



Environmental standards and beneficial uses of waste-to-energy (WTE) residues in civil engineering applications

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Abstract

The waste-to-energy (WTE) technologies are now recovering energy and materials from over 300 million tonnes of municipal solid wastes worldwide. Extensive studies have investigated substituting natural construction materials with WTE residues to relieve the environmental cost of natural resource depletion. This study examined the beneficial uses of WTE residues in civil engineering applications and the corresponding environmental standards in Europe, the U.S., and China. This review presents the opportunities and challenges for current technical approaches and the environmental standards to be met to stabilize WTE residues. The principal characteristics of WTE residues (bottom ash and fly ash) and the possible solutions for their beneficial use in developed and developing countries are summarized. The leaching procedures and environmental standards for pH, heavy metals, and polychlorinated dibenzo-*p*-dioxins/furans (PCDD/Fs) are compared. The current practice and engineering properties of materials using WTE residues, including mixtures with stone aggregate or sand, cement-based or hot-mix asphalt concrete (pavement), fill material in the embankments, substitute of Portland cement or clinker production, and ceramic-based materials (bricks and lightweight aggregate) are comprehensively reviewed.

Keywords Waste-to-energy (WTE) · Bottom ash · Fly ash · Construction building materials · Civil engineering applications · Leaching standards

Abbreviations

APC	Air pollution control (system)	EPA	Environmental Protection Agency (US)
BA	Bottom ash	EU	European Union
BS	British Standards	GB	The National Standards of the People's Republic of China (Mandatory)
CEN/TC	European Committee for Standardization/ Technical Committee	GB/T	The National Standards of the People's Republic of China (Recommended)
CEN/TS	European Committee for Standardization/ Technical Specification	GGBFs	Ground granulated blast-furnace slag
EC	European Commission	GHG	Greenhouse gas
EN	European Standards	HJ/T	Environmental Protection/Technical Specification (China)
		L/A	Liquid-to-surface area ratio
		L/S	Liquid-to-solid ratio
		LEAF	Leaching Environmental Assessment Framework (US)
		MSW	Municipal solid waste
		PCDD/Fs	Polychlorinated dibenzo- <i>p</i> -dioxins/furans
		RCRA	Resource Conservation and Recovery Act (US)
		TCLP	Toxic Characteristic Leaching Procedure (US)
		WAC	Waste acceptance criteria (UK)
		WTE	Waste-to-energy

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Introduction

Municipal solid waste (MSW) is a heterogeneous source with significant energy and material potential. Worldwide, the generation of MSW is consistently increasing yearly, from 2.01 billion tonnes in 2016 to 2.59 billion tonnes by 2030 and 3.40 billion tonnes annually by 2050 [1]. The MSW management depends on various factors, including MSW composition, gross domestic product (GDP), population density, land source, education, policy/regulations, infrastructures, etc. [2–7]. After all possible recycling and composting (e.g., fermentation, anaerobic digestion, etc.), two options for a significant fraction are called the post-recycled MSW: landfilling or waste-to-energy (WTE). The term waste-to-energy (or WTE) is now commonly used for all types of controlled combustion with energy and metals/materials recovery. The disposal of MSW has become a high cost; thus, the order of priority of various waste management methods indicated that sanitary landfilling is lower than WTE [8].

The combustion process converts chemical energy in postrecycled MSW to produce superheated steam to drive a turbine for electricity generation [9–13]. Grate combustion is the most common and simplest technology for MSW applied worldwide, operating at 850–1000 °C with complete oxidation, which can reduce the MSW volume by 85%–90% and the mass by 80% [8, 14, 15]. WTE has many advantages over landfilling, including land saving, electricity generation, and reducing associated greenhouse gas (GHG) [16].

The combustion process of MSW produces two residues: bottom ash and fly ash, in the daily generation ratio of 6:1 to 10:1 [17]. The bottom ash is the combustion residue discharged from the end of the grate furnace, about 20% of the total MSW, classified as nonhazardous waste. In comparison, fly ash is the air pollution control (APC) residue, commonly about 1%–5% of the total MSW, which is classified as hazardous waste because it contains heavy metals and polychlorinated dibenzo-*p*-dioxins/furans (PCDD/Fs). The proper beneficial uses of WTE residues as resourceful materials require environmental specifications, regulations, and local legislation related to specific leaching procedures and standards regionally that were used as a guideline to evaluate the treatment effectiveness [18]. However, the reuse of WTE fly ash is a challenging topic worldwide due to its hazardous characteristics, which may require proper pretreatment [19–21].

As a renewable energy source, there were over 512 WTE plants in Europe in 2016, providing a total capacity of 93 million tonnes [22]. In 2020, European Union 27 countries (EU-27), 61 million tonnes of MSW (27% of total MSW) were treated by WTE, estimated to generate 14 million tonnes of residues annually, as shown in Fig. 1 (fly ash is estimated to be about 3% of the total MSW for EU and the U.S.) [23].

Following the circular economy principles, the European Commission encourages the utilization of the mineral fraction of WTE bottom ash (after proper ferrous and nonferrous metals recycling) as secondary construction materials in the civil engineering sector [24, 25]. Even though a significant variance is present in the reuse rate, from 0 to 100% in different countries, the overall reutilization rate in the EU in construction works is approximately 54%, as indicated by the previous findings that utilization does not depend on how well-regulated bottom ash utilization is, but as a result of political commitment to bottom ash recycling and economic interest [26]. Besides, European countries have restricted laws and legislation that prevent the mix of bottom ash and fly ash, and the management involves appropriate treatment prior to a final disposal of fly ash, including backfilling to underground mines or quarry, and chemical–physical stabilization with binding agents (commonly cement) followed by landfilling at the current stage [26, 27].

Currently, 75 WTE facilities are operated in the 25 states of the U.S., mainly in the Northeast, combusting about 29 million tonnes (11% of total MSW) in 2018 and generating about 7 million tonnes of residues annually [28, 29]. A large amount of land, less dense population, and low economic cost of MSW sanitary landfill caused the WTE facilities in the U.S. to be less common than in the EU countries (Fig. 1). U.S. WTE industries process combined ash (the mix of fly ash and bottom ash in the daily generation ratios) as a single stream and dispose of it in the landfills after it passes the Toxic Characteristic Leaching Procedure (TCLP) [17, 30]. About 10% of WTE combined ash is reused in road construction and landfill cover [31, 32]. In recent years, researchers and scientists in the U.S. have been driving public attention to the GHG emissions from landfills to convert the waste management framework to WTE technologies and enhance the energy and metals/materials recovery, which requires the support and development from the legislation and interests in markets [33–39].

China has risen to 228 million tonnes of MSW generated nationwide in 2018, with 102 million tonnes of WTE capacity; the MSW generation is concentrated in eastern coastal provinces due to the dense pollution, developed economy, and urbanization [40]. The annual generation of total residues in China is estimated to be about 26 million tonnes (fly ash is estimated to be 5% of the total MSW, considering that the differentials of combustion processes in China generated more residues from the APC system). Cement stabilization/solidification is the most common way of fly ash disposal in landfills, which can be implemented easily at a relatively low cost [41]. Besides, the existing cement kiln treats approximately 6% of the total fly ash generated in China [42]. However, there is no clear data source for the bottom ash reutilization rate [31].

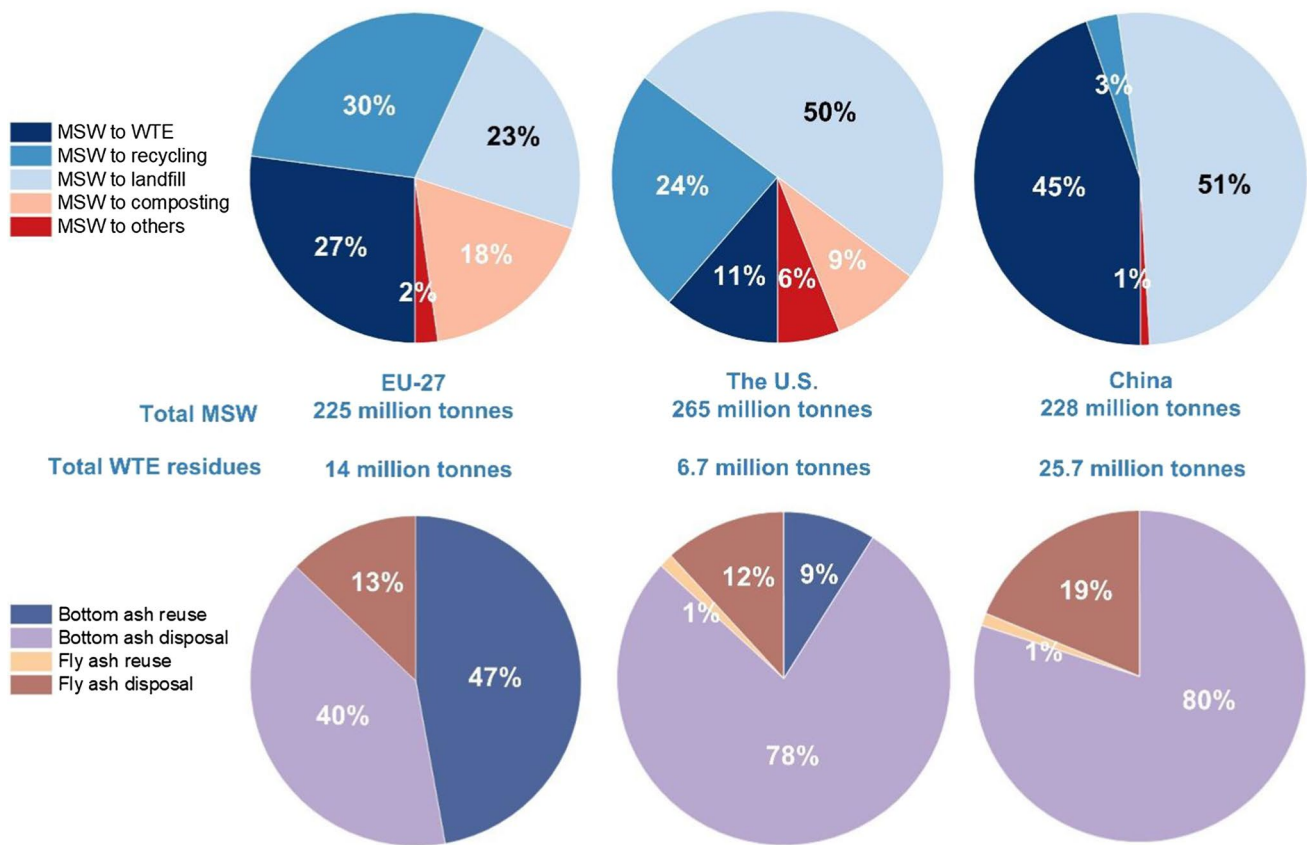


Fig. 1 MSW management framework and WTE residues reutilization status in the EU, the U.S., and China. *MSW* municipal solid waste, *WTE* waste-to-energy

This review innovatively compared the beneficial uses of WTE residues in civil engineering applications from technical perspectives and their corresponding environmental standards in European countries, the U.S., and China, presenting the opportunities and challenges to verify the effectiveness of WTE residues stabilization, the gaps of promoting WTE residues to reutilization, and the demands from construction. The overall characteristics of WTE residues (bottom ash and fly ash), and their practice in civil engineering applications, were also summarized, which indicates the possible solutions and framework to apply the beneficial uses of WTE residues in current and future scenarios to meet the demands of both developed and developing countries.

Common standards and speciation

Leaching procedure and standards

Heavy metals are the predominant concern for the environmental impacts when the WTE residues are disposed of in landfills or reused as construction materials. Meanwhile, some elements or components (e.g., chlorine, dissolved

organic carbon (DOC), etc.) also have environmental concerns; if the waste is discharged to the landfills, it may generate pollutants in the soil or groundwater through the leaching. A comparison of the most commonly used leaching procedures used in European countries (the UK is listed as a representative), the U.S., and China are shown in Fig. 2, where the detailed procedure and parameters are summarized from the standards listed in Sects. “[EU leaching procedure and standards](#)”, “[The U.S. leaching procedure and standards](#)”, and “[China leaching procedure and standards](#)” [41, 43–49]. Owing to the pH being a primary influence on the leachability of heavy metals, the investigations and measurement of pH in the different regions are also included.

EU leaching procedure and standards

The European Committee for Standardization (CEN) developed standards and guidance on the leaching tests and chemical analysis to evaluate the End-of-life waste materials: CEN/TC 292 “Characterization of waste” and CEN/TC 351 “Construction products-Assessment of the release of dangerous substances” [45, 50–52]. CEN/TC 292 consists of

basic characterization (Liquid-to-solid ratio (L/S), leachant composition, pH redox, complexing capacity, and physical parameters), compliance testing, and onsite verification. CEN/TS 16637-2 of CEN/TC 351 applied tank test: dynamic monolithic leaching test at liquid-to-surface area ratio (L/A) of $8 \text{ cm}^3/\text{cm}^2$ by demineralized water as a function of time [53]. The following specific tests are proposed for the leaching properties as summarized in Table 1 for (1) pH dependence tests (CEN/TS 14429, CEN/TS 14997) [54, 55]; (2) Percolation tests (CEN/TS 14405, CEN/TS 16637-3 of CEN/TC 351) [56, 57]; and (3) Batch tests (EN 12457-1, 2, 3, 4) [50, 58–61].

The EU members are required by EU legislation to follow the CEN standards; thus, the individual countries derived their own regulations and criteria based on their specific situations [62]. One of the widely mentioned version in academic publications is the BS EN 12457-2 (Characterization of waste-Leaching-Compliance test for leaching of granular waste materials and sludges-Part 2): One-stage batch test at a liquid-to-solid ratio of 10 mL/g for materials with particle size below 4 mm (with or without particle size reduction) [44]. The leaching results by deionized water via BS EN 12457-2 are used to compare a solid to the UK waste acceptance criteria (WAC, Table 2), which classify landfill sites as suitable for hazardous, nonhazardous, or inert waste [43, 63, 64].

The U.S. leaching procedure and standards

TCLP and Resource Conservation and Recovery Act (RCRA) standards The EPA Method 1311-TCLP is currently

applied in the U.S. industry, as described in Table 3 [49]. It determines whether the waste is below the levels mandated by the RCRA and, thus, can be disposed of in non-hazardous landfills [68]. The leaching results of the TCLP test are compared to eight RCRA metal regulatory standards (Table 4) to determine whether the wastes can be disposed of in nonhazardous landfills (MSW or sanitary landfills) or hazardous landfills in the U.S. [49, 69, 70].

Leaching Environmental Assessment Framework (LEAF) The LEAF is useful in estimating the environmental impacts of utilizing secondary materials, primarily as construction materials or disposal scenarios [46]. The LEAF evaluation system consists of four leaching methods summarized in Table 1. Method 1313-Liquid-Solid Partitioning as a Function of Extract pH Using a Parallel Batch Extraction Procedure; Method 1314-Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio for Constituents in Solid Materials Using an Up-Flow Percolation Column Procedure; Method 1315-Mass Transfer Rates of Constituents in Monolithic or Compacted Granular Materials Using a Semi-Dynamic Tank Leaching Procedure; Method 1316-Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio Using a Parallel Batch Extraction Procedure [48, 65–67].

Among these four methods, Method 1313 of pH dependence (Table 1) is the most important test to investigate the leachability of constituents [48]. The parallel batch extractions of solid material receive equilibrium conditions over a wide range of eluate pH values (0.5–13). Specimens are crushed and milled to the particle sizes (Table 5) for different minimum dry mass, contact time, and extracted with

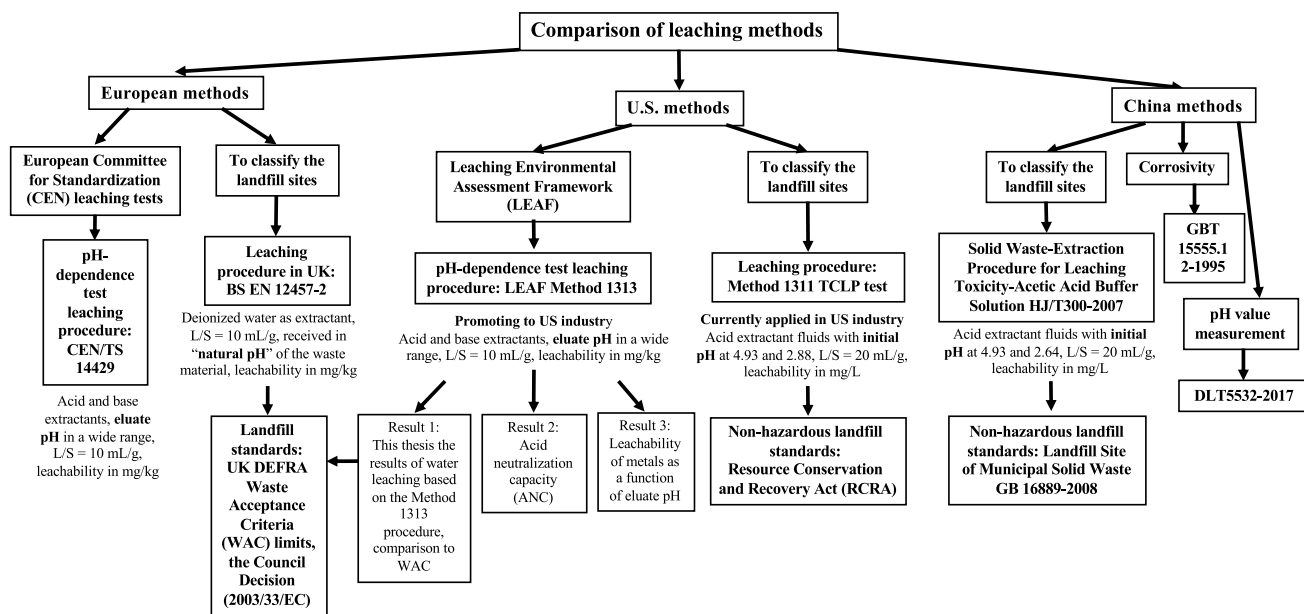


Fig. 2 Comparison of leaching procedure and standards for heavy metals in WTE residues used in Europe, the U.S., and China

Table 1 Summary of leaching tests: European Standardization Committee and U.S. EPA Leaching Environmental Assessment Framework (LEAF)

Region	Test	Standard	Particle size	Liquid-to-solid (L/S)	Leachant	Description
European standardization committees [51]	pH dependence	CEN/TS 14429 [54], CEN/TS 14997 [55]	< 1 mm	10 L/kg	Leaching as a function of eluate pH (4–12, the range can be expanded if necessary)	CEN/TS 14429 obtained different pH values through initial acid or base addition, compared to the pH values through CEN/TS 14997 [55] obtained through feedback control and continuous addition of acid or base
		Percolation	Granular or size-reduced material 95% < 4 mm	CEN/TS 14405 (7 eluate fractions L/S=0–0.1, 0.1–0.2, 0.2–0.5, 0.5–1, 1–2, 2–5, and 5–10 L/kg in up-flow columns) is required by Belgium, Finland, Netherlands, and Sweden	DeminerIALIZED water	Leaching as a function of L/S
	Batch	EN 12457–1 [58], EN 12457–2 [59], EN 12457–3 [60], EN 12457–4 [61]	Granular or size-reduced material 95% < 4 mm	EN 12457–1: One-stage batch test, L/S=2 L/kg, 24 h agitated by Denmark EN 12457–2: One-stage batch test, L/S=10 L/kg, 24 h EN 12457–3: two-stage batch test at L/S=2 L/kg and 8 L/kg to an accumulated L/S of 10 L/kg, 6 h and 18 h EN 12457–4: L/S=10 L/kg, but with particle size below 10 mm	For the purpose of this European Standard the leachant is water	It is included when it is used for compliance or factory production control) indicate that leaching tests, as a function of L/S, are required by different countries, for example: EN 12457–1: Denmark EN 12457–2: France, Germany, and Italy EN 12457–3: Finland EN 12457–4: no need to reduce particle size is required by Austria, the Czech Republic, France, and Spain For single batch leaching test, a fixed amount of material is leached in one step with a fixed amount of leachant. For serial batch leaching test for two or more subsequent extractions of the same portion of material with a fresh amount of leachant

Table 1 (continued)

Region	Test	Standard	Particle size	Liquid-to-solid (L/S)	Leachant	Description
U.S. EPA LEAF [46]	Batch: pH dependence	Method 1313 [48]	Extraction parameters as function of maximum particle size (as Table 5)	10 mL/g-dry	Acid (2 mol/L HNO ₃) and base (1 mol/L KOH) added in reagent water	Liquid–Solid Partitioning as a Function of Extract pH Using a Parallel Batch Extraction Procedure
	Up-Flow Percolation	Method 1314 [65]	85% of the test material should pass through a 2.38 mm (U.S. No. 8) sieve	Set the constituent as a function of L/S from 0 to 10 mL/g-dry at natural pH. Set the flow rate of the pump to 0.75±0.25 L/S (eluate production rate) per day, towards liquid–solid equilibrium over the residence time of eluent in the column	Most materials: reagent water. High clay content materials: 1.0 mmol/L calcium chloride in reagent water (i.e., to prevent deflocculation of clay layers) or high organic matter (i.e., to moderate mobilization of dissolved organic carbon)	Liquid–Solid Partitioning as a Function of Liquid–Solid Ratio for Constituents in Solid Materials Using an Up-Flow Percolation Column Procedure
	Monolithic or compacted Granular Materials	Method 1315 [66]	A minimum sample size of 5 cm in the direction of mass transfer must be employed	Liquid-surface-area ratio (L/A) must be maintained at 9±1 mL/cm ² . Eluate concentrations are measured as a function of time until they approach equilibrium	Reagent water	Mass Transfer Rates of Constituents in Monolithic or Compacted Granular Materials Using a Semi-Dynamic Tank Leaching Procedure
	Batch: L/S ratios	Method 1316 [67]	Extraction parameters as function of maximum particle size (as Table 5)	L/S values from 0.5 mL to 10 mL eluent/g-dry material	Reagent water	Liquid–Solid Partitioning as a Function of Liquid–Solid Ratio Using a Parallel Batch Extraction Procedure

Table 2 UK Waste acceptance criteria (WAC) leaching limits as set in Council Decision 2003/33/EC (European Union) [43]

Elements	Leachability (mg/kg) batch tests at L/S=10 mL/g		
	Acceptable for hazardous waste landfill	Acceptable for nonhazardous waste landfill	Inert waste landfill
As (arsenic)	25	2	0.5
Ba (barium)	300	100	20
Cd (cadmium)	5	1	0.04
Cr (chromium, total)	70	10	0.5
Cu (copper)	100	50	2
Hg (mercury)	2	0.2	0.01
Mo (molybdenum)	30	10	0.5
Ni (nickel)	40	10	0.4
Pb (lead)	50	10	0.5
Sb (antimony)	5	0.7	0.06
Se (selenium)	7	0.5	0.1
Zn (zinc)	200	50	4
Cl ⁻ (chloride)	25,000	15,000	800
F ⁻ (fluoride)	500	150	10
SO ₄ ²⁻ (sulfate)	50,000	20,000	1000
TDS	100,000	60,000	4000
Dissolved organic carbon	1000	800	500

TDS Total dissolved solids

HNO₃ solutions of various concentrations at a liquid/solid ratio of 10 mL solution per gram of dry sample. The samples are mixed in a turn-over-turn at 28 rpm and room temperature, 20 °C. The equilibrium (eluate) pH is recorded after the rotating reaction. The extracted solutions are filtered through 0.45 μm filtration membranes for leachability analysis.

The UK WAC limits meet the BS EN 12457–2 leaching test. A study by International Solid Waste Association (ISWA) stated that the leaching criteria for utilization of WTE residues must be at least the same as or lower than the leaching criteria (WAC) for disposal to landfill [32]. Currently, there are no criteria or landfill limits for the U.S. EPA LEAF tests, while the procedure and parameters of Method 1313 using water leaching are the same as BS EN 12457–2. Thus, it is suggested by authors that using deionized water leaching, following the Method 1313 procedure in their previous research, and the results were compared to the WAC limits as a reference for the future enactment of LEAF criteria [17, 30, 76, 77]. This comparison can contribute to estimating the environmental influence of reusing WTE residues as secondary construction materials in the U.S.

China leaching procedure and standards

This section summarized the commonly used leaching procedure and standards by previous articles from China. The corrosivity of WTE residues is measured by the Solid Waste-Glass Electrode Test-Method of Corrosivity (GB/T 15555.12–1995) by using 100 g-dry samples with 1 L distilled water (liquid-to-solid ratio (L/S) at 10 mL/g) mixing in a shaker for 8 h at room temperature, and settling down for 16 h before the pH value measurement. The residues were considered corrosive when pH value <2 or ≥12.5 [72, 78]. Meanwhile, the Code for Fly Ash Test-Method (DL/T 5532-2017) is used for the pH value measurement of WTE residues, following the 10 g-dry samples immersed in the 200 mL distilled water (L/S at 20 mL/g), mixed for 10 min on the shaker, settled down for 30 min before the pH value measurement [72, 79].

Table 3 Summary of leaching tests: U.S. EPA Toxic Characteristic Leaching Procedure (TCLP) and China Solid Waste-Extraction Procedure for Leaching Toxicity-Acetic Acid Buffer Solution Method (HJ/T 300-2007) [49, 71]

Test	Sample preparation	Reaction	Extraction fluid	L/S	Determination of appropriate extraction fluid
U.S. EPA TCLP [49]	Crushed and sieved to <3/8 inch (9.5 mm)	Turn-over-turn TCLP apparatus for 18 h	Two extraction acid solutions were prepared by acetic acid/sodium hydroxide: Extraction Fluid #1 at pH = 4.93±0.05 and Extraction Fluid #2 at pH = 2.88±0.05	20 mL/g	5 g samples react with 96.5 mL reagent water and stir for 5 min. If the pH < 5.0, use extractant #1 and proceed with the leaching test. If the pH > 5.0, add 3.5 mL 1 mol/L HCl slurry briefly, cover with a watch glass, heat to 50 °C, and hold at 50 °C for 10 min, then measure the pH of the solution. Cooled to room temperature: if the pH < 5.0, use extractant #1 for leaching test; if the pH > 5.0, use extractant #2 for leaching test
China HJ/T 300–2007 [41, 71–74]	Oven-drying, crushing, and sieving to <9.5 mm	Turn-over-turn rotator at 30 rpm for 18± 2 h	Two acidic extraction solutions were prepared with acetic acid and sodium hydroxide solution: extractant #1 at pH = 4.93±0.05 and extractant #2 at pH = 2.64±0.05	20 mL/g	

Table 4 The comparison of the U.S. EPA Resource Conservation and Recovery Act (RCRA) standards for heavy metals by Toxic Characteristic Leaching Procedure (TCLP) test and the China Ministry of Ecology and Environment Standard for Pollution Control on the Landfill Site of Municipal Solid Waste (GB 16889–2008) by Solid Waste-Extraction Procedure for Leaching Toxicity-Acetic Acid Buffer Solution Method test (HJ/T 300–2007) for safe disposal in nonhazardous landfills [49, 70, 71, 75]

Heavy metals standards	U.S. EPA RCRA (mg/L)	China GB 16889–2008 (mg/L)
Ag (silver)	5.0	
As (arsenic)	5.0	0.3
Ba (barium)	100.0	25
Be (Beryllium)		0.02
Cd (cadmium)	1.0	0.15
Cr (chromium)	5.0	(Total Cr) 4.5 (Cr ⁶⁺) 1.5
Cu (copper)		40
Hg (mercury)	0.2	0.05
Ni (Nickel)		0.5
Pb (lead)	5.0	0.25
Se (selenium)	1.0	0.1
Zn (zinc)		100

The procedure measures the total concentration of heavy metals in WTE residues: Soil Quality-Analysis of Soil Heavy Metals-Atomic Absorption Spectrometry with Aqua Regia Digestion (NY/T 1613–2008) [80]. Previous researchers adjusted the procedure, using 1 g of WTE residue samples (sieved less than 0.149 mm) added with 10 mL of aqua regia (HNO₃:HCl=1:3 in volume, L/S=100 mL/g), setting in the boiling water bath for 2-h of heating, shaking 1–2 times, then cooling the digested solutions to room temperature and using the supernatant for Inductively coupled plasma optical emission spectroscopy (ICP-OES) measurement [72].

The leaching toxicity of WTE residues was measured by the Solid Waste-Extraction Procedure for Leaching Toxicity-Acetic Acid Buffer Solution Method (HJ/T300-2007) [41, 71–74]. The procedure of HJ/T300-2007 is compared to that of the U.S. EPA TCLP test, as shown in Table 3. The heavy metals leaching toxicity measurement in Chinese standards is similar to that in U.S. EPA TCLP standards. Landfill Site of Municipal Solid Waste (GB 16889–2008) is used as the standard to evaluate the leachability of heavy metals of WTE residues after proper treatment for safe disposal in nonhazardous landfills in China (Table 4) [75].

Dioxin-related procedure and speciation

Dioxin refers to a group of toxic chemical compounds sharing certain chemical structures, and biological

Table 5 U.S. EPA LEAF Method 1313 and 1316 extraction parameters as a function of maximum particle size [48, 67]

Particle size (< 85% in weight) (mm)	Minimum dry mass (g-dry)	Contact time (h)	Suggested vessel size (mL)
0.3	20±0.02	24±2	250
2.0	40±0.02	48±2	500
5.0	80±0.02	72±2	1000

characteristics, including PCDDs, polychlorinated dibenzofurans (PCDFs), and certain polychlorinated biphenyls (PCBs), those with chlorines at positions 2,3,7 and 8 are toxic [81]. The public perception of WTE fly ash is sometimes negative because it contains dioxins, another challenge of reusing it in civil engineering applications [82–85]. The U.S. EPA established a comprehensive dioxin database, methods, and tools to monitor and measure dioxin for controlling emissions and preventing exposure [86].

EPA Method 1613B measures tetra-through octa-chlorinated dioxins and furans (PCDD/Fs) by high-resolution gas chromatography/high-resolution mass spectrometry (HRGC/HRMS) using isotope dilution to quantify very low concentrations of individual PCDD/Fs congeners [87]. This method has been widely applied as pretreatment steps (extraction, concentration, and column separation) for dioxins concentration measurement of WTE fly ash in academic research papers in recent years [88–90]. Besides, EPA Method 8280B (detection limit 1–5 ppm in ash samples) and Method 8290A (detection limit at parts-per trillion (ppt) to parts-per quadrillion (ppq)), while less sensitive than Method 1613B, were also used in the previous papers [91–93].

For landfill disposal, the concentration of dioxins in WTE fly ash must meet the environmental standard of 3 ng/g in China according to the China national standard GB 16889–2008, which is significantly lower than the U.S. hazardous limit of dioxin disposal at 10 ng/g and EU Statutory Order on Persistent Organic Pollutants at 15 ng/g [41, 74, 75, 77, 94]. However, due to WTE fly ash being categorized as hazardous waste, there is still a long journey to be beneficially reused as a resourceful material in civil engineering applications. A previous study also mentioned that dioxins and furans do not easily leach, while releasing these contaminants is of major concern because of their toxicity [95]. In August 2020, China launched the first technical specification (HJ 1134–2020) for reusing treated WTE fly ash as a resource for further application, which required the total remaining dioxins (not exceeding 50 ng-TEQ/kg-dry via the treatment processes, including low-temperature thermal decomposition, high-temperature sintering, or high-temperature

melting, etc.), heavy metals leachability (standards GB 8978 by using HJ 557), total Cl (<2%, preferred to <1%), the standards for reuse as a cement manufacturing feed material (GB 30485 and HJ 662), and not allowed to be used in sintering brick [96–100].

Characteristics of WTE residues

For bottom ash, the ash discharge system after the combustion chamber significantly influences its characteristics (Table 6) and potential beneficial uses. The wet-discharge system by Ulrich Martin drops the combusted ash particles from the end of the moving grate into a water tank for quenching and forming agglomerated bottom ash, which is the most common ash discharge process [101, 102]. The water and air sealing wall in the discharger prevents the flue gas and other pollutants from being released outside the furnace. The ram continuously pushes the bottom ash to the drop-off edge. The freshly quenched bottom ash was characterized by amorphous and microcrystalline calcium-silicate-hydrate phases and the formation of quench products (e.g., calcite, Friedel's salt, hydrocalumite, portlandite, etc.) were controlled by very fine particles (<0.425 mm) [103]. The processing parameters in the quenching water tank (e.g., water content, etc.) may also influence the characteristics of bottom ash. The bottom ash in the U.S. (Fig. 3a) are stone-like granulate particles, while the bottom ash in China WTE facilities is dustier and looser.

The wet-discharged bottom ash commonly contains moisture of about 10%–60%, which is classified as a non-hazardous material; except for moisture, the bottom ash typically contains 50%–70% mineral fraction, 15%–30% glass and ceramics, 5%–13% ferrous metals, 2%–5% non-ferrous metals, and 1%–5% unburned organics [17, 31, 68, 104–106]. Modern WTE facilities commonly apply ferrous (magnetic separation) and nonferrous (eddy current) metal recycling units to extract metal scraps from bottom ash; thus, the remaining stone-like fractions after metal recycling can be used in civil engineering applications depending on the ash characteristics [107]. The particle size distribution of bottom ash is significant when the material is used as a substitute for secondary building material or other utilization purposes [108]. A previous review study reported that 60%–90% of ash is found in 0.02–10 mm, whereas 0–30% bottom ash may contain >10 mm larger particles, which are ferrous and nonferrous metals, slag, and construction-type waste materials, which can be further recycled in metal separation processes [31]. Tian 2022 also found that 80% of the bottom ash after metal recycling is 1–20 mm, as shown in Fig. 3 [17].

To increase the mechanical metal recycling rate, the dry discharge system was developed in WTE facilities in Japan and Switzerland, which showed a 45% increase in ferrous metals and a 50% increase in nonferrous metals over the wet-discharge method, also resulting in a significant fine fraction generated (approximately 45% of total bottom ash) due to the absence of water during quenching [109].

Table 6 Summary of WTE bottom ash and fly ash characteristics

Characteristics	Bottom ash [17]	Fly ash [110]
Classification	Nonhazardous waste	Hazardous waste
Particle size	Wet-discharged: agglomerated particles with wide particle size distribution (around 0.1–30 mm) Dry-discharged: a significant amount of fine fraction (about 45% of total bottom ash)	High-moisture process: 0.03–30 mm (large ash size due to the agglomeration of particles in the presence of water) Low-moisture process: 0.02–0.2 mm
Moisture	10%–60%	High-moisture process: 20%–30% Low-moisture process: 2%
Components (except of moisture)	50%–70% mineral fraction, 15%–30% glass and ceramics, 5%–13% ferrous metals, 2%–5% nonferrous metals, and 1%–5% unburned organics	Collected residues discharged from the boiler, scrubber, and fabric-filter baghouse in the APC system, containing particles from the furnace carried in the process gas and the newly-formed particles when absorbents enter the scrubbers, including hydrated lime/lime slurry and activated carbon
Possible mineral phases	Amorphous phases (76%), quartz (SiO ₂), calcite (CaCO ₃), anhydrite (CaSO ₄), akermanite (Ca ₂ Mg[Si ₂ O ₇]), corundum (Al ₂ O ₃), alunite (KAl ₃ (OH) ₆ (SO ₄) ₂), magnetite (Fe ₃ O ₄), gehlenite (Ca ₂ Al[AlSiO ₇])	Amorphous phases (50%–55%), portlandite (Ca(OH) ₂), calcite (CaCO ₃), vaterite (CaCO ₃), halite (NaCl), sylvite (KCl), chloromagnesite (MgCl ₂), calcium hydroxide chlorides (CaClOH), anhydrite (CaSO ₄), bassanite (CaSO ₄ · 0.5H ₂ O), alunite (KAl ₃ (SO ₄) ₂ (OH) ₆), wurtzite (ZnS), tricalcium aluminate (Ca ₃ Al ₂ O ₆), Ye'elimite (Ca ₄ Al ₆ O ₁₂ SO ₄), hemicarboaluminate (Ca ₄ Al ₂ (CO ₃) _{0.5} (OH) ₁₃ · 5.5H ₂ O), ettringite (Ca ₆ Al ₂ (SO ₄) ₃ (OH) ₁₂ · 26H ₂ O), Friedel's salt (Ca ₂ Al(OH) ₆ (Cl,OH) · 2H ₂ O), quartz (SiO ₂), wollastonite (CaSiO ₃), tricalcium silicate (Ca ₃ SiO ₅), diopside (MgCaSi ₂ O ₆), gehlenite (Ca ₂ Al[AlSiO ₇])

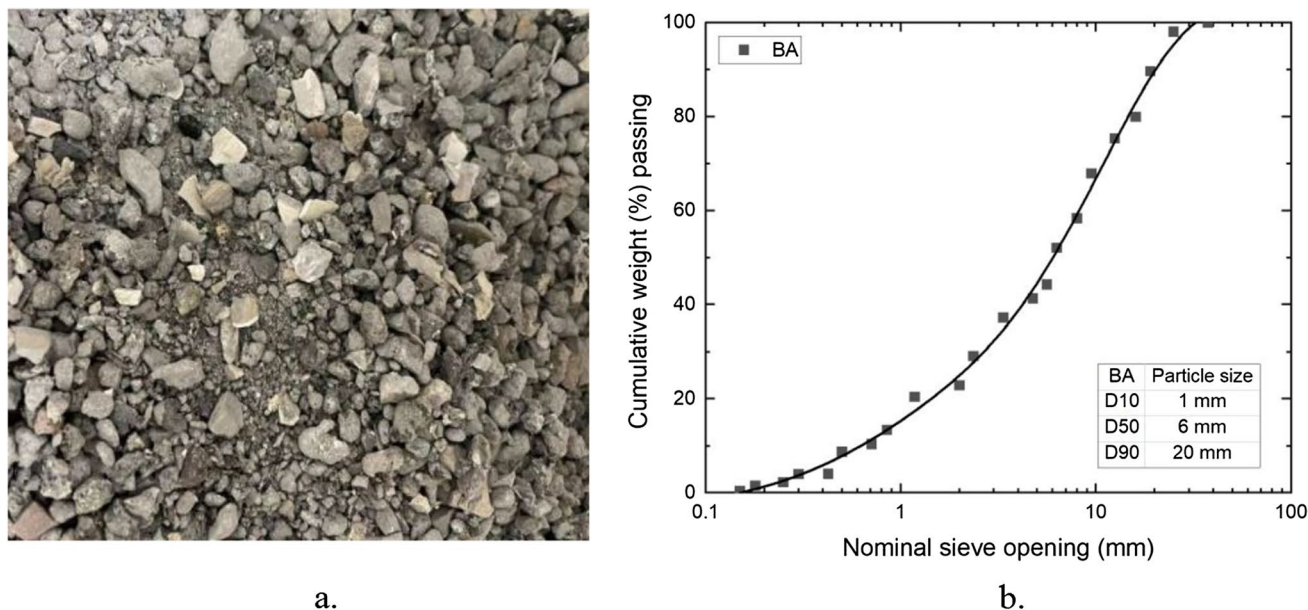


Fig. 3 As-received bottom ash after ferrous and nonferrous metal recycling: **a.** photo (by the corresponding author, 2019, Columbia University, New York, USA); **b.** particle size distribution (D10, D50, D90: the portion of particles with diameters below this value is 10%, 50%, and 90%)

Table 7 presents the elemental concentrations of WTE bottom ash and fly ash [17, 110]. Fly ash is dominant in Si (202 g/kg, average value, same as followed) and Ca (150 g/kg), and has a high concentration of Ca (222 g/kg) and Cl (145 g/kg) due to the hydrated lime slurry injection in the APC system and its reaction with HCl in the flue gas. Pb (3513 mg/kg), Zn (9 g/kg), and Cd (178 mg/kg) are mainly considered as the concern of leaching of toxicity, which may release into the soil or groundwater and cause environmental risks. Tian et al. systematically investigated the detailed characteristics of fly ash [110].

The ternary composition reviewed from the literature is normalized and presented in Fig. 4, when compared with the composition of ordinary Portland cement (OPC), the common cementitious supplementary materials from industrial residues (blast-furnace slag, coal fly ash Class C/F, coal bottom ash), waste glass, silica fume, and some clays commonly applied in cement material (bentonite, kaolin, metakaolin) [166–173]. The experience of utilizing other industrial residues or aluminosilicate materials also references the beneficial uses of WTE residues.

Beneficial uses of WTE residues in civil engineering applications

Numerous studies (Fig. 5) of the uses of WTE residues are categorized based on demands of civil engineering applications. The applications of WTE bottom ash are more widely accepted and discussed in this review study than fly ash

because it is a nonhazardous material, and its generation is 6–10 times the latter.

Alternative aggregates in concrete or cement-based concrete pavement

U.S. American Society for Testing and Materials (International standards organization, ASTM) C33/C33M Standard Specification for Concrete Aggregates defines the requirements for grading and quality of the coarse and fine aggregates for use in concrete with different nominal sizes (sieves with Square Openings) [174]. Typically, the coarse aggregate sizes are larger than 4.75 mm and generally range between 9.5 mm and 37.5 mm; the fine aggregate sizes are less than 4.75 mm, and the limit for material finer than the 75 μm (No. 200 sieve) shall be 5.0% maximum [174–176]. Natural coarse aggregate is extracted from mines, consisting of gravel (deposits), crushed gravel, and crushed stone for particle size, angularity, and texture demands. In addition to stone, sand, as another essential industrial construction material, is the most consumed natural resource in the world after water and has become a limited resource in recent years due to exhausted extraction. The sand (fine aggregates) is classified as fine sand (0.075–0.425 mm), medium sand (0.425–2 mm), and coarse sand (2–4.75 mm), consisting of pit sand (2–4.75 mm), river sand (0.06–2 mm), sea sand (0.06–2 mm, containing salt, so it is avoided for concrete structure), manufactured sand (0.6–4.75 mm) [177–180]. Industrial residues in similar particle size ranges and

Table 7 Elemental concentrations of WTE bottom ash [24, 103, 111–134] and fly ash [24, 63, 118, 121, 134–165]

Elemental concentration (g/kg)	Bottom ash			Fly ash		
	Min	Max	Ave	Min	Max	Ave
Ca	69	250	150	52	397	222
Cl	3	14	8	7	356	145
S	5	164	38	7	115	36
Si	168	224	202	0.1	132	55
K	3	190	29	3	91	37
Na	9	38	22	10	221	53
Mg	6	17	13	2	30	11
Zn	0.3	8	2	0.01	49	9
Al	30	70	48	3	74	29
P	3	6	4	0.5	59	7
Fe	11	109	39	2	37	12
Ti	7	7	7	0.4	12	6
Elemental concentration (mg/kg)	Min	Max	Ave	Min	Max	Ave
Pb	23	5,195	912	50	19,000	3513
Mn	100	1246	679	100	3540	738
Cu	36	6532	1833	90	5400	1420
Sr	219	366	293	196	1408	469
Ba	1240	2239	1758	70	1590	757
Cr	79	1224	281	12	14,916	659
Cd	0	101	11	0.3	610	178
Ni	13	2107	163	9	1889	138
Se				0.1	130	22
As	4	138	48	1	460	101
Hg	0.03	0.8	0.14	1	16	5
Ag				1	40	19

strengths are expected to be used as supplementary sand materials to relieve the shortage of sand.

The granulated WTE bottom ash is used extensively to replace coarse aggregates due to the increasing environmental cost of natural mining stone. In contrast, the sorting of sizes in WTE bottom ash varies depending on the applications of the particle size ranges discussed above. Most of the previous studies explored the performance of WTE bottom ash in particle sizes >4.75 mm [111, 181, 182]. Some modern WTE facilities use a 9.5 mm screen to separate the sizes of WTE bottom ash mainly for enhancing the recovery of nonferrous metals; therefore, bottom ash <9.5 mm to replace coarse aggregate was investigated in a previous study [183].

In Denmark, UK, the Netherlands, and Norway, the utilization rate of the mineral fraction of bottom ash is more than 60% in concrete structures or cement-based concrete pavement [31, 32, 184, 185]. The compressive strength varies from 17 MPa (2500 psi) to 28 MPa (4000 psi) and is higher in residential and commercial structural concrete. Research using mixed bottom ash and fly ash (ratio 90/10) completely replacing both natural coarse and fine aggregates showed a compressive strength above 15 MPa, which is suitable for use as nonstructural concrete [24]. A prior study by the author examines the performance of WTE combined ash (the mix of bottom ash and fly ash in the daily generation ratio) after washing and crushing in the sizes of 9.5–25 mm and 2–9.5 mm as coarse aggregate 100% substitute natural crushed stone received exceeding 28 MPa of compressive strength in produced structural concrete [30]. To produce granulate aggregate materials with low dust and chloride and higher mechanical strength, typical pretreatments of bottom ash involve washing and natural weathering before further processing [24, 183, 186–188], which results in significant improvements in the quality of the mineral fractions for cement-based concrete production [189].

As for the replacement of fine aggregate, the fine size previous studies widely investigated the size range of bottom ash <4.75 mm or 5 mm [181, 182, 190–194], and some studies investigated the performance of bottom ash <2.36 mm or 2 mm [112, 195, 196]. The fine size bottom ash is a lightweight porous material containing metallic aluminum, which caused the reaction with alkaline compounds in cementitious phases and generated hydrogen gas, resulting in bubbling and swelling in cement products [17, 30]. The highest cumulative amount of hydrogen gas collected in the particle size ranges (<0.6 mm, 0.6–1 mm, 1–2 mm, 2–4.75 mm) within 20 days was 8.4–39.4 L/kg-dry bottom ash [197]. To relieve the swelling, academic research has explored alkaline treatment for bottom ash (immersion in sodium hydroxide solutions for 15 days), resulting in up to 50% replacement and exhibiting

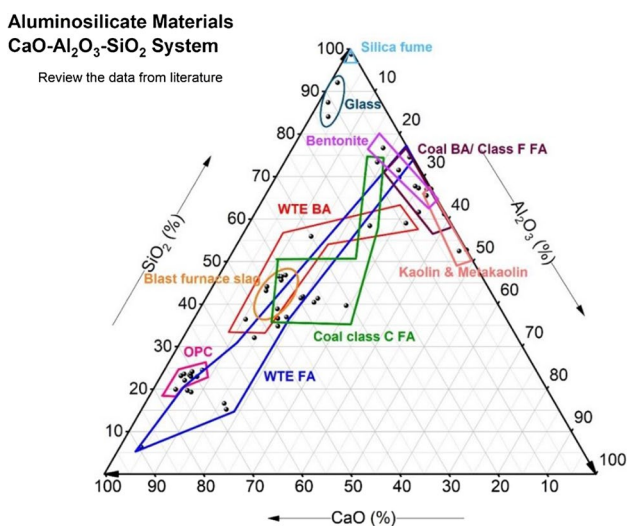


Fig. 4 CaO–Al₂O₃–SiO₂ ternary diagram for the composition of industrial residues and other aluminosilicate materials data reviewed by the author (Tian 2022) [17]

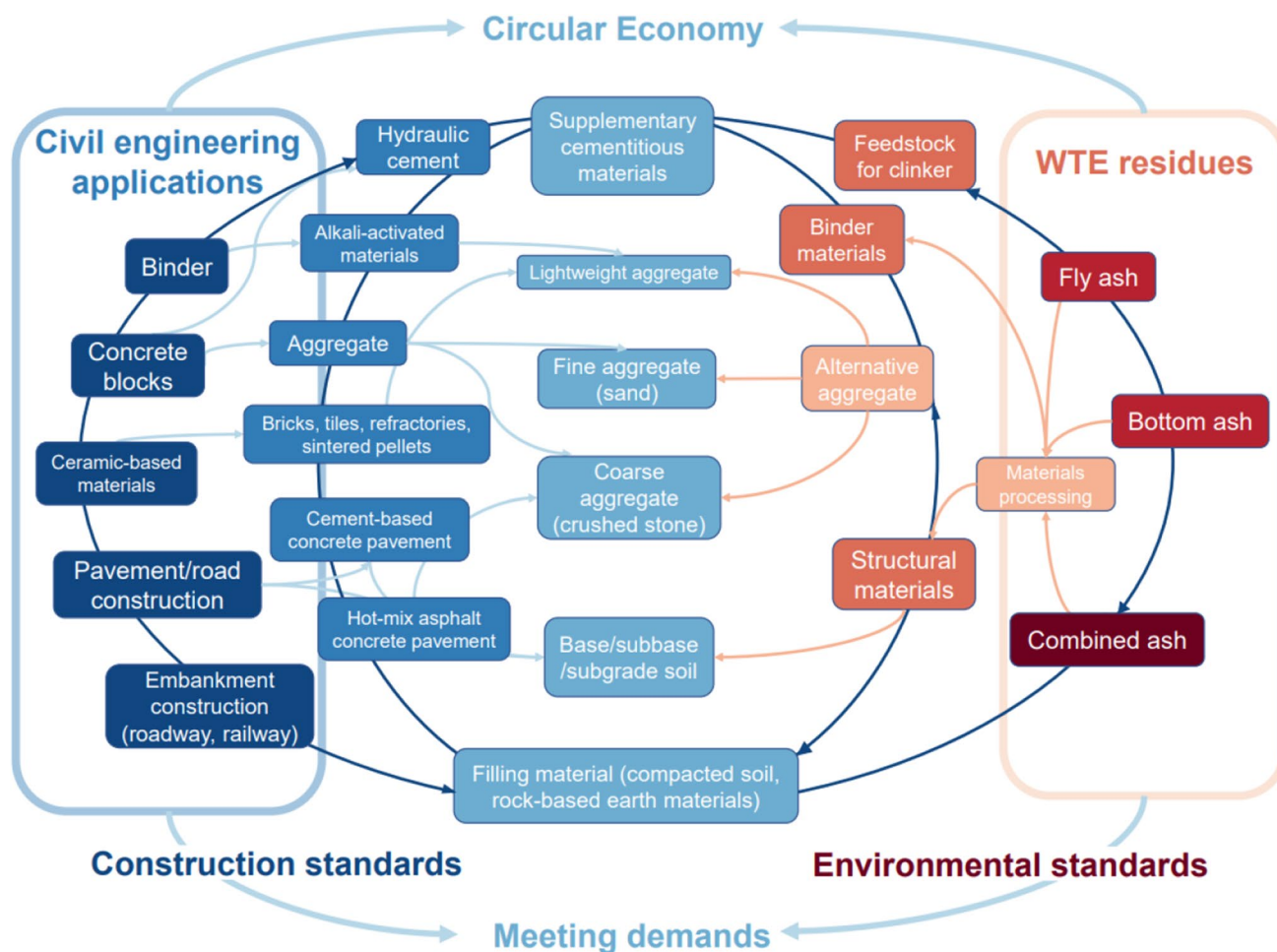


Fig. 5 The framework of beneficial uses of WTE residues in civil engineering applications

compressive strength of 25 MPa [111, 182]. A previous study by the author found that the compressive strength of 28 MPa was obtained in cement mortar using <2 mm combined ash as a fine aggregate up to 50% volume replacement in the mixture design with water compensation to the absorption rate (13%) of ash, reaching 50% of the compressive strength by only using natural sand [17]. Similar mixture adjustments were also concluded in the recent T.-P Huynh et al. [194] study when the fine bottom ash was adjusted to the saturated surface dry condition before use and the novel method (densified mixture design algorithm [198]) was used as the mixture design, using fine bottom ash as a 30%–50% replacement for natural sand in mortar mixtures caused 35% loss of compressive strength, and 100% replacement caused 48% loss in the compressive strength.

Cement stabilization/solidification can effectively encapsulate the heavy metals from WTE residues and prevent their leaching into the environment. The ash-derived construction products comply with civil engineering and stringent

environmental standards related to the leachability of metals and are used commercially [45, 123, 199, 200].

Alternative aggregates in hot-mix asphalt/bituminous concrete pavement

Unlike Portland cement concrete, which is made of cement, stone aggregate, sand, and water and is used as the surface course of rigid pavement, flexible pavement is used asphalt or bituminous to bind aggregates in a hot mix for the surface course. The bitumen encapsulation mechanisms are applied in hot-mix asphalt concrete to solidify and utilize WTE bottom ash as the stone aggregate and be used as pavement for road construction [201–203]. Numerous studies have investigated the performance of bitumen-bound bottom ash asphalt mixture, indicating that the ash–concrete mixture needed higher asphalt content than the mixture of a commercial asphalt concrete pavement [204–206]. Another research found that the increase in bottom ash substitution in the asphalt pavement mixture lowered the tensile strength

and concluded the optimal formula of 10%–40% bottom ash as a substitute for natural aggregate and 3.5%–9.5% bitumen as the binder [201]. Some studies indicated that the percentage of bottom ash substitution was limited to 20% to control the tensile strength ratio within 75% [185, 201].

The TCLP leaching test results showed that heavy metal concentrations were below the detectable levels [201, 206, 207]. The low leachability of in bottom ash-containing asphalt mixture resulted in the hydrophobic nature of the binding system and the surface cover, which prevented the contact of bottom ash with water and significantly decreased infiltration and element mobility [185, 208].

Base, subbase, and subgrade soil for pavement construction

Besides its uses as alternative aggregates, WTE bottom ash is widely used as an unbound or hydraulically bound structural material for the base, subbase, and subgrade soil, which has been widely investigated in numerous field experiments [209–213]. In unbound form, the shear strength, elastic modulus, and bearing capacity of bottom ash showed similar performance to natural sand, and the California bearing ratio (CBR) values of bottom ash are 20%–30% higher than the recommended subbase values [214]. The size of unbound bottom ash generally fulfills the grading requirement as the Type 1 unbound mixture, but grading adjustments can be required. It has been found that unbound bottom ash provided 70% of the strength of crushed rock as a desirable subbase material in field tests [213]. Additionally, the water content as the critical factor of aging reactions was less than 0.1–0.5 L/kg after ten years; thus, the aging phenomenon was not observed in deformation properties under loaded conditions [211].

Hydraulically bound bottom ash utilizes cement or other binders to improve the mechanical performance of the pavement base, which requires a compact to 95% of the maximum dry density to meet the SHW Series 800 standard [214]. Adding cement or lime can improve the compressive strength and elastic modulus of bound bottom ash to receive the confining pressure at 70 kPa [212, 214, 215]. The leachability of heavy metals of unbounded and hydraulically bounded bottom ash in road construction was widely studied in a previous study, which indicated that although the asphalt on the top layer prevents infiltration of rainwater, the large surface area of unbonded/bounded bottom ash in the base/subbase/subgrade soil resulted in the susceptible exposure of contaminant to the environment [213, 216, 217].

Zimar et al. [218] explored WTE fly ash for treating expansive/high-plastic clays and utilized the WTE fly ash stabilized clay as subgrade or subbase soil to improve the performance of highway pavement when wetted and shrunk during drying. Due to the increasing cost of raw

construction materials, multiple studies have investigated the utilization of stabilized industrial residues as subgrade soils for road constructions [219–222]. With the development of effective stabilization technology for WTE fly ash, it is promising to develop stabilized WTE fly ash in road constructions rather than disposing of it in landfills. For instance, Colangelo et al. developed the preliminary washed WTE fly ash mixed with 20% of cement for road base constructions [223].

Filling material in embankment construction

Another essential practical reuse option for bottom ash is embankment construction [224]. Embankments are compacted soil or rock-based earth material barriers with stability to avoid terrain level changes, typically near the roadway or railway to provide structural support. Based on the types of construction materials, embankments are classified into reinforced embankments, earthfill embankments, and rock-fill embankments [225]. When the mechanical properties of bottom ash are similar to those of a controlled low-strength material with a compressive strength of 8.3 MPa or less, bottom ash is a suitable alternative to conventional compacted fill [31, 226]. Compacted bottom ash at the optimum water content has a lower density value. It yields a higher friction angle and cohesion value than most construction fills, resulting in higher shear strength. The permeability of WTE bottom ash is also comparable to that of sand, allowing the free drainage of water and preventing the buildup of pore water pressures [227]. Reusing WTE bottom ash in embankment construction also prevents direct exposure to humans and reduces leaching risk to water suppliers. In several European countries, including Germany, France, the Netherlands, and Denmark, the WTE bottom ash has been widely used in practice as an embankment fill with reuse rates of 83% in Germany, 75% in France, and 90% in the Netherlands [224].

Supplementary cementitious material

Portland cement is the most common type of cement, a hydraulic binder that can set and harden via the hydration reaction with water. The supplementary cementitious materials are used either as substitute cement (blended cement) or added separately to the mixture, contributing to the properties of hardened cementitious phases through hydraulic or pozzolanic activity or filler effects (inert materials) [166]. The most commonly used commercial supplementary cementitious materials contain silica fume, coal fly ash (Class C/F), blast-furnace slag (a byproduct from pig iron production), fine limestone, metakaolin, and natural pozzolans [166].

Because the large sizes of WTE bottom ash can be successfully used as a stone aggregate substitute in concrete

production, the fine bottom ash with high porosity has been widely investigated as a supplementary cementitious material. Li et al. [228] found that the cementitious reactivity is lower than that of Portland cement, and its addition to cement may lead to retardation of cement hydration. The replacement was controlled below 30%, resulting in the blended cement of strength class 32.5 according to GB 175–2007 (Chinese National Standard), and the leachability of heavy metal is far lower than GB 5085.3–2007 [228–230]. Also, the function of potential filler material (minor additional constituent, 5% in weight) by using milled fines (0.125–3 mm) was discussed by Loginova et al. [231]. The pozzolanic reactivity via the Si and Al components in ash (mainly amorphous phases) reacts with hydration products, $\text{Ca}(\text{OH})_2$, to form calcium silicate hydrate gel [228, 232, 233]. It is acknowledged that the presence of metallic aluminum causes deleterious expansion due to hydrogen evolution. Therefore, Carsana et al. [124] proposed the wet-grinding of bottom ash to a fine slurry to react the metallic aluminum particles with water, and then added it to the mix, which received even higher compressive strength in self-compacting concrete due to the pozzolanic reaction. Other pretreatments were mentioned in the previous research before the fine bottom ash was used as supplementary cementitious materials to enhance the ash properties, including thermally treated (550–800 °C) [234, 235] and chemically activated by hydroxides [120]. Garcia-Lodeiro et al. [135] investigated the performance of hybrid cement with bottom ash (83%) and fly ash (17%) in the replacement of 40% of cement clinker, which exhibited an upward trend of 32.5 MPa for 28-day compressive strength. Tian [17] also concluded that the washed fine combined ash powder that received 50% compressive strength of the reference group by 25% replacement cement.

Using WTE fly ash as supplementary cementitious material has been widely investigated due to its advantages in chemical composition and particle sizes. Different from the single purpose of stabilization/solidification for landfill disposal or foundation reinforcement soil, via the mix of fly ash, cement, water, and sometimes adding the accelerating admixtures or activators [236–239], structural aggregate materials were used in the civil products to receive the required mechanical strength. It is found that about 10% replacement of Portland cement by WTE fly ash can receive even higher mortar strength, and 25% replacement is the suggested maximum dosage, which can also pass the leaching standards in different countries [77, 141, 240]. Ground granulate blast-furnace slag (GGBFs) is popular to be used with Portland cement and mixed with cement in a ternary hydration system for better heavy metal stabilization effects and is eco-friendly [241, 242]. A previous study by the author concluded that the reactive compounds in WTE fly ash chemically reacted with water and enhanced the

hydration degrees of the cementitious system [77]. Aubert et al. developed three successive steps for WTE fly ash pretreatment: water washing, phosphating with phosphoric acid to stabilize heavy metals, and to calcinate at a temperature higher than 600 °C to eliminate organic compounds [243]. Tian et al. [77] proved that the phosphoric acid stabilized fly ash could still react with the cementitious hydration products and received the optimal cement replacement at 25%. To control the leachability of heavy metals, melting (1300–1500 °C) was applied to fly ash before it was blended into cement by Wang et al. [244]. Ren et al. [245] investigated the pretreatment of WTE fly ash with CO_2 via slurry carbonation and dry carbonation with subsequent water washing, resulted in the CO_2 -pretreated WTE fly ash can replace cement by up to 30% without sacrificing the long-term strength and mechanical properties, which are also far below the regulatory limits.

Alkali-activated material

Alkali-activated materials (also known as geopolymers), including natural aluminosilicate clay or inorganic industrial residues (containing aluminate and silicate components) as precursors, added to strong alkaline solutions (NaOH , KOH , Na_2SiO_3 , Na_2CO_3 , or their mixtures) as activators, form highly amorphous binding phases which can form hardened structures through geopolymerization [246]. Every kilogram of Portland cement manufactured emitted 0.66–0.82 kg of CO_2 , resulting in the cement industry contributing to 5%–7% of global anthropogenic CO_2 emissions [247]. The alkali-activated binders are identified to have the potential for sustainable utilization in the construction materials industry, offering a like-for-like replacement of Portland cement across its full applications [248].

Zhang et al. [249] started the attempts to use ground WTE bottom ash as a precursor with the increasing interest in alkali-activated materials, followed by Lancellotti et al. [250] and Chen et al. [251] as two representative studies to understand the reaction mechanisms of WTE bottom ash; then, it has flourished in the last five years, widely investigated WTE bottom ash and fly ash as alkali-activated materials [252, 253]. 8 mol/L alkaline NaOH was suggested in the study by Chen et al. by only using bottom ash as the precursor, forming Si–O or Si–O ring structure in final products with 1–3 MPa compressive strength in the hardened pastes, while most of the heavy metals except Cr were effectively immobilized [251]. Zhu et al. [254] used mixed sodium hydroxide (8 mol/L) and sodium silicate solution at a mass ratio of 1:2 as the alkali-activator to react with bottom ash. To enhance the mechanical strength, the WTE bottom ash was mixed with other geopolymer precursors, such as metakaolin, or coal fly ash, observed in the combination of C–(A)–S–H,

(C,N)–A–S–H, and N–A–S–H gels depending on the addition ratios, and received optimal replacement at about 40%–50% [255, 256]. Maldonado-Alameda et al. [257] investigated the effects of WTE bottom ash particle size on alkali-activated binder performance. Zhu et al. [258] used the separated glass materials from WTE bottom ash and received the highest compressive strength of 70 MPa in the hardened paste products. Suescum-Morales et al. [259] investigated the accelerated CO₂ curing effects on WTE bottom ash-coal fly ash mix and resulted in the formation of aragonite.

An essential reason to incorporate WTE fly ash with geopolymer precursors (coal fly ash, metakaolin, GGBFs, etc.) is to effectively immobilize the heavy metals in the fly ash and reduce the leachability in civil products [149, 260–265]. Tan et al. [266] developed a co-disposal of construction and demolition waste and WTE fly ash, and Ye et al. [267] developed a co-disposal of Bayer red mud and WTE fly ash via alkali activation. The compressive strength of WTE fly ash-alkali-activated products mostly received the compressive strength of 1–10 MPa (a few studies exceeded 30 MPa) varied by different fly ash addition, the types of other precursors involved, and the composition of alkali activators [268]. The stabilized products by alkali activation can pass the limits recommended by regional standards (e.g., Chinese CSEPA GB 5085.1–2007) [269, 270].

Geopolymer artificial aggregates and geopolymer bricks as green manufacturing processes, compared to the traditional sintered lightweight aggregate or fired bricks at temperatures over 1000–1200 °C, have been explored in several previous studies [271–274]. Tian et al. 2022 [76] utilized the WTE challenging tailings, including fine combined ash (30% in volume) and filter cake ash (15% in volume) collected from wastewater of combined ash water washing, to mix with metakaolin and react through alkali activation, resulting in the leachability of products that can pass the very restricted UK WAC nonhazardous limits.

Feed material for Portland cement production

Portland cement is produced by heating limestone and clay silicate materials at higher temperatures of about 1400–1500 °C in a rotating kiln, mixing with gypsum after it is cooled, and finally ground to a highly uniform fine power [275]. Numerous studies have investigated the usage of WTE residues as a replacement for raw materials in cement production because of the advantages of their chemical composition [15, 20, 276, 277]. Clavier et al. [278] assessed the feasibility of incorporating WTE bottom ash into raw cement kiln feed materials at 2.8%; leaching tests of characterization data of a cement product were comparable to the results from OPC, which ventured WTE bottom

ash-amended cement production in North America, that assisted the navigation of a new recycling market for WTE bottom ash. Clavier et al. [20] concluded from the existing studies that the untreated WTE ash (bottom ash or fly ash) addition in raw materials is limited to below 10%, while may increase viable addition to 30%–50% to control harmful substances with some exceptions.

Besides, the high temperature of the cement kiln is efficient in decomposing the harmful organic compounds in the WTE residues, especially the PCDD/Fs in the WTE fly ash, which motivates the recycling of WTE fly ash to be beneficially used in civil engineering applications. The Cl concentration in Portland cement is regulated as <0.02% or <0.035% in certain countries to minimize steel corrosion in the reinforced concrete or industrial equipment (cement kiln, flue gas ducts, and fans) [156]. Thus, it may downgrade the cement quality without the pretreatments of WTE fly ash for reducing total Cl and heavy metals [279–281]. The allowable limits of Cl in the WTE fly ash and bottom ashes were 1.75% and 3.5%, respectively, compared to its average concentrations of 15% and 0.8% in Table 2 [126]. Washing is the most common pretreatment method to reduce water-soluble chlorides and leachable heavy metals [137, 184, 282]. The uses as the raw material replacement for cement clinker production ranged from 5%–10% to 25% WTE bottom ash [20, 283, 284]. The washed WTE fly ash can be used up to 35% for cement manufacturing [285, 286].

Ceramic-based materials

Ceramic materials contain products, including tiles, bricks, refractories, etc., manufactured at high temperatures (900–1200 °C), used in numerous civil engineering applications due to their good insulation, high hardness, and chemical resistance [287]. Ceramics are commonly used in construction, and are made from a mixture of minerals, typically silica sand, clay, or other materials, mixed with water (~30%) [288]. Incorporating WTE residues with clay in ceramic-based materials manufacturing reduces the usage of clay and the environmental cost of mineral extraction.

Using WTE bottom ash in the bricks production has been widely investigated by the previous researchers, indicating that the mechanical strength of bricks is affected by the sintering temperature, sintering method, bottom ash percentage, and bottom ash chemical composition [289]. Increasing the sintering temperature up to 950 °C increases the density of sintered bricks, and higher temperatures (≥1000 °C) can cause an increase in the concentration of coarse pore, which is known as bloating phenomenon. The increase in bottom ash percentage also leads to a higher percentage of porosity, which causes a decrease in the mechanical properties [290]. Both flexural strength and the

elastic modulus are reduced to about half when bloating occurs [291]. However, the presence of pores can provide special thermal and acoustic insulation characteristics, and the compressive strength values obtained passed European standards even for 100% bottom ash brick, with a significant reduction in the leaching of heavy metals by leaching test (UNE-EN 772–5) [292].

It is noted that the reactive heavy metals and transition metals in bottom ash can promote the sintering process and save energy during the firing process [293]. As for the transformation of bottom ash, calcination changes the crystalline phase, thereby giving higher green density and low firing shrinkage, and giving the high density, low water absorption, and high Vickers microhardness to sintered ceramics [62, 294]. The pH-dependent leaching results of ceramics produced by calcinated untreated bottom ash were compared, and the leachabilities of heavy metals were reduced through encapsulation [294]. Leaching results showed a low risk for metal contamination as heavy metals were well fixed into the coexistence system of amorphous and crystalline phases [295].

Zhang et al. [296] found that the optimal mixture for WTE fly ash in ceramic bricks was fly ash:red ceramic clay:felspar:gang sand=20:60:10:10 by mass, and the optimal sintering temperature was 950 °C, while leachability of As, Hg, Pb, Zn, and Cd exceeded the China standard limit (GB5085.3–2007) by Horizontal Vibration Extraction Procedure (HVEP) and Available Leaching Toxicity (ALT) leaching procedures [230]. Zhang et al. 2007 [297] found that WTE fly ash (20% in the mix) can be mixed with cream-colored clay, fired clay, and limestone to produce ceramic tiles, which received a compressive strength of 18.6 MPa after sintering at 960 °C, reaching the requirements of China GB4100-83 and effectively immobilizing the heavy metals. Researchers have been aiming to improve the quality of the WTE fly ash ceramic bricks in recent years [298]. For example, the fired bricks developed by Sun et al. [299] incorporated 10% washed fly ash, and their heavy metals leachability could satisfy regulation limitations and can be used in harsh scenarios. Another improvement in the quality and environmental safety of ash-ceramic bricks by Chen et al. [300] was adding electric arc furnace slag (EAFS) as the pore plugger to overcome the disadvantages brought by involving WTE fly ash. However, Chinese technical specification for WTE fly ash HJ 1134-2020 specified WTE fly ash, and its treated products cannot be used for sintering bricks production at the current legislation stage due to there being no well-developed APC in most of the brick factories to capture the toxic emission from the sintering process of the WTE fly ash.

Starting from Bethanis and Cheeseman [301] and Cheeseman et al. [302], WTE bottom ash fine fractions (<8 mm) were used to produce sintered lightweight aggregate in the

temperature range of 900–1140 °C. The sintered lightweight aggregate pellets were produced in a pelletizer with a controlled water amount of 24%, mixing the WTE bottom ash with other clay or industrial residue (previous studies used rice husk, pulverized fuel ash, red mud, etc.), dried overnight at 105 °C, fired at various temperatures, then received the density of 1.55–2.6 g/cm³ and crushing strength of 4–7 MPa [301–303]. Sun et al. [304] increased the crushing strength of sintered lightweight aggregate to 27 MPa with 1046.73 kg/m³ of bulk density and 1783.44 kg/m³ of apparent density by the mix ratio of WTE bottom ash:red mud=1:1 at 1070 °C. Shao et al. [305] improved the strength of fly ash-lightweight aggregate by preheating (at 400 °C), received optimal raw material ratio of WTE fly ash, civil sludge, contaminated soil, and flint clay at 30%:40%:15%:15%, and its leaching of heavy metals was far less than the Chinese standard GB5085.3–2007 [230]. Han et al. 2022 [306] developed the super-lightweight aggregate (bulk density < 500 kg/m³) by mixing 70% WTE fly ash and 30% bentonite with 0.3% SiC addition as a bloating agent, and the sintered products could pass HJ 1134–2020 [96].

Conclusions

This paper summarized WTE residue characteristics, leaching procedure and environmental standards, and the current practice, challenges, and opportunities of WTE residues beneficially used in civil engineering applications. It is estimated that about 46.3 million tonnes of WTE residues are generated in the EU, the U.S., and China; currently, 7.3 million tonnes (16%) are used beneficially in construction.

WTE generates two residues: bottom ash (nonhazardous waste, about 20% of MSW) and fly ash (hazardous waste with leachable heavy metals, high chloride content, and minor PCDD/Fs, about 1%–5% MSW). The particle size distribution primarily influences the applications of bottom ash beneficial uses. The stabilization effects of heavy metals in fly ash are the dominant concern during the utilization, with the second concern controlling the potential emission of PCDD/Fs during product manufacturing or practice scenarios.

European standardization committees developed standards and guidance on the leaching tests and chemical analysis to evaluate End-of-life waste materials. Individual European countries adopted the procedure and established limits based on regional conditions. The derived civil engineering products must be examined by leaching tests to prevent potential environmental risks. The U.S. widely applies the TCLP procedure to fit with RCRA limits for landfill disposal. At the same time, EPA LEAF consists of four leaching methods to estimate the environmental impacts of utilizing secondary materials, primarily as construction materials or

disposal scenarios. It is highlighted that China launched the first technical specification (HJ 1134–2020) for reusing the treated WTE fly ash as a resource for further applications.

For the beneficial uses of WTE residues, coarse-size fractions of bottom ash and combined ash after washing can be used as coarse aggregate to substitute crushed stone in structural concrete, cement-based, or asphalt hot-mix concrete pavement. Fine fractions can partially replace sand as fine aggregates; however, swelling due to the metallic aluminum in fine ash mainly challenges its utilization in cementitious phases. Attributed to the particle size and strength advantages, bottom ash can also be applied as an unbound or hydraulically bound structural material in the base, sub-base, or subgrade soil in the pavement. Utilizing chemically stabilized fly ash as pavement subgrade soil is a future trend for avoiding landfill disposal. Embankment construction is also an essential practical reuse of bottom ash as compacted soil/rock for structural support.

Fly ash presents higher reactivity and mechanical strength when used as supplementary cementitious material than bottom ash. Bottom ash exhibits reactivity as an alkali-activated material, in contrast to the alkali-activation studies about fly ash is more related to the effects of heavy metals stabilization. Portland cement production assists in navigating a new recycling market for bottom ash and fly ash, which also contributes to destroying the PCDD/Fs. Washing is required to reduce the Cl content, and substituting raw feed materials is strictly limited to guarantee cement quality. Ceramic brick is another option for bottom ash reuse, while it may be limited in China due to technical specification. Sintered lightweight aggregate can be produced by both bottom ash and fly ash. Innovative geopolymer aggregate or cold-binding cement aggregate was also investigated.

Future perspectives

- WTE opportunities in developing countries: there are several completed or under development of WTE projects in Africa (e.g., Morocco, South Africa, Ethiopia, Ghana, etc.), South Asia (e.g., Indonesia, Malaysia, India, Thailand, Philippines, Vietnam, etc.), middle east (e.g., Turkey, Iran, etc.), and South America (e.g., Brazil, Chile, Mexico, etc.), which also combined international support and collaboration [307–315].
- Current studies focus on MSW management regionally to meet the rapid urbanization and electricity demands. Establishing the economically viable WTE residues management system and beneficial uses strategies in the meantime of WTE facilities infrastructure benefits the sustainable operation of WTE plants at the next stage.

- The acceleration of meeting the environmental standards with the construction standards for WTE residues will increase the utilization rate and stimulate the interests of markets that require comprehensive technical specification and legislation.

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Data availability Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Yixi Tian is the Guest Editor of the special issue *Thermal processing of post-recycling urban wastes (WTE)*.

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