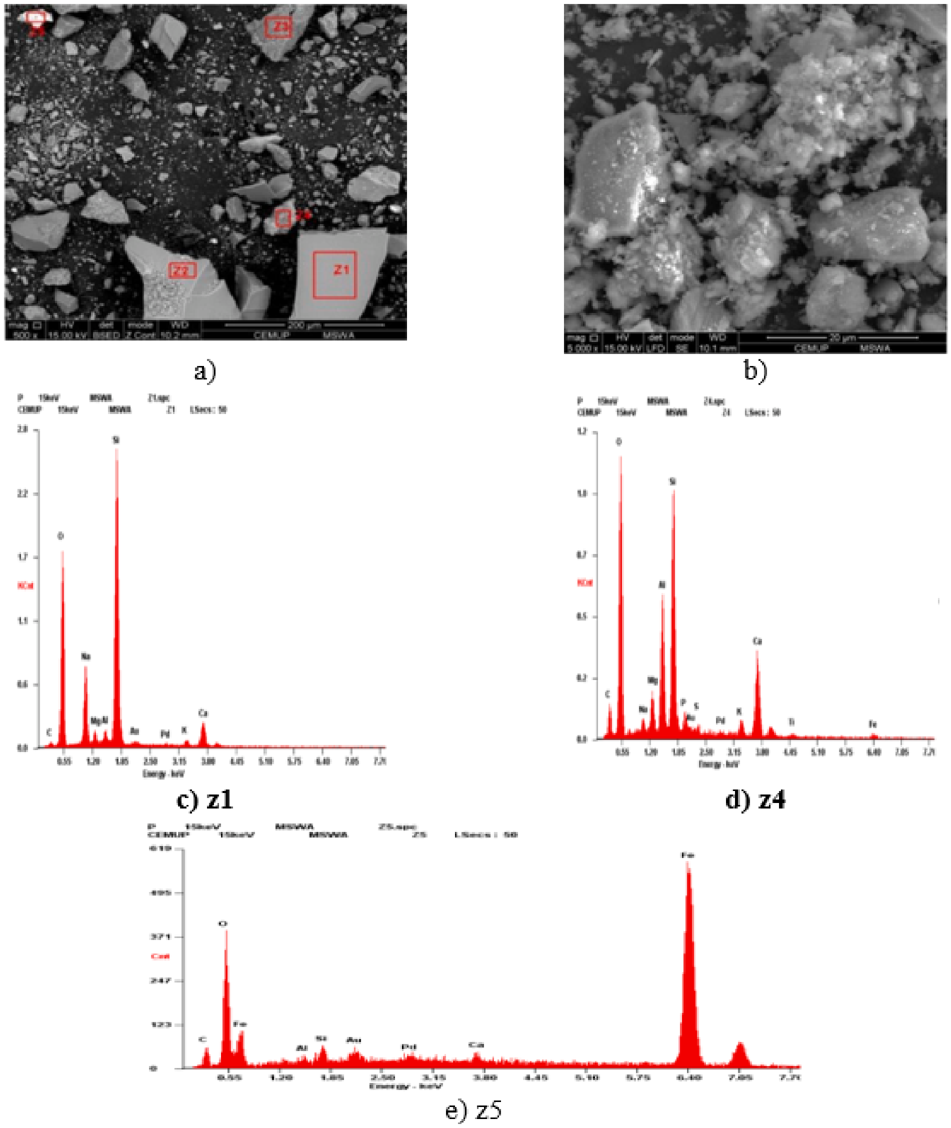


Fig. 4: SEM image in secondary electron imaging of bottom ash granules: a) overall particle overview (× 500); b) particle specifics (× 5000); c) EDX spectra related to area z1; d) EDX spectra related to area z4; e) EDX spectra related to area z5

The mineral composition and its implications for concrete production are discussed, particularly emphasizing the phases that influence hydration and durability.

The primary constituents in MSWI bottom ash are metals and minerals [45]. Weathered bottom ash from MSWI contains various minerals, including silica, iron oxides, different phosphates, hydroxides, carbonates, sulfates, non-ferrous metal oxides, silicates, chloride salts, sulfides, and other minerals. These minerals are classified into 11 distinct categories, detailed in Table 4. Silicates are categorized into four subgroups: pyroxene, melilite, feldspar, and other silicates. The literature often references minerals like iron oxides, quartz, and calcite. Typically, the

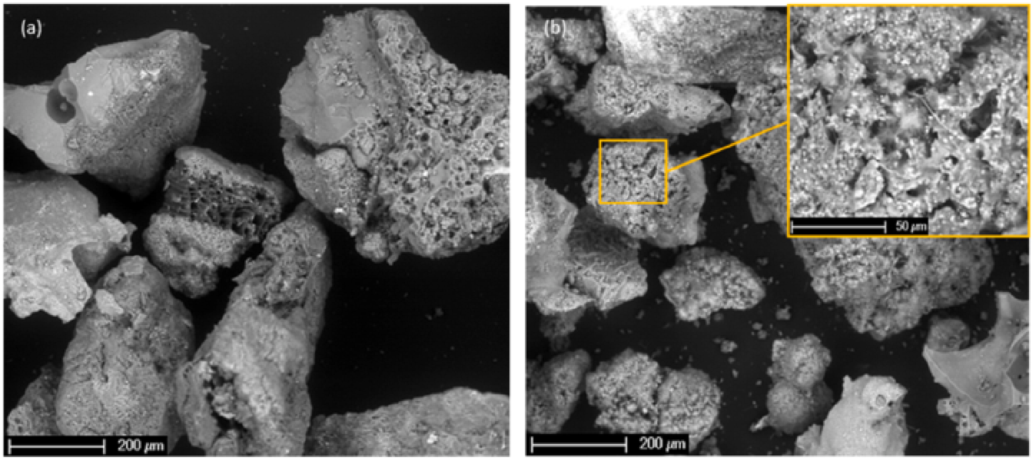


Fig. 5: Morphology of air-recovered MSWI bottom ash (0–2 mm) directed by SEM (100 and 500 × enlargement, using an acceleration voltage of 10 kV)

content of iron oxides is below five wt%, with magnetite being the predominant component. The overall silicate content in the ash usually does not exceed 15 wt% and includes common silicates like gehlenite, akermanite, albite, anorthite, and diopside [46].

As determined by the XRD method (Figure 6), the ash contains primary mineral phases such as quartz (SiO_2), calcite ($CaCO_3$), and minerals like akermanite and magnetite. The distribution of these mineral phases affects how the ash interacts with cement and influences the hydration process [29].

A. Characteristics of concrete when using MSWI bottom ash

Evaluating its durability, which informs its long-term performance, is crucial to achieving sustainable concrete. The durability of concrete that incorporates treated bottom ash depends on its interaction with environmental factors and the penetration of deleterious agents. Consequently, pore structure and movement characteristics such as capillary absorption velocity, air flow, chloride penetration, and carbonation were evaluated to compare the long-term performance between concrete mixes containing treated bottom ash and standard reference mixes [64].

Kim et al. [65] utilized MSWI bottom ash to replace fine aggregate. The mixtures' compressive strength, hydration temperature, and shrinkage performance were assessed. These findings provide insights into the effects of bottom ash from MSWI on the properties of mortar and its potential application as an additive in the construction industry, particularly in producing mortar and concrete [65].

Compressive strength of concrete

The investigation carried out by Li et al. [66] assessed the impact of bottom ash from MSWI fine powder in conjunction with variations in the water-binder ratio on the concrete's compressive strength (Table 5). Figure 7 shows the compressive strength of concrete containing bottom ash from MSWI micro powder after 28 and 90 days. The compressive strength of standard concrete and concrete with bottom ash from MSWI fine particles appear comparable. As the water-binder ratio rises, the compressive strength of the concrete diminishes. Also, when the curing time is long and the mixing amounts are the same, the compressive strength of regular concrete is not as high as that of concrete with bottom ash from MSWI fine particles [66].

Table 4: Categories of minerals found in weathered bottom ash from MSWI

Category	Minerals / Mineral Group	References
Silicon Dioxide	Quartz, Cristobalite	[18, 22, 47–59]
Iron Oxides	Magnetite, Hematite, Wustite	[18, 22, 47, 48, 50, 51, 53, 54, 56, 58, 60]
Silicates	Melilite, Feldspar, Pyroxene, Other silicates (Gehlenite, Akermanite, Albite, Anorthite)	[18, 22, 47, 48, 50, 51, 54–57, 60, 61]
Carbonates	Calcite, Dolomite	[18, 22, 47, 49, 60]
Sulfates	Ettringite, Gypsum, Anhydrite	[48, 50, 52, 53, 56–59]
Chloride Salts	Halite, Sylvite	[18, 52, 56, 57]
Phosphates	-	-
Non-ferrous Metal Oxides	Rutile, Corundum	[18, 45, 62]
Hydroxides	Gibbsite, Goethite, Lepidocrocite, Ferrihydrite	[45, 48, 52, 59, 62]
Sulfides	Copper-containing and other sulfides	[45, 63]
Other Minerals	-	-

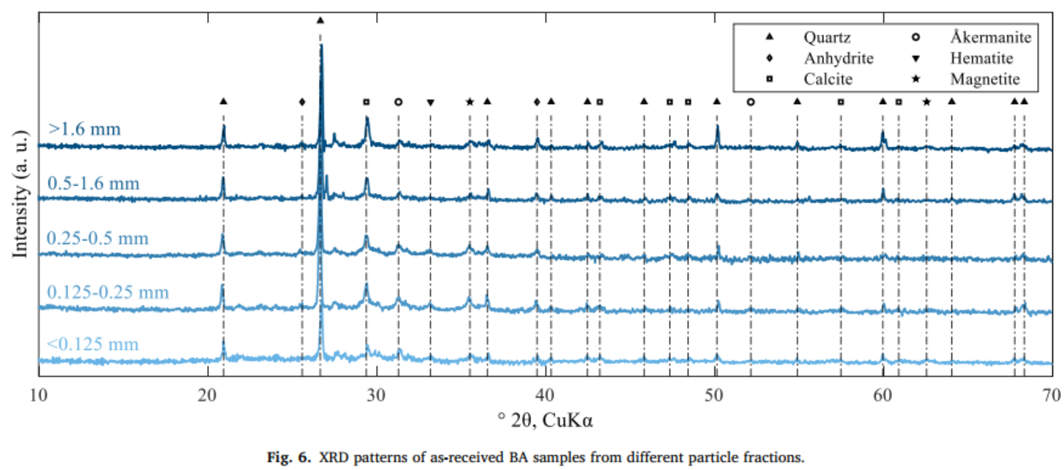


Fig. 6: XRD spectra of original bottom ash samples from various particle sizes

Adding 30% bottom ash from MSWI fine powder decreases the compressive strength by about 25%, while a 10% addition only reduces it by 8%. With a water-binder ratio of 0.4 and an acceptable powder content of 10%, the compressive strength of bottom ash from MSWI fine particle concrete surpasses that of regular concrete. Over 28 to 90 days, the increase in compressive strength for bottom ash from MSWI fine particle concrete surpasses that of regular concrete, especially at 20% and 30%, achieving more than 20%. Bottom ash from MSWI fine particle concrete displays a slower hydration reaction, gradually increasing compressive strength with prolonged curing time, Figure 7 [66].

The substitution ratio of bottom ash from MSWI in granite aggregate and concrete strength performance was determined based on compression test results in hydrated conditions. The data shows an inverse relationship between strength and substitution ratio. Concrete with 50% MSWI aggregate achieved strength comparable to the batch with 50% Litex at one day and 28 days. The one-day strength was 12.4 MPa, increasing to 25.3 MPa after 28 days, meeting ASTM C90 requirements for structural concrete strength [68].

MSWI bottom ash and its effect on the mechanical properties of concrete and cement mortar, comprising different compressive strength values, with some reaching approximately 40 MPa [41].

Table 5: Proportion of concrete mixture with fine particles of bottom ash from MSWI

W/B	Dosage (%)	Water (kg)	Water reducer (kg)	Cement (kg)	Ash micro Powder (kg)	Sand (kg)	Stone (kg)
0.60	0	180	1.2	300.0	0.0	742	1064
	10	180	1.2	270.0	30.0	742	1064
	20	180	2.4	240.0	60.0	742	1064
	30	180	2.4	210.0	90.0	742	1064
0.40	0	170	2.5	425.0	0.0	777	985
	10	170	2.5	382.5	42.5	777	985
	20	170	2.9	340.0	85.0	777	985
	30	170	5.1	297.5	127.5	777	985
0.20	0	165	10.8	825.0	0.0	700	726
	10	165	10.8	742.5	82.5	700	726
	20	165	13.0	660.0	165.0	700	726
	30	165	13.0	577.5	247.5	700	726

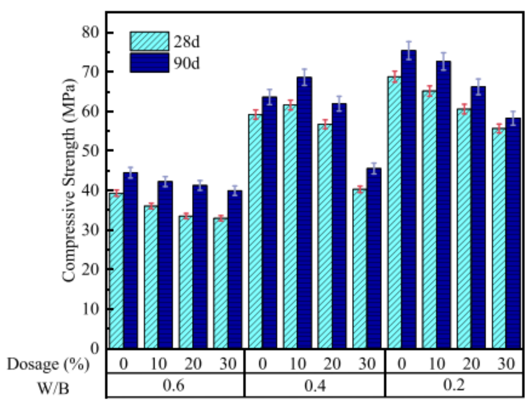


Fig. 7: Compressive strength of bottom ash from MSWI micro powder concrete

When utilizing processed MSWI ash (involving screening, self-milling, as well as magnetic segregation), the resulting cement samples demonstrated excellent compressive strength alongside a minimal waste content (less than 5% of total aggregates by weight) when the substitution ratio of ash was increased (exceeding 10%), mechanical properties exhibited a significant decline [38].

Evaluating water permeability

Wet-ground MSWI bottom ash exhibits effective pozzolanic properties. Replacing 30% of Portland cement using this ash results in a notable durability enhancement and a considerable decrease in concrete permeability [23].

The water absorption rate of bottom ash from MSWI is more significant than that of sand with grain dimensions ranging from 0.063 mm up to 2 mm and gravel with grain sizes ranging from 2 mm to 60 mm generated through soil washing [30].

Evaluating porosity

Weng et al. [67] employed bottom ash from MSWI as a concrete mixture to create unique aerated blocks. As shown in Table 6, replacing aggregate with bottom ash from MSWI micro powder influences the porosity of concrete, particularly at a high replacement level (30%). Porosity generally decreases over the curing period in most cases, except for the sample with 30% bottom ash from MSWI micro powder at a W/B proportion of 0.2, where porosity slightly increases after 90 days [66].

Numerous presumptions rely on the approximated amount of water not involved in the lubrication of materials or the filling of voids. This water within the bottom ash particles via capillary water storage does not help form capillary pores [69, 70]. While water absorption by bottom ash changes the planned water content in concrete usability, this impact causes the ash to function as a permeable aggregate, serving as water storage for the cement moisture process in the future [71–76].

Table 6: Porosity of concrete with varying proportions

W/B	Dosage	Porosity	
		28d	90d
0.4	0%	12.91%	11.31%
	10%	11.96%	10.71%
	30%	14.75%	13.83%
0.2	0%	9.66%	9.33%
	30%	12.54%	12.77%

Expansion and shrinkage

Various factors contribute to expansion, including gel creation due to the generation of ettringite, the oxidation of metallic aluminum, and the hydration of lime and magnesium oxide. However, the impact of the last factor is not as pronounced as the first two mechanisms [77].

The amount of sulfate quantified as SO_3 is crucial because high levels of sulfates can induce harmful expansion in the cementitious matrix. From stoichiometric estimations based on the SO_4^{2-}, a mean SO_3 concentration of 0.41% was determined for processed bottom ash. Hence, the role of processed bottom ash as a Supplementary Cementitious Material (SCM) in influencing overall sulfate quantities might be minimal. The magnesium levels can affect the integrity of cement-based materials. Still, the amount found in ground bottom ash is modest (2.83%), aligning with a study conducted by Matos et al. [78].

The concentration of acid-soluble sulfate is greater in coarse MSWI bottom ash with particle dimensions ranging from 0 to 10 μm, which could lead to concrete expansion. A reduced water/cement ratio and sulfate-resistant cement are advised when concrete incorporates coarse bottom ash. Across all types of waste, the level of water-soluble sulfate is lower than that of acid-soluble sulfate by at least an order of magnitude [79].

Kim et al. [65] researched the expansion and shrinkage of mortar blends containing MSWI bottom ash through a series of tests. In Figure 8, the value of 10 denotes that 10% of the natural sand in the composition is replaced with bottom ash in the sample. The aggregate that is unaltered bottom ash from MSWI is labeled as M10. The aggregate is bottom ash from MSWI bottom ash immersed in a 3% sodium chloride solution, as indicated by the symbol M10-C. The aggregate is MSWI bottom ash immersed in seawater, as indicated by the symbol M10-S. The aggregate is MSWI bottom ash soaked in tap water, as indicated by the symbol M10-T. The aggregate immersed in deionized water is denoted as M10-D [65].

Figure 8a indicates that all the specimens expanded in length for the first 12 hours after they were cast. Following this, while the control specimens started to contract, those with MSWI bottom ash expanded gradually until approximately the second day after casting. Such expansion is linked to the creation of ettringite crystals from the phase containing aluminum and sulfate ions [80]. The M10-S sample showed the most significant expansion, possibly due to sulfate ions from seawater processing and calcium ions in the bottom ash [65].

Regarding shrinkage, the samples were kept enclosed for the initial seven days before their dry shrinkage was assessed in Figure 8b. By day 113, all the mortar specimens with MSWI bottom ash demonstrated more shrinkage than the control, with increases of 21.84%, 21.62%, 26.62%, and 14.05% for M10, M10-C, M10-S, M10-T, and M10-D, respectively, compared to the control. This may be attributed to the elevated porosity of the MSWI bottom ash particles, facilitating more effortless water movement during the hydration phase [65].

B. Treatment measures to increase the usage rate of bottom ash in concrete

Metal scrap in bottom ash from MSWI can be recycled. Besides metal extraction, reusing the minerals found in MSWI bottom ash is crucial. This measure will assist in reducing the exhaustion of the world's essential mineral reserves because land-based mineral mines cannot be regenerated within a human lifetime [81].

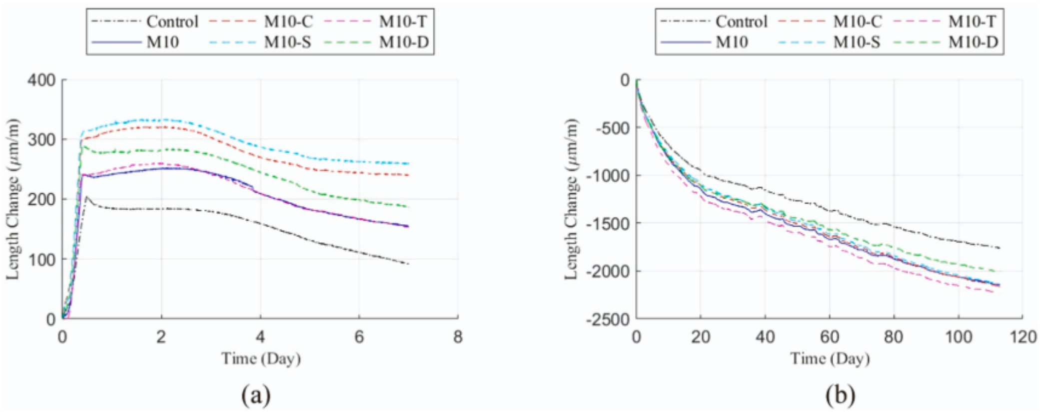


Fig. 8: Comparison of length variation between Portland cement and MSWI incorporated mortars: a) Expansion prior to demolding, b) Shrinkage after demolding

Treatment at a waste incineration plant

When newly generated, bottom ash from MSWI is often treated within the facility to recover metal residues and minimize the release of toxic metallic ions into the surroundings. At the plant level, these processes include reducing particle size, extracting metals, stabilizing, cleansing, and categorizing the ash, each utilizing specific methodologies [79, 80]. Reducing particle size is essential as it helps free the bound components fused during incineration, making subsequent material separation and categorization more efficient. Metric extraction focuses on reclaiming ferrous and non-ferrous metals through magnetic and eddy current separators [82, 83]. Additionally, fresh MSWI bottom ash undergoes stabilization via weathering, which leads to a decrease in pH levels and a reduction in the leaching of heavy metals [48, 84–88]. This weathering, typically one to three months, stabilizes the ash and lowers the danger of heavy metal seepage, enhancing its suitability as an alternative aggregate in concrete production. Table 7 presents the by-product crystals and gel phases identified post-weathering of fresh bottom ash from MSWI. Therefore, MSWI bottom ash demonstrates considerable potential for expanded use in building material production, particularly as natural aggregates become increasingly scarce [89].

Treatment using chemical methods

The analysis of pretreatment procedures focused on eliminating metallic contents, as these metals can lead to staining or rust formation near the surface of the concrete. Additionally, ensuring no presence of uncombusted substances and maintaining residual moisture below 30There are three primary chemical treatment methods for MSWI bottom ash: treatments with alkaline solutions, water, and acid solutions. The treatment using an alkaline solution, often employing NaOH, is designed to eliminate metallic Al and Zn levels. The effectiveness of this treatment is influenced by several factors, including the size of the particles, the sodium hydroxide solution concentration, the liquid-to-solid ratio, and the heating temperature [96–99]. Following this treatment, the slurry of MSWI bottom ash can be directly utilized to create AAM, or it can partly replace aggregate in concrete after a water wash to eliminate excess alkalis [98]. The water treatment process generates an alkaline environment by dissolving the alkalis from MSWI in the bottom ash. Its effectiveness is determined by the particle size and the water-to-solid ratio [100], and it enhances the physical properties of the ash when it substitutes for aggregate. Acid treatment, coupled with water washing, markedly lowers the chloride and sulfate levels, improving the ash's fitness for use in concrete [101]. Furthermore,

Table 7: By-product mineral and gel structures formed during the weathering process

Category	Phase Type	Most Commonly Observed Phases
Secondary Minerals	Carbonate Minerals	Calcite [57–59, 90, 91]
	Hydrous Sulfate Minerals	Gypsum [50, 58, 59, 92], Ettringite [45, 57–59, 92–94]
	Crystallized Metal Hydroxides	Aluminum hydroxides: Gibbsite [45, 52, 59, 93], Nordstrandite [93] Iron hydroxide: Goethite [48, 62, 93], Lepidocrocite [45, 62], Ferrihydrite [94].
	Zeolite Minerals	Boggsite [93], Chabazite [45, 92], Gismondine [93], Heulandite [59], Laumontite [59, 93].
	Other Minerals	Tobermorite [45], Weddellite [59, 93]
Amorphous Gel Phases	Amorphous Hydroxides	Amorphous Aluminum Hydroxide, Amorphous Iron Hydroxide [48, 90, 95]
	Metal-Silicate Gels	Al-Si-rich Gel [95], Ca-Al-Si-rich Gel [84, 95], Fe-Si-rich Gel [62], Fe-Al-Si-rich Gel [95]

adding Na_2CO_3 to water not only boosts the removal of sulfate salts but also strengthens the alkaline conditions in the concrete mix, thereby enhancing the strength and overall performance of concrete made with treated ash [102].

The washing of bottom ash helps diminish the concentration of pollutants, except for elements such as iron, arsenic, barium, and manganese. With the same particle size, the contaminants in bottom ashes are lower than in soil washing by-products. Unwashed bottom ashes exhibit inferior qualities. The larger particles of washed bottom ashes from MSWI and gravel from soil washing demonstrate superior characteristics to natural aggregates [30].

Treatment using mechanical methods

Typically, the by-products from the washing process and the coarser granular sizes exhibit the most favorable properties. Indeed, the washing treatment efficiently removes pollutants, and contaminants tend to be concentrated in the finer fractions [30].

Mechanical processing techniques for MSWI bottom ash encompass dry grinding and screening, which aim to diminish particle size and ensure a consistent composition. This grinding enlarges the surface area and enhances the ash's reactivity, rendering it more appropriate for incorporation as a concrete aggregate. Brief, low-speed dry grinding fractures brittle minerals and converts ductile metals into flaky pieces, easily separated in the screening phase [43]. This approach can eliminate up to 80 wt% of metal-like aluminum in weathered bottom ash from MSWI. Introducing water into the grinding process amplifies the oxidation of metallic aluminum, fostering an alkaline setting that aids this transformation. However, only some metallic aluminum undergoes oxidation during the wet grinding interval [24]. Following its mechanical processing, MSWI bottom ash is not only devoid of metals but also possesses characteristics conducive to replacing part of the aggregate in concrete, thanks to modified particle sizes and enhanced physical properties.

Treatment using thermal methods

Thermal processing of bottom ash from MSWI effectively enhances the quality of the ash by eliminating organic compounds, encouraging the development of reactive phases, immobilizing heavy metals, and facilitating the oxidation of aluminum and zinc [43, 55, 60, 103–106]. The temperature range of this treatment, between 500–900^{o}C and 1000–1500^{o}C, influences the process's efficiency, particularly in minimizing the leaching of elements such as Cu and Sb [43, 107, 108]. This treatment improves the bottom ash's compressive strength and reactive characteristics as an alternative concrete aggregate [43, 109]. Moreover, the high-temperature treatment also diminishes the levels of metallic aluminum, eradicates heavy metals through volatilization, and augments the proportion of amorphous phases, thereby enhancing the suitability of bottom ash from MSWI as a pozzolanic additive in concrete [11, 15, 104–105, 110]. This elevates the quality of concrete and contributes to environmental protection by reducing landfill waste.

Table 8: Chemical compositions of MSWI residues

Oxide	MSWI bottom ash	Treated MSWI bottom ash	BLA	APC ash
	Composition wt%			
CaO	16.21	22.91	40.03	49.12
SiO_2	26.69	28.64	27.34	2.44
Al_2O_2	9.66	14.18	15.16	1.42
Fe_2Oa	6.20	6.49	4.50	0.31
MnO	0.14	0.17	0.31	0.02
MgO	2.27	2.62	4.08	1.22
Na_2O	2.36	2.63	-	-
K_2O	1.00	1.12	0.05	0.65
TiO_2	1.85	2.88	4.76	0.22
P_2O_5	1.74	2.34	3.42	0.12
Cl	2.14	2.62	0.20	14.82
LOI	29.74	14.87	0.15	29.65
Total-C	19.30	3.13	0.10	2.31
Total-S	0.59	1.17	2.06	1.01

Bottom ash processing is designed to enhance its incorporation rate into green concrete, substituting some of the granite used. MSWI bottom ash was subjected to pyrolysis at 200°C to tackle the high carbon content and LOI values, effectively reducing both the carbon and LOI content values, as indicated in Table 8. Following this, the bottom ash underwent magnetic separation and was sorted by size to be ready for storage and future use. Additionally, the study included commercial Litex aggregate and granite as reference materials to aid in assessing the suitability of bottom ash for concrete application [68].

Cheeseman et al. [111] investigated the characteristics of lightweight aggregates produced through fast sintering incinerator bottom ashes for use in concrete and other purposes. The researchers found that heating at temperatures ranging from 1,000 to 1,050^{o}C yielded pellets with density, water absorption, and compressive strength properties that were on par with commercially available lightweight aggregates [30].

IV. CONCLUSION

In the past few years, the application of MSWI bottom ash in concrete production has received significant attention due to its ability to replace natural aggregates and help reduce environmental impact. Studies have shown that MSWI bottom ash can effectively produce construction materials, especially for concrete, unfired bricks, and agricultural land reclamation applications. Additionally, one of the prominent advantages of MSWI bottom ash is its ability to improve the physical and chemical properties of concrete, thanks to its diverse chemical composition, including large amounts of CaO, SiO_2, and Al_2O_3, essential components for the hydration process in cement. Furthermore, the treatment process of bottom ash from MSWI, such as dry grinding, screening, and thermal treatment, helps remove pollutants and heavy metals, thereby increasing the possibility of utilizing bottom ash as an additive in concrete.

However, there are still challenges in the widespread application of MSWI bottom ash due to the complexity of its chemical composition, which can affect the hydration process and the mechanical properties of concrete. This requires researchers to continue exploring and developing new treatment methods and applications to optimize the benefits of MSWI bottom ash. In increasingly scarce natural resources, the search and application of alternative materials are essential. MSWI bottom ash reduces waste sent to landfills and opens new directions for the construction industry in sustainable development. Research and practical applications show that MSWI bottom ash has the potential to become one of the leading materials in the future of the concrete production and building materials industry.

REFERENCES

[1] Kaza S, Yao LC, Bhada-Tata P, Van Woerden F. *What a waste 2.0: A global snapshot of solid waste management to 2050*. Washington, DC: World Bank; 2018. https://doi.org/10.1596/978-1-4648-1329-0.

[2] Tozlu A, Özahi E, Abuşoğlu A. Waste to energy technologies for municipal solid waste management in Gaziantep. *Renewable and Sustainable Energy Reviews*. 2016;54: 809–815. https://doi.org/10.1016/j.rser.2015.10.097.

[3] Bunge R. Recovery of metals from waste incinerator bottom ash. In: Holm O, Thome-Kozmiensky E (eds.). *Removal, treatment and utilisation of waste*

incineration bottom ash. Macau: UMTEC; 2015. p. 63–143.

[4] Kim J, Nam BH, Al Muhit BA, Tasneem KM, An J. Effect of chemical treatment of MSWI bottom ash for its use in concrete. *Magazine of Concrete Research*. 2015;67(4): 179–186. https://doi.org/10.1680/macr.14.00170.

[5] Liu C, Nishiyama T, Kawamoto K, Sasaki S. *CCET guideline series on intermediate municipal solid waste treatment technologies: Waste-to-energy incineration*. United Nations Environment Programme; 2020. https://www.researchgate.net/publication/342170580_CCET_guideline_series_on_intermediate_municipal_solid_waste_treatment_technologies_Waste-to-Energy_Incineration [Accessed 25th May 2024].

[6] Pan SY, Du MA, Huang IT, Liu IH, Chang EE, Chiang PC. Strategies on implementation of waste-to-energy (WTE) supply chain for circular economy system: a review. *Journal of Cleaner Production*. 2015;108: 409–421. https://doi.org/10.1016/j.jclepro.2015.06.124.

[7] Li M, Xiang J, Hu S, Sun LS, Su S, Li PS, et al. Characterization of solid residues from municipal solid waste incinerator. *Fuel*. 2004;83(10): 1397–405. https://doi.org/10.1016/j.fuel.2004.01.005.

[8] Phua Z, Giannis A, Dong ZL, Lisak G, Ng J. Characteristics of incineration ash for sustainable treatment and reutilization. *Environmental Science and Pollution Research*. 2019;26: 16974–16997. https://doi.org/10.1007/s11356-019-05217-8.

[9] Margallo M, Taddei M, Hernández-Pellón A, Aldaco R, Irabien A. Environmental sustainability assessment of the management of municipal solid waste incineration residues: A review of the current situation. *Clean Technologies and Environmental Policy*. 2015;17: 1333–1353. https://doi.org/10.1007/s10098-015-0961-6.

[10] Chimenos JM, Segarra M, Fernández MA, Espiell F. Characterization of the bottom ash in municipal solid waste incinerator. *Journal of Hazardous Materials*. 1999;64(3): 211–222. https://doi.org/10.1016/S0304-3894(98)00246-5.

[11] Lin KL, Lin DF. Hydration characteristics of municipal solid waste incinerator bottom ash slag as a pozzolanic material for use in cement. *Cement and Concrete Composites*. 2006;28(9): 817–823. https://doi.org/10.1016/j.cemconcomp.2006.03.003.

[12] Li YM, Wu XQ, Wang LJ, Li RQ, Huang TY, Wen XQ. Comparative study on utilization of different types of municipal solid waste incineration bottom ash for clinker sintering. *Journal of Material Cycles and Waste Management*. 2020;22(6): 1828–1843. https://doi.org/10.1007/s10163-020-01067-6.

[13] Zhang Z, Wang J, Liu L, Ma J, Shen B. Preparation of additive-free glass-ceramics from MSW incineration bottom ash and coal fly ash. *Construction and Building Materials*. 2020;254: 119345. https://doi.org/10.1016/j.conbuildmat.2020.119345.

[14] Appendino P, Ferraris M, Matekovits I, Salvo M. Production of glass–ceramic bodies from the bottom ashes of municipal solid waste incinerators. *Journal of the European Ceramic Society*. 2004;24(5): 803–810. https://doi.org/10.1016/S0955-2219(03)00264-4.

[15] Monteiro RCC, Alendouro SJG, Figueiredo FML, Ferro MC, Fernandes MHV. Development and properties of a glass made from MSWI bottom ash. *Journal of Non-Crystalline Solids*. 2006;352(2): 130–135. https://doi.org/10.1016/j.jnoncrysol.2005.11.008.

[16] Rambaldi E, Esposito L, Andreola F, Barbieri L, Lancellotti I, Vassura I. The recycling of MSWI bottom ash in silicate based ceramic. *Ceramics International*. 2010;36(8): 2469–2476. https://doi.org/10.1016/j.ceramint.2010.08.005.

[17] Taurino R, Karamanov A, Rosa R, Karamanova E, Barbieri L, Atanasova-Vladimirova S, et al. New ceramic materials from MSWI bottom ash obtained by an innovative microwave-assisted sintering process. *Journal of the European Ceramic Society*. 2017;37(1): 323–331. https://doi.org/10.1016/j.jeurceramsoc.2016.08.011.

[18] Vegas I, Ibañez JA, San José JT, Urzelai A. Construction demolition wastes, Waelz slag and MSWI bottom ash: A comparative technical analysis as material for road construction. *Waste Management*. 2008;28(3): 565–574. https://doi.org/10.1016/j.wasman.2007.01.016.

[19] Pera J, Coutaz L, Ambroise J, Chababbet M. Use of incinerator bottom ash in concrete. *Cement and Concrete Research*. 1997;27(1): 1–5. https://doi.org/10.1016/S0008-8846(96)00193-7.

[20] Li XG, Lv Y, Ma BG, Chen QB, Yin XB, Jian SW. Utilization of municipal solid waste incineration bottom ash in blended cement. *Journal of Cleaner Production*. 2012;32: 96–100. https://doi.org/10.1016/j.jclepro.2012.03.038.

[21] Tang P, Chen W, Xuan D, Zuo Y, Poon CS. Investigation of cementitious properties of different constituents in municipal solid waste incineration bottom ash as supplementary cementitious materials. *Journal of Cleaner Production*. 2020;258: 120675. https://doi.org/10.1016/j.jclepro.2020.120675.

[22] Maldonado-Alameda A, Giro-Paloma J, Svobodova-Sedlackova A, Formosa J, Chimenos JM. Municipal solid waste incineration bottom ash as alkali-activated cement precursor depending on particle size. *Journal of Cleaner Production*. 2020;242: 118443. https://doi.org/10.1016/j.jclepro.2019.118443.

[23] Bertolini L, Carsana M, Cassago D, Quadrio Curzio A, Collepardi M. MSWI ashes as mineral additions in concrete. *Cement and Concrete Research*. 2004;34(10): 1899–1906.

https://doi.org/10.1016/j.cemconres.2004.02.001.

[24] Clavier KA, Watts B, Liu Y, Ferraro CC, Townsend TG. Risk and performance assessment of cement made using municipal solid waste incinerator bottom ash as a cement kiln feed. *Resources, Conservation and Recycling*. 2019;146: 270–279. https://doi.org/10.1016/j.resconrec.2019.03.047.

[25] Oehmig WN, Roessler JG, Blaisi NI, Townsend TG. Contemporary practices and findings essential to the development of effective MSWI ash reuse policy in the United States. *Environmental Science & Policy*. 2015;51: 304–312. https://doi.org/10.1016/j.envsci.2015.04.024.

[26] Van Eck NJ, Waltman L. Visualizing bibliometric networks. In: Ding Y, Rousseau R, Wolfram D (eds.). *Measuring scholarly impact: Methods and practice*. Cham: Springer; 2014. p. 285–320. https://doi.org/10.1007/978-3-319-10377-8_13.

[27] Zhang S, Ghouleh Z, Shao Y. Green concrete made from MSWI residues derived eco-cement and bottom ash aggregates. *Construction and Building Materials*. 2021;297: 123818. https://doi.org/10.1016/j.conbuildmat.2021.123818

[28] Mian MM, Zeng X, Bin Nasry AAN, Al-Hamadani S. Municipal solid waste management in China: a comparative analysis. *Journal of Material Cycles and Waste Management*. 2016;19: 1127–1135. https://doi.org/10.1007/s10163-016-0509-9.

[29] Sun Y, Chen B, Zhang S, Blom K, Luković M, Ye G. Characterization, pre-treatment, and potential applications of fine MSWI bottom ash as a supplementary cementitious material. *Construction and Building Materials*. 2024;421: 135769. https://doi.org/10.1016/j.conbuildmat.2024.135769.

[30] Sorlini S, Abbà A, Collivignarelli C. Recovery of MSWI and soil washing residues as concrete aggregates. *Waste Management*. 2011;31(2): 289–297. https://doi.org/10.1016/j.wasman.2010.04.019.

[31] Ginés O, Chimenos JM, Vizcarro A, Formosa J, Rosell JR. Combined use of MSWI bottom ash and fly ash as aggregate in concrete formulation: Environmental and mechanical considerations. *Journal of Hazardous Materials*. 2009;169(1): 643–650. https://doi.org/10.1016/j.jhazmat.2009.03.141.

[32] Loginova E, Schollbach K, Proskurnin M, Brouwers HJH. Municipal solid waste incineration bottom ash fines: Transformation into a minor additional constituent for cements. *Resources, Conservation and Recycling*. 2021;166: 105354. https://doi.org/10.1016/j.resconrec.2020.105354.

[33] Barros RM. MSW ash. In: Siddique R, Cachim P (eds.). *Waste and supplementary cementitious materials in concrete*. United Kingdom: Woodhead Publishing; 2018. p. 513–557.

[34] Kurda R, Silva RV, de Brito J. Incorporation of Alkali-activated municipal solid waste incinerator bottom ash in mortar and concrete: a critical review. *Materials (Basel)*. 2020;13(15): 3428. https://doi.org/10.3390/ma13153428.

[35] Lynn CJ, Dhir Obe RK, Ghataora GS. Municipal incinerated bottom ash characteristics and potential for use as aggregate in concrete. *Construction and Building Materials*. 2016;127: 504–517. https://doi.org/10.1016/j.conbuildmat.2016.09.132.

[36] An J, Kim J, Nam BH. Investigation on impacts of municipal solid waste incineration bottom ash on cement hydration. *ACI Materials Journal*. 2017;114(5): 701–711. https://doi.org/10.14359/51689712.

[37] Quenee B, Li G, Siwak JM, Basuyau V. The use of MSWI (Municipal solid waste incineration) bottom ash as aggregates in hydraulic concrete. In: Woolley GR, Goumans JJJM, Wainwright PJ (eds.). *Waste Management Series*. 1. Elsevier; 2000. p.422–437. https://doi.org/10.1016/S0713-2743(00)80054-9.

[38] Shih PH, Chang JE, Chiang LC. Replacement of raw mix in cement production by municipal solid waste incineration ash. *Cement and Concrete Research*. 2003;33(11): 1831–1836. https://doi.org/10.1016/S0008-8846(03)00206-0.

[39] Ministry of Natural Resources and Environment of Vietnam. QCVN 07:2009/BTNMT. *National technical regulation on hazardous waste thresholds [Quy chuẩn kỹ thuật quốc gia về ngưỡng chất thải nguy hại]*. Hanoi, Vietnam: Ministry of Natural Resources and Environment of Vietnam; 2009. https://cdnmedia.eurofins.com/apac/media/311741/qcvn-07-ch%E1%BA%A5t-th%E1%BA%A3i-nguy-h%E1%BA%A1i.pdf [Accessed 19th May 2024].

[40] Siddique R. Utilization of municipal solid waste (MSW) ash in cement and mortar. *Resources, Conservation and Recycling*. 2010;54(12): 1037–1047. https://doi.org/10.1016/j.resconrec.2010.05.002.

[41] Matos AM, Sousa-Coutinho J. Municipal solid waste incineration bottom ash recycling in concrete: Preliminary approach with Oporto wastes. *Construction and Building Materials*. 2022;323: 126548. https://doi.org/10.1016/j.conbuildmat.2022.126548.

[42] Chang FY, Wey MY. Comparison of the characteristics of bottom and fly ashes generated from various incineration processes. *Journal of Hazardous Materials*. 2006;138(3): 594–603. https://doi.org/10.1016/j.jhazmat.2006.05.099.

[43] Tang P, Florea MVA, Spiesz P, Brouwers HJH. Application of thermally activated municipal solid waste incineration (MSWI) bottom ash fines as binder substitute. *Cement and Concrete Composites*. 2016;70: 194–205. https://doi.org/10.1016/j.cemconcomp.2016.03.015.

[44] Ministry of Science and Technology of Vietnam. TCVN 7572:2006. *Aggregates for concrete and mortar - test methods [Cốt liệu cho bê tông và vữa – Phương pháp thử]*. Hanoi, Vietnam: Ministry

of Science and Technology of Vietnam; 2006. http://vntvietnam.com/xem-tin/tcvn-75722006-cot-lieu-cho-be-tong-va-vua-phuong-phap-thu-380.html [Accessed 17th May 2024].

[45] Bayuseno AP, Schmahl WW. Understanding the chemical and mineralogical properties of the inorganic portion of MSWI bottom ash. *Waste Management*. 2010;30(8): 1509–1520. https://doi.org/10.1016/j.wasman.2010.03.010.

[46] Valle-Zermeño R, Gómez-Manrique J, Giro-Paloma J, Formosa J, Chimenos JM. Material characterization of the MSWI bottom ash as a function of particle size. *Effects of glass recycling over time. Science of The Total Environment*. 2017;581: 897–905. https://doi.org/10.1016/j.scitotenv.2017.01.047.

[47] Maldonado-Alameda À, Giro-Paloma J, Alfocea-Roig A, Formosa J, Chimenos JM. Municipal Solid Waste Incineration Bottom Ash as Sole Precursor in the Alkali-Activated Binder Formulation. *Applied Sciences*. 2020;10(12): 4129. https://doi.org/10.3390/app10124129.

[48] Saffarzadeh A, Shimaoka T, Wei Y, Gardner KH, Musselman CN. Impacts of natural weathering on the transformation/neoformation processes in landfilled MSWI bottom ash: A geoenvironmental perspective. *Waste Management*. 2011;31(12): 2440–2454. https://doi.org/10.1016/j.wasman.2011.07.017.

[49] Giro-Paloma J, Maldonado-Alameda A, Formosa J, Barbieri L, Chimenos JM, Lancellotti I. Geopolymers based on the valorization of Municipal Solid Waste Incineration residues. *IOP Conference Series: Materials Science and Engineering*. 2017;251(1): 012125. https://doi.org/10.1088/1757-899X/251/1/012125.

[50] Santos RM, Mertens G, Salman M, Cizer Ö, Van Gerven T. Comparative study of ageing, heat treatment and accelerated carbonation for stabilization of municipal solid waste incineration bottom ash in view of reducing regulated heavy metal/metalloid leaching. *Journal of Environmental Management*. 2013;128: 807–821. https://doi.org/10.1016/j.jenvman.2013.06.033.

[51] Flesoura G, Garcia-Banos B, Catala-Civera JM, Vleugels J, Pontikes Y. In-situ measurements of high-temperature dielectric properties of municipal solid waste incinerator bottom ash. *Ceramics International*. 2019;45(15): 18751–18759. https://doi.org/10.1016/j.ceramint.2019.06.101.

[52] De Windt L, Dabo D, Lidelöw S, Badreddine R, Lagerkvist A. MSWI bottom ash used as basement at two pilot-scale roads: Comparison of leachate chemistry and reactive transport modeling. *Waste Management*. 2011;31(2): 267–280. https://doi.org/10.1016/j.wasman.2010.06.002.

[53] Le NH, Razakamanantsoa A, Nguyen ML, Phan VT, Dao PL, Nguyen DH. Evaluation of physicochemical and hydromechanical properties of MSWI bottom ash for road construction. *Waste Management*. 2018;80: 168–174. https://doi.org/10.1016/j.wasman.2018.09.007.

[54] Cheeseman CR, Monteiro da Rocha S, Sollars C, Bethanis S, Boccaccini AR. Ceramic processing of incinerator bottom ash. *Waste Management*. 2003;23(10): 907–916. https://doi.org/10.1016/S0956-053X(03)00039-4.

[55] Qiao XC, Ng BR, Tyrer M, Poon CS, Cheeseman CR. Production of lightweight concrete using incinerator bottom ash. *Construction and Building Materials*. 2008;22(4): 473–480. https://doi.org/10.1016/j.conbuildmat.2006.11.013.

[56] Gori M, Bergfeldt B, Pfrang-Stotz G, Reichelt J, Sirini P. Effect of short-term natural weathering on MSWI and wood waste bottom ash leaching behaviour. *Journal of Hazardous Materials*. 2011;189(1): 435–443. https://doi.org/10.1016/j.jhazmat.2011.02.045.

[57] Chimenos JM, Fernández AI, Miralles L, Segarra M, Espiell F. Short-term natural weathering of MSWI bottom ash as a function of particle size. *Waste Management*. 2003;23(10): 887–895. https://doi.org/10.1016/S0956-053X(03)00074-6.

[58] Zevenbergen C, Van Reeuwijk LP, Bradley JP, Comans RNJ, Schuiling RD. Weathering of MSWI bottom ash with emphasis on the glassy constituents. *Journal of Geochemical Exploration*. 1998;62(1): 293–298. https://doi.org/10.1016/S0375-6742(97)00033-2.

[59] Freyssinet P, Piantone P, Azaroual M, Itard Y, Clozel-Leloup B, Guyonnet D, et al. Chemical changes and leachate mass balance of municipal solid waste bottom ash submitted to weathering. *Waste Management*. 2002;22(2): 159–172. https://doi.org/10.1016/S0956-053X(01)00065-4.

[60] Qiao XC, Tyrer M, Poon CS, Cheeseman CR. Novel cementitious materials produced from incinerator bottom ash. *Resources, Conservation and Recycling*. 2008;52(3): 496–510. https://doi.org/10.1016/j.resconrec.2007.06.003.

[61] Speiser C, Baumann T, Niessner R. Characterization of municipal solid waste incineration (MSWI) bottom ash by scanning electron microscopy and quantitative energy dispersive X-ray microanalysis (SEM/EDX). *Fresenius' Journal of Analytical Chemistry*. 2001;370(6): 752–759. https://doi.org/10.1007/s002160000659.

[62] Wei Y, Shimaoka T, Saffarzadeh A, Takahashi F. Alteration of municipal solid waste incineration bottom ash focusing on the evolution of iron-rich constituents. *Waste Management*. 2011;31(9): 1992–2000. https://doi.org/10.1016/j.wasman.2011.04.021.

[63] Yao J, Qiu Z, Kong Q, Chen L, Zhu H, Long Y, et al. Migration of Cu, Zn and Cr through municipal solid waste incinerator bottom ash layer in the simulated

landfill. *Ecological Engineering*. 2017;102: 577–582. https://doi.org/10.1016/j.ecoleng.2017.02.063.

[64] Alderete NM, Joseph AM, Van den Heede P, Matthys S, De Belie N. Effective and sustainable use of municipal solid waste incineration bottom ash in concrete regarding strength and durability. *Resources, Conservation and Recycling*. 2021;167: 105356. https://doi.org/10.1016/j.resconrec.2020.105356.

[65] Kim HJ, Yamada Y, Zeng H, Iwanami M. A study of chloride pretreatment methods for enhancing strength of mortar by recycling Municipal Solid Waste Incineration (MSWI) bottom ash. *Case Studies in Construction Materials*. 2023;19: e02349. https://doi.org/10.1016/j.cscm.2023.e02349.

[66] Li H, Shi D, Li H, Han P. Analysis of pore structure characteristics of MSWI bottom ash micro powder concrete. *Case Studies in Construction Materials*. 2024;20: e02999. https://doi.org/10.1016/j.cscm.2024.e02999.

[67] Weng R. Experimental study on autoclaved aerated concrete using MSW incinerator fly ash. *New Building Materials*. 2013;4: 37–42.

[68] Andrade LB, Rocha JC, Cheriaf M. Influence of coal bottom ash as fine aggregate on fresh properties of concrete. *Construction and Building Materials*. 2009;23(2): 609–614. https://doi.org/10.1016/j.conbuildmat.2008.05.003.

[69] Cheriaf M, Rocha JC, Péra J. Pozzolanic properties of pulverized coal combustion bottom ash. *Cement and Concrete Research*. 1999;29(9): 1387–1391. https://doi.org/10.1016/S0008-8846(99)00098-8

[70] Zhang C, Wang A, Tang M, Liu X. The filling role of pozzolanic material. *Cement and Concrete Research*. 1996;26(6): 943–947. https://doi.org/10.1016/0008-8846(96)00064-6.

[71] Andrade LB, Rocha JC, Cheriaf M. Evaluation of concrete incorporating bottom ash as a natural aggregates replacement. *Waste Management*. 2007;27(9): 1190–1199. https://doi.org/10.1016/j.wasman.2006.07.020.

[72] Andrade LB, Rocha JC, Cheriaf M. Aspects of moisture kinetics of coal bottom ash in concrete. *Cement and Concrete Research*. 2007;37(2): 231–241. https://doi.org/10.1016/j.cemconres.2006.11.001.

[73] Weber S, Reinhardt HW. A new generation of high performance concrete: concrete with autogenous curing. *Advanced Cement Based Materials*. 1997;6(2): 59–68. https://doi.org/10.1016/S1065-7355(97)00009-6.

[74] Shukla A, Bose A. Uptake and loss of water in a cenosphere–concrete composite material. *Cement and Concrete Research - CEM CONCR RES*. 2003;33: 1681–1686. https://doi.org/10.1016/S0008-8846(03)00148-0.

[75] Bai Y, Darcy F, Basheer PAM. Strength and drying shrinkage properties of concrete containing furnace bottom ash as fine aggregate. *Construction and Building Materials*. 2005;19(9): 691–697. https://doi.org/10.1016/j.conbuildmat.2005.02.021.

[76] Kasemchaisiri R, Tangtermsirikul S. A method to determine water retainability of porous fine aggregate for design and quality control of fresh concrete. *Construction and Building Materials*. 2007;21(6): 1322–1334. https://doi.org/10.1016/j.conbuildmat.2006.01.009.

[77] Pecqueur G, Crignon C, Quénée B. Behaviour of cement-treated MSWI bottom ash. *Waste Management*. 2001;21(3): 229–233. https://doi.org/10.1016/S0956-053X(00)00094-5.

[78] Mafalda Matos A, Sousa-Coutinho J. Municipal solid waste incineration bottom ash recycling in concrete: Preliminary approach with Oporto wastes. *Construction and Building Materials*. 2022;323:126548.

[79] Chandler AJ, Eighmy TT, Hjelmar O, Kosson DS, Sawell SE, Vehlow J, et al. *Municipal solid waste incinerator residues*. Amsterdam: Elsevier; 1997.

[80] Vaičienė M, Simanavičius E. The effect of municipal solid waste incineration ash on the properties and durability of cement concrete. *Materials*. 2022;15(13): 4486. https://doi.org/10.3390/ma15134486.

[81] Prior T, Giurco D, Mudd G, Mason L, Behrisch J. Resource depletion, peak minerals and the implications for sustainable resource management. *Global Environmental Change*. 2012;22(3): 577–587. https://doi.org/10.1016/j.gloenvcha.2011.08.009.

[82] Vries Wd. *The use of advanced dry recovery in recycling fine moist granular materials*. Doctoral thesis. Netherlands: Delft University of Technology; 2017. https://doi.org/10.4233/UUID:C3C8578D-FD2C-493F-B4C5-79E63BC6D70C.

[83] Šyc M, Simon FG, Hykš J, Braga R, Biganzoli L, Costa G, et al. Metal recovery from incineration bottom ash: State-of-the-art and recent developments. *Journal of Hazardous Materials*. 2020;393: 122433. https://doi.org/10.1016/j.jhazmat.2020.122433.

[84] Speiser C, Baumann T, Niessner R. Morphological and chemical characterization of calcium-hydrate phases formed in alteration processes of deposited municipal solid waste incinerator bottom ash. *Environmental Science & Technology*. 2000;34(23): 5030–5037. https://doi.org/10.1021/es990739c.

[85] Saffarzadeh A, Arumugam N, Shimaoka T. Aluminum and aluminum alloys in municipal solid waste incineration (MSWI) bottom ash: A potential source for the production of hydrogen gas. *International Journal of Hydrogen Energy*. 2016;41(2): 820–831. https://doi.org/10.1016/j.ijhydene.2015.11.059.

[86] Yao J, Li WB, Kong Q, Xia F, Shen DS. Effect of weathering on the mobility of zinc in municipal solid waste incinerator bottom ash. *Fuel*. 2012;93: 99–104. https://doi.org/10.1016/j.fuel.2011.11.026.

[87] Chimenos JM, Fernández AI, Nadal R, Espiell F. Short-term natural weathering of MSWI bottom ash. *Journal of Hazardous Materials*. 2000;79(3): 287–299. https://doi.org/10.1016/S0304-3894(00)00270-3.

[88] Meima JA, Comans RNJ. The leaching of trace elements from municipal solid waste incinerator bottom ash at different stages of weathering. *Applied Geochemistry*. 1999;14(2): 159–171. https://doi.org/10.1016/S0883-2927(98)00047-X.

[89] Chen B, Perumal P, Illikainen M, Ye G. A review on the utilization of municipal solid waste incineration (MSWI) bottom ash as a mineral resource for construction materials. *Journal of Building Engineering*. 2023;71: 106386. https://doi.org/10.1016/j.jobe.2023.106386.

[90] Yao J, Li WB, Tang M, Fang CR, Feng HJ, Shen DS. Effect of weathering treatment on the fractionation and leaching behavior of copper in municipal solid waste incinerator bottom ash. *Chemosphere*. 2010;81(5): 571–576. https://doi.org/10.1016/j.chemosphere.2010.08.038.

[91] Meima JA, van der Weijden RD, Eighmy TT, Comans RNJ. Carbonation processes in municipal solid waste incinerator bottom ash and their effect on the leaching of copper and molybdenum. *Applied Geochemistry*. 2002;17(12): 1503–1513. https://doi.org/10.1016/S0883-2927(02)00015-X.

[92] Alam Q, Schollbach K, van Hoek C, van der Laan S, de Wolf T, Brouwers HJH. In-depth mineralogical quantification of MSWI bottom ash phases and their association with potentially toxic elements. *Waste Management*. 2019;87: 1–12. https://doi.org/10.1016/j.wasman.2019.01.031.

[93] Piantone P, Bodénan F, Chatelet-Snidaro L. Mineralogical study of secondary mineral phases from weathered MSWI bottom ash: implications for the modelling and trapping of heavy metals. *Applied Geochemistry*. 2004;19(12): 1891–904. https://doi.org/10.1016/j.apgeochem.2004.05.006.

[94] Meima JA, Comans RNJ. Geochemical modeling of weathering reactions in municipal solid waste incinerator bottom ash. *Environmental Science & Technology*. 1997;31(5): 1269–1276. https://doi.org/10.1021/es9603158.

[95] Wei Y, Saffarzadeh A, Shimaoka T, Zhao C, Peng X, Gao J. Geoenvironmental weathering/deterioration of landfilled MSWI-BA glass. *Journal of Hazardous Materials*. 2014;278: 610–619. https://doi.org/10.1016/j.jhazmat.2014.05.093.

[96] Xuan D, Poon CS. Removal of metallic Al and Al/Zn alloys in MSWI bottom ash by alkaline treatment. *Journal of Hazardous Materials*. 2018;344: 73–80. https://doi.org/10.1016/j.jhazmat.2017.10.002.

[97] Mathews G, Moazeni F, Smolinski R. Treatment of reclaimed municipal solid waste incinerator sands using alkaline treatments with mechanical agitation. *Journal of Material Cycles and Waste Management*. 2020;22(5): 1630–1638. https://doi.org/10.1007/s10163-020-01053-y.

[98] Liu Y, Sidhu KS, Chen Z, Yang E-H. Alkali-treated incineration bottom ash as supplementary cementitious materials. *Construction and Building Materials*. 2018;179: 371–378. https://doi.org/10.1016/j.conbuildmat.2018.05.231.

[99] Huang G, Yang K, Chen L, Lu Z, Sun Y, Zhang X, et al. Use of pretreatment to prevent expansion and foaming in high-performance MSWI bottom ash alkali-activated mortars. *Construction and Building Materials*. 2020;245: 118471. https://doi.org/10.1016/j.conbuildmat.2020.118471.

[100] Mary Joseph A, Snellings R, Nielsen P, Matthys S, De Belie N. Pre-treatment and utilisation of municipal solid waste incineration bottom ashes towards a circular economy. *Construction and Building Materials*. 2020;260: 120485. https://doi.org/10.1016/j.conbuildmat.2020.120485.

[101] Lo FC, Lo SL, Lee MG. Effect of partially replacing ordinary Portland cement with municipal solid waste incinerator ashes and rice husk ashes on pervious concrete quality. *Environmental Science and Pollution Research*. 2020;27(19): 23742–23760. https://doi.org/10.1007/s11356-020-08796-z.

[102] Saikia N, Mertens G, Van Balen K, Elsen J, Van Gerven T, Vandecasteele C. Pre-treatment of municipal solid waste incineration (MSWI) bottom ash for utilisation in cement mortar. *Construction and Building Materials*. 2015;96: 76–85. https://doi.org/10.1016/j.conbuildmat.2015.07.185.

[103] Qiao XC, Tyrer M, Poon CS, Cheeseman CR. Characterization of alkali-activated thermally treated incinerator bottom ash. *Waste Management*. 2008;28(10): 1955–1962. https://doi.org/10.1016/j.wasman.2007.09.007.

[104] Boyu C, Marc Brito van Z, Arno K, Guang Y. Thermal treatment on MSWI bottom ash for the utilisation in alkali activated materials. *KnE Engineering*. 2020;2020: 25–35. https://doi.org/10.18502/keg.v5i4.6792.

[105] Ferraris M, Salvo M, Ventrella A, Buzzi L, Veglia M. Use of vitrified MSWI bottom ashes for concrete production. *Waste Management*. 2009;29(3): 1041–1047. https://doi.org/10.1016/j.wasman.2008.07.014.

[106] Xiao Y, Oorsprong M, Yang Y, Voncken JHL. Vitrification of bottom ash from a municipal solid waste incinerator. *Waste Management*. 2008;28(6): 1020–1026. https://doi.org/10.1016/j.wasman.2007.02.034.

[107] Troxler WL, Goh SK, Dicks LWR. Treatment of pesticide-contaminated soils with thermal desorption technologies. *Air & Waste*. 1993;43(12): 1610–1617. https://doi.org/10.1080/1073161X.1993.10467230.

[108] van Zomeren A, Comans RNJ. Contribution of nat-

ural organic matter to copper leaching from municipal solid waste incinerator bottom ash. *Environmental Science & Technology*. 2004;38(14):3927–3932. https://doi.org/10.1021/es035266v.

[109] Saikia N, Mertens G, Van Balen K, Elsen J, Van Gerven T, Vandecasteele C. Pre-treatment of municipal solid waste incineration (MSWI) bottom ash for utilisation in cement mortar. *Construction and Building Materials*. 2015;96: 76–85. https://doi.org/10.1016/j.conbuildmat.2015.07.185

[110] Stabile P, Bello M, Petrelli M, Paris E, Carroll MR. Vitrification treatment of municipal solid waste bottom ash. *Waste Management*. 2019;95: 250–258. https://doi.org/10.1016/j.wasman.2019.06.021.

[111] Cheeseman CR, Makinde A, Bethanis S. Properties of lightweight aggregate produced by rapid sintering of incinerator bottom ash. *Resources, Conservation and Recycling*. 2005;43(2): 147–162. https://doi.org/10.1016/j.resconrec.2004.05.004.