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Review Article

Physical and Chemical Properties, Pretreatment, and Recycling of Municipal Solid Waste Incineration Fly Ash and Bottom Ash for Highway Engineering: A Literature Review

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Municipal solid waste incineration (MSWI) has been widely used due to its benefits in reducing waste and recovering energy. However, MSWI fly ash and bottom ash are increasing rapidly, causing harm to human health and the environment. This paper discussed the production process, physical and chemical properties, leaching properties, pretreatment methods, and applications of fly ash and bottom ash. By summarizing the previous literature, it is found that MSWI fly ash and bottom ash have mechanical properties similar to natural aggregate. Many beneficial attempts have been made in cement concrete aggregates, ceramic raw materials, and highway engineering materials. Due to concerns about the leaching of heavy metals in fly ash, its application in highway engineering is limited. The application of bottom ash in asphalt pavement is rare because of the side effect on the performance of asphalt mixture. Considering the solidification effect of cement on heavy metals and the low cost of fly ash and bottom ash, the application in cement-stabilized macadam base has broad application prospects. This is beneficial to reduce the construction cost and promote the process of waste incineration, especially in developing countries.

1. Introduction

With the development of economy and the process of urbanization, more than 20 billion tons of municipal solid waste (MSW) is generated in the world every year. According to estimates, about 34 billion tons of MSW will be produced in 2050 [1–4]. However, 33% of them are not harmlessly treated, especially in low-income and middle-income countries [5–7]. If MSW could not be dealt with in an ecofriendly manner, it will cause many social and environmental problems, such as occupying valuable urban area, generating harmful bacteria, viruses, and other microorganisms, and polluting the surrounding environment [8–10]. What's worse, the toxic substances are able to spread to the atmosphere and groundwater by wind or rain and even cause a huge impact on the global ecological environment.

The main treatment methods to treat MSW include landfill, composting, and incineration [11–13]. Landfill is to build isolation facilities underground or ground to separate the MSW from the surrounding environment. This is a low-cost and low-tech processing method [14]. However, the quantity of MSW has far exceeded the capacity of landfills. Furthermore, if the waste is not harmlessly treated, the remaining bacteria, viruses, heavy metals, and other pollutants will exist for a long time and may pollute the surrounding environment [15, 16]. Composting refers to the treatment of degradable organic waste by biochemical technology [17–19]. The organics in the MSW are decomposed and converted into stable soil humus. The types of composting can be roughly divided into anaerobic fermentation and aerobic fermentation [20, 21]. The process can decompose organics to produce carbon dioxide, water, methane, and soil humus. Composting is suitable for the treatment with high content of perishable organics, and its investment is much lower than that of incineration. However, composting cannot deal with nonperishable organic and inorganic substances [22, 23]. Municipal solid waste incineration (MSWI) refers to reduce the volume of waste through proper thermal decomposition, combustion, melting, and other reactions. The heat of incineration can be used to generate electricity. However, improper control of incineration conditions will cause air pollution [24–26].

Comprehensively comparing the abovementioned methods, MSWI has become more extensive because of its advantages in reducing the amount of garbage, reducing environmental pollution, and recycling energy [27, 28]. However, fly ash and bottom ash are produced in large quantities caused by incomplete combustion of MSW. Among them, fly ash accounts for about 2.5%, and bottom ash accounts for about 7.5%. According to estimation, more than 500 million tons of fly ash and 1.5 billion tons of bottom ash are produced every year [29]. With the increase of MSWI, these by-products will soon have no place to store and can only be piled up or landfilled at will, which will take up land resources. What's more, after incineration, heavy metals still remain in fly ash and bottom ash. When they enter into soil or water, the environment will be polluted and people's health will be threatened [30, 31].

Fly ash and bottom ash have potential to be reused in many ways. If treated by appropriate methods, the economic and ecological benefits can be achieved. Fly ash contains many toxic substances, and the leaching of some heavy metals exceeds the relevant standards [32, 33]. Therefore, it must be harmless before direct landfill or utilization. The pretreatment methods of fly ash mainly include separating, solidification/stabilization, and heat treatment [34–36]. Considering its good strength, fly ash can be used as building materials, as the aggregate of cement concrete, asphalt concrete, or ceramics [37–40]. Due to its adsorption ability, fly ash can also be used to make adsorption materials to purify industrial or agricultural waste water. Bottom ash is less toxic and can be directly reused. The benefits obtained by these methods are different; hence, they need to be selected according to the characteristic of the bottom ash and the recycling method. The recycling methods of bottom ash mainly include cement concrete aggregates, asphalt concrete aggregates, ceramic materials, bricks, and other materials [41–45].

This paper mainly summarizes the physical and mechanical properties, leaching characteristics, and pretreatment methods of MSWI fly ash and bottom ash and discusses the utilization. What's more, the applications and of MSWI fly ash and bottom ash are studied to promote further utilization, especially in highway engineering.

2. MSWI Process

MSWI mainly includes the following steps: waste storage, waste incineration, waste heat power generation, flue gas treatment, waste leachate treatment, and by-products treatment [46–49]. The MSWI process is shown in Figure 1.

The harmful and incombustible substances in MSW are picked out. The remaining MSW is put into the waste storage pool after weighing. The MSW in the storage must be stirred and crushed to make sure the even distribution, and the leachate generated in the process should be collected to avoid polluting the environment [50–52].

After the storage process, MSW is sent into the incinerator through the related equipment, and the waste incineration begins. After the waste is burned, bottom ash is generated, and it must be cleaned up regularly. The incinerator is divided into a grate furnace, circulating fluidized bed furnace, and grate furnace with different incineration methods [53, 54]. Waste incineration power generation technology also has two types of equipment, waste heat boilers and steam turbine generators. After the waste is incinerated in the incinerator, the heat generated by the waste heat boiler is converted into steam, which can be used by the turbogenerator to generate electricity.

MSWI produces many harmful substances such as heavy metal, dioxin, smoke dust, and so on. If these harmful substances cannot be handled well, they will cause secondary pollution to the environment [55, 56]. The flue gas needs to be purified by different types of reaction towers.

After the incinerator burns MSWI, fly ash and bottom ash are collected. The treated by-products can be used as a material for making bricks, building materials, and pavement materials. The fly ash must be treated in a harmless manner before it is landfilled.

3. Physicochemical and Leaching Properties

3.1. Physicochemical Properties. MSWI fly ash is gray or dark gray with an irregular structure [57]. The particle size of fly ash is larger than that of cement, and its density is about 1.5–2.4 g/cm^3 [58]. The particle size distribution is shown in Figure 2. MSWI fly ash has a high porosity and adsorption, and some volatile heavy metals are adsorbed on the surface of MSWI fly ash [59].

Due to the influence of the waste source, incineration mode, and purification system, the composition of fly ash is quite different. At higher temperature, the loss on ignition is about 13% [60]. Fly ash is mainly composed of Ca, Si, Al, Fe, and other elements, and the main components are SiO_2, CaO, Al_2O_3, N_a2O, and K_2O, as shown in Table 1 [61–64]. Because it contains some soluble salts, its composition will change after washing. In addition, fly ash also contains heavy metals, such as Zn, Pb, Cr, Cu, and others.

MSWI bottom ash is a mainly spherical structure, which varies with different physical composition, and its density varies in the range of 1.4–1.8 g/cm^3 [65]. The particle size distribution is uneven, which means it can form a good structure [66]. The bottom ash mainly contains ceramics, glass fragments, metal products, and some unburned or

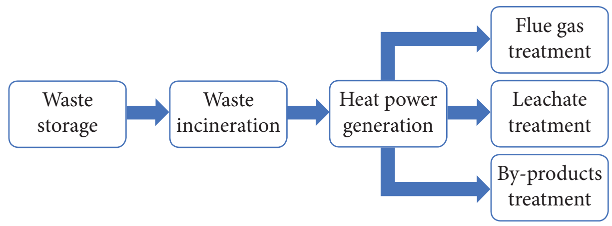

Figure 1: MSWI process.

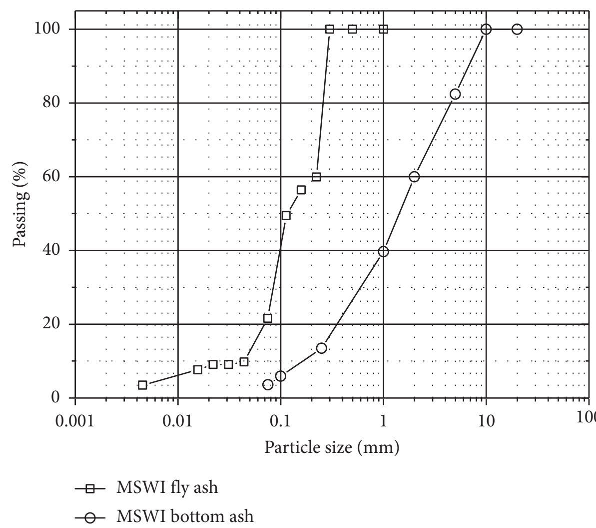

Figure 2: Particle size distribution of MSWI fly ash and bottom ash.

Table 1: Compounds of MSWI fly ash and bottom ash.

Compound	Fly ash (wt.%)				Bottom ash (wt.%)			
	China	Portugal	Japan	France	China	Portugal	France	Italy
SiO_2	19.81	3.25	12.01	27.23	55.2	43.75	49.3	37.78
CaO	23.63	38.7	13.86	16.42	15.9	22.77	16.3	23.29
Al_2O_3	6.79	2.31	8.1	11.72	9.6	6.81	7.5	11.88
Na_2O	6.68	11.57	17.19	5.86	5.1	7	6	3.7
K_2O	6.23	8.35	7.41	5.8	1.7	3.12	1.1	1.63
Fe_2O_3	4	0.39	1.21	1.8	5.7	2.03	7.6	8.01
MgO	3.78	1.67	2.62	2.52	2.6	5.11	2.6	3.87
ZnO	2.79	0.54	1.19	1.37		0.65		0.58
Cl	10.16	27.06	14.95	7.2		2.42	0.3	
SO_3	8.74	4.59	5.54	3	0.9	6.34	0.4	
Others	7.39	1.57	15.92	17.08	3.3	0	8.9	9.26

nonburned substances. Since bottom ash needs to be cooled by water washing, the fresh bottom ash has high water content and a slight pungent odor. The color of the freshly burned bottom ash is gray-black, and it becomes gray-white after drying. The large-diameter bottom ash is mainly made of ceramic pieces, bricks, and metal products, and the small-diameter part is mainly made of glass and ash. Because the bottom ash contains a large amount of metal elements, its pH value exceeds 7 and the aqueous solution is alkaline.

The main composition of bottom ash is mainly determined by MSW. The loss on ignition is 1%–4%. It is mainly composed of Si, Ca, Al, Fe, and other elements. Compared with fly ash, the ratio of SiO_2 and CaO in bottom ash is more than 60%, which is very helpful for the strength of bottom ash [67–69]. The content of heavy metals in bottom ash is less than that in fly ash, which is more environment friendly.

It should be noted that due to the different sources, types, and incineration conditions of MSW, the properties of MSW vary in different regions. However, in the same region, this difference is not obvious. The data in this paper are the average values in the literature.

3.2. Leaching Characteristics of Heavy Metals. Since MSWI fly ash and bottom ash contain heavy-metal elements, the leaching of heavy metals should be detected to assess the impact on the environment. The heavy metals in them are mainly Zn, Cu, Pb, and Cr, but the content of heavy metals in bottom ash is lower than that in fly ash. The heavy metals in them are shown in Table 2 [70–73].

Due to the heavy metals in them, leaching tests need to be carried out to evaluate the environmental influence. The leaching amount of Zn, Pb, Cd, and Cr in fly ash is relatively large, which exceeds the relevant requirements. The leaching concentration is shown in Table 3 [74–77]. Therefore, pretreatment must be carried out before use.

Leaching is related to raw materials, pH value, liquid-solid ratio, particle size, and other factors [78–81]. Due to the different contents of heavy metals in different raw materials, the leaching results are quite different. Generally, higher content of heavy metals in raw materials means greater leaching amount. The effect of pH is complex, which is related to the heavy metals. For heavy metals such as Ba, Cu, and Ti, the leaching concentration in acidic condition is much higher than that in $pH = 7$ [82–84]. However, for Mn and Zn, the change of pH has little effect. Higher liquid-solid ratio means lower leaching concentration of heavy metals [85]. When the solid-liquid ratio is low, the solution is easy to be saturated and cannot continue to leach heavy metals. When the solid-liquid ratio increases gradually, the leaching of heavy metals begins to increase until the upper limit of leaching is reached. The particle size determines the specific surface area of the particles [86]. A smaller particle means a larger specific surface area and a larger reaction area [87]. However, because both bottom ash and fly ash have certain adsorption capacity, leaching and adsorption reactions are conducted in the leaching process, both of which are sensitive to specific surface area [88–92]. Therefore, the influence of particle size is complex, which needs to be evaluated according to the type of heavy metals. According to the relevant research, the leaching concentration of Cd and Cr increases with the decrease in particle size, while this is the opposite for Cu, Ba, and Mn [83, 93–95].

The leaching characteristics of heavy metals in bottom ash are similar to those in fly ash [96, 97]. Different from fly ash, due to the composition and structure of bottom ash, heavy-metal leaching is much less than fly ash [98]. According to the research, the leaching of bottom ash can basically meet the requirements of various national standards, which means that it can be directly used without pretreatment [99–101]. However, in the case of low pH value, the leaching of heavy metals may still exceed the requirements. In addition, the long-term leaching characteristics of bottom ash still need to be observed.

4. Pretreatments of MSWI Fly Ash and Bottom Ash

The pretreatments of MSWI fly ash and bottom ash are divided into separation, solidification/stabilization, and heat treatments. The comparison of different pretreatments is shown in Table 4.

4.1. Separation. Separation refers to the separation of heavy metals, soluble salts, and other substances by physical, chemical, or biological methods. The commonly used separation methods are washing, leaching, and electro-osmosis. Among them, washing is mainly used to separate soluble salts and surface dust, leaching is mainly used to remove and recover heavy metals, and electro-osmosis is used to remove heavy metals and chlorides.

4.1.1. Washing. Washing is a common pretreatment method to remove soluble salts by water. Washing can effectively remove soluble substances, such as Na^+, K^+, and Cl^- [102]. In the washing process, with the increase in the liquid-solid ratio, the extraction efficiency of Pb and Ca increased. When the liquid-solid ratio was 100, the maximum extraction efficiency was 78% and 78.25%, respectively. However, the increase in the liquid-solid ratio had no obvious effect on the extraction efficiency of Cu, Zn, Cr, and Cd. After washing, the main components are silicates and metal sulfides. However, Zn and Cd cannot be effectively removed after washing [102]. After washing, by adjusting the pH value to 6.5–7.5, Al is precipitated in the form of metal hydroxide, and other heavy metals can be adsorbed on $Al(OH)_3$ colloid. The remaining resulting sludge can be mixed in cement for solidification [103].

The washing process is easy to operate, its cost is low, and it can effectively remove the dust and soluble substances on the surface, so it is widely used in practice [104–106]. However, the effect on the removal of insoluble salt or slightly soluble salt is not good. After washing, heavy metals still cannot meet the requirements of relevant standards [107–109]. It can be used in combination with other processing methods.

4.1.2. Leaching. In order to extract heavy metals further, other solvent solutions can be used. The leaching agents can be divided into three types: the acid leaching agent, alkaline leaching agent, and biological leaching agent. Heavy metals, such as Zn, Pb, Cu, and Al, can be recovered by the leaching process. The effect of leaching depends on heavy metals, leaching agents, pH value, and liquid-solid ratio. It is also affected by temperature and time. In general, higher heavy-metal concentration and liquid-solid ratio can get greater leaching amount. The acid leaching agents include HCl, H_2SO_4, HNO_3, and other inorganic acids [82]. Acid leaching has good leaching effect and high extraction efficiency, but it is expensive [110, 111]. Compared with the acid leaching agent, the alkaline leaching agent has better effect on specific metal elements (such as Zn and Pb) [112]. In addition, the combination of chemical leaching and washing can further improve the removal efficiency of soluble salt in fly ash. Bioleaching is the use of microbial redox reactions in life activities to separate heavy metals. The typical application is hydrometallurgy. Compared with chemical leaching, bioleaching is more environment friendly. The factors affecting the bioleaching of fly ash include pretreatment, concentration of fly ash, and bacteria species [113]. Bioleaching was

Table 2: Heavy metals in MSWI fly ash and bottom ash.

	Country	Heavy metal concentration (mg/kg)					
		Cr	Pb	Cu	Zn	Cd	Ni
Fly ash	China	180	2710	990	4530	90	70
	Spain	790	398	156	15900	6	90
	Japan	235	3750	1800	21000	225	
	Italy	109	964	173		85	45
Bottom ash	China	577	470	841	9782	9.9	142
	Japan	185	2462	586	1694	83.4	61
	USA	1421	4300	3090	1360	71	49
	Spain	112	3334	4859	3518	0.5	127

Table 3: Leaching concentration of MSWI fly ash and bottom ash.

Heavy metal	Fly ash (mg/L)	Bottom ash (mg/L)	Limit value (mg/L)
Cd	2.35	<0.01	0.03
Cu	0.21	3.30	0.5
Cr	0.42	0.18	0.5
Ni	0.23	0.15	0.75
Pb	0.14	0.16	1.3
Zn	36.99	0.73	2.8

Table 4: Pretreatment methods of MSWI fly ash and bottom ash.

	Separation			Solidification/stabilization			
	Washing	Leaching	Electrodialysis	Cement solidification technology	Melt curing technology	Chemical stabilization	Heat treatment
Removal effect of heavy metals	Bad	Excellent	Good	Excellent	Excellent	Excellent	Excellent
Secondary pollution	Yes	Yes	Yes	No	Yes	No	Yes
Cost	Low	High	High	Medium	Medium	Medium	Medium
Technical difficulty	Low	Medium	High	Low	Medium	Medium	Low
Strength increase	Low	Low	Low	High	Medium	Mid	Medium

originally used to extract metals from minerals, and the application of bioleaching in fly ash is still relatively rare.

Leaching can effectively remove heavy metals, and the operation is relatively simple. However, chemical leaching needs to consume a lot of chemical reagents, and because of the low content of heavy metals in fly ash, the economic benefit is not good. Compared with chemical leaching, bioleaching is more environment friendly. However, it takes a lot of time to culture bacteria, and bioleaching technology is not mature enough. Further research is needed for bioleaching.

4.1.3. Electrodialysis. The principle of electrodialysis is the reduction/oxidation reaction at the interface between the electrode and electrolyte [114]. In the process of electrodialysis, the reduction reaction of the cathode produces hydrogen and metal and the oxidation reaction of the anode produces oxygen. The influence factors include current density, temperature, mixing conditions, and pH value. In the process of metal precipitation, the inert metal is first precipitated, and then, the active metal is precipitated. The toxicity of inert metals is generally greater than that of active metals, so this method has a good removal of toxicity of fly ash [115]. In addition, acidic agent, alkaline agent, or complexing agent can be added to the solution to increase the conductivity of the solution and improve the efficiency of metal leakage. The selective ion exchange membrane can also increase the metal precipitation efficiency [116].

Electrodialysis can effectively remove dissolved heavy metals and chlorides. However, electrodialysis is not effective for the removal of insoluble or slightly soluble heavy metals [117]. This method needs a lot of electric energy, and the economic benefit is not good.

4.2. Solidification/Stabilization Technology. Solidification/stabilization technology originated from the treatment of radioactive waste in the 1950s, and it developed rapidly in the 1980s. The solidification/stabilization technology mainly includes cement solidification, chemical agent stabilization, melting solidification, and chemical stabilization.

Solidification refers to the process in which the hazardous substances in the waste become immobile and form a compact solid after mixing the curing agent with the waste, and stabilization refers to the process in which the harmful substances in the waste are transformed into toxic substances by adding chemicals.

4.2.1. Cement Solidification Technology. Cement solidification technology refers to mixing MSWI ash into the cement and water for the hydration reaction to occur and form a calcium silicate hydrate product with low heavy-metal leaching toxicity and good long-term stability [118–120]. In the hydration process of cement, heavy metals can react with cement by adsorption, sedimentation, ion exchange, passivation, and other ways [36]. Cement curing after washing has no effect on the setting time of cement, and its strength is improved compared with ordinary cement [121, 122]. However, the addition of excessive fly ash may lead to longer initial and final setting times, and the flexural and compressive strength of cement will also decrease [112].

Cement solidification technology is the most commonly used solidification technology for hazardous waste treatment in the world, with the advantages of wide sources of materials, simple equipment and technology, low treatment cost, and high strength of solidified products [123]. However, this method requires a lot of cement, and the volume after treatment has an obvious increase. If the solidified fly ash is put in the landfill site, it will occupy more spaces and increase the cost [124]. Thus, it is reasonable to be used as construction materials after solidification.

4.2.2. Melt Curing Technology. Melting and solidification is a process in which the fly ash is heated to 1400°C to make it melt and then cooled into slag by a certain program. The volume reduction of fly ash after melt treatment can reach 1/3–1/2, and most of dioxins in fly ash are decomposed [125]. The final product of melt is a completely amorphous and homogeneous vitreous body [34]. Adding SiO_2, MgO, CaF_2, borax, coke, and other auxiliary materials to the fly ash can reduce the melting temperature and reduce the volatilization. The slag can also be made into building materials or used as raw materials for glass, ceramics, and other industries to realize the resource utilization of ash [126]. With the increase of heat treatment temperature, the volatilization of pollutants also increases. This treatment also reduced weight loss and enhanced the solidification of pollutants.

Although the melt solidification technology can greatly reduce the volume of fly ash and the leaching toxicity of heavy metals and realize the resource utilization while reducing and harmless, the melting solidification technology has large energy consumption and high cost. Generally, it is only considered to use when processing high-dose radioactive waste or highly toxic waste, so it is limited to a large extent. At the same time, due to the volatilization of Pb, Cd, and other low-boiling point heavy-metal salts in fly ash under high temperature conditions, the content of heavy metals in flue gas is very high and the flue gas needs to be treated strictly, which increases the cost.

4.2.3. Chemical Stabilization. Medicament stabilization is a process of making toxic and harmful substances into low-toxicity substances through chemical reactions [127]. Chemical agents can be divided into inorganic curing agents and organic curing agents. Inorganic curing agents include NaOH, Na_2S, phosphate, and ferrous salt, while organic curing agents include EDTA and its sodium salt, polyamines, and their derivatives [128]. It is found that the leaching rate of heavy metals in fly ash after phosphate treatment is very small, and the fly ash treated by ferrite has good leaching resistance [81]. However, after using an inorganic curing agent to solidify heavy metals in MSWI fly ash, when the environmental pH value changes, it may lead to the secondary leaching of heavy metals, which makes the leaching toxicity in the treated residues exceed the standard. It is difficult to meet the long-term safety requirements of hazardous waste treatment [129]. The fly ash treated with a heavy-metal chelating agent has strong acid and alkaline impact resistance power.

Compared with other curing and stabilization methods, the chemical reagent stabilization method has the advantages of being harmless, less or no compatibilization, and lower treatment cost and has recently become a hot spot in international environmental research. However, due to the complexity of fly ash components and heavy metal forms and the relatively high cost of chemical stabilizers, it is difficult to find a widely applicable chemical stabilizer. Moreover, the stabilized compounds treated with fly ash lack of cementitious substances, and its strength cannot be improved.

4.3. Heat Treatment. Heat treatment can remove heavy metals or form stable oxides by evaporation at high temperature. This method has a good effect on Zn, Pb, Cr, and Ca. Dioxins can also decompose at high temperatures. Heat treatment is usually carried out at 1300–1400°C [130]. The waste gas of heat treatment contains heavy metal pollutants and needs to be treated separately. By using additives, controlling temperature, or other pretreatment methods, the concentration of pollutants in the gas can be reduced and the performance of heat treatment can be improved [131]. Heat treatment works in two ways: thermal separation and thermal curing. Thermal separation refers to the separation of heavy metals by evaporation at high temperature. Thermal solidification refers to the immobilization of heavy metals in the products by the formation of stable products. Compared with that before heat treatment, the porosity of the products after heat treatment is lower, and the strength is higher [132].

Due to the different evaporation temperatures of various metals, it is theoretically possible to remove different heavy metals by adjusting the temperature. The strength of products after heat treatment is higher than that before heat treatment. However, this process requires a lot of energy and produces pollution gas [133]. The application of heat treatment in fly ash needs further research.

5. Utilization of MSWI Fly Ash and Bottom Ash

5.1. Utilization of MSWI Fly Ash. MSWI fly ash is rich in many harmful heavy metals and salts, such as Cd, Pb, Zn, Cr, and so on. Therefore, considering the heavy metals and its characteristics of easy enrichment and nondegradation, fly ash is considered as a hazardous waste. Fly ash must be pretreated before transportation and safe landfill disposal [134]. The comparison of different utilization methods is shown in Table 5.

5.1.1. Cement Raw Meal. MSWI fly ash contains CaO, SiO_2, Al_2O_3, and some other silicate and aluminosilicate, which means that the composition of MSWI fly ash is similar to that of cement. Therefore, MSWI fly ash can be used as cement raw meal [135]. CaO in ordinary cement needs to be generated by calcining limestone at high temperature, so the energy consumption is relatively high [136]. Compared with Portland cement, cement with part of MSWI fly ash has the advantages of low energy consumption and short setting time. What's more, it can also reduce the emission of CO_2, which is known as greenhouse gas [29]. With the increase of fly ash content, the burnability of cement raw meal is obviously improved, but the strength of clinker will reduce. When fly ash is used as raw meal for sulphate aluminate cement, the content of fly ash in raw meal should not exceed 30% [137]. However, the quality of cement will be affected by the high content of chloride in MSWI fly ash, and the accumulation of heavy metals in cement may lead to environmental problems. If the content of heavy metal can be effectively removed by fly ash pretreatment and the dosage of fly ash is strictly limited, the product quality and the environmental pollution can be controlled [138].

5.1.2. Cement Concrete Aggregate. Due to the small particle size and good strength of it, fly ash can be used as cement concrete aggregate. Lightweight aggregate can be prepared by using the mixture of cement, fly ash, and bottom ash, but the fly ash content should be less than 10% to meet the performance requirements. The strength of cement concrete is not as good as that without fly ash [139, 140]. In addition, water washing pretreatment can improve the quality of cement concrete. Although many studies have shown that the leaching toxicity of heavy metals is not high, the environmental pollution risk of long-term heavy metal leaching behavior is possible [141, 142].

5.1.3. Ceramic. Because the fly ash contains SiO_2, Al_2O_3, and CaO, it can replace part of clay to produce ceramics without pretreatment. Pollutants such as dioxins and heavy metals can be solidified in amorphous glass and removed by high-temperature verification [143]. By mixing fly ash, broken glass, feldspar, and other materials, ceramic products have good chemical stability and strength, which is equivalent to the properties of industrial alkali lime glass [144]. Since fly ash contains some glass phase, silicate, aluminum silicate, and quartz, it can be used as a mixture of ceramic tiles [145]. By sintering at temperatures above 900°C, heavy metals can be consolidated, and the leaching toxicity can be greatly reduced. According to relevant research, the leaching amount of Cd, Zn, and Pb is reduced to 0.53%, 0.59%, and 0.08%, respectively [146]. Therefore, using fly ash as tiles is an effective method to stabilize heavy metals including Cd, Hg, Pb, and Zn.

5.1.4. Fertilizer or Soil Improver. Because of the potassium element in fly ash, it can replace part of fertilizer application. In addition, fly ash can be added to the soil instead of lime to adjust the pH value of the soil [147–149]. Heavy metals in fly ash are toxic to animals and plants, and high salinity will lead to plant salt imbalance. Therefore, independent of whether fly ash is used as a plant fertilizer or soil improver, the amount of fly ash should be strictly controlled.

5.1.5. Adsorbent. Adsorption technology is widely used to remove pollutants from wastewater [150–152]. The development and research of adsorbents with better performance and lower cost has become one of the current hot spots. MSWI bottom ash has been used to remove dyes, heavy metals, and other pollutants from wastewater. MSWI fly ash and bottom ash can be used as adsorbents with good performance for pollutants in sewage and agricultural runoff [153]. However, the problem of using fly ash as adsorbent to treat wastewater is the leaching risk of heavy metals because the toxicity in leaching solution is very high, and this limits the use value of fly ash as an adsorbent [154].

5.1.6. Highway Engineering Material. In the aspect of road materials, most studies focus on the incineration bottom ash or the mixture of bottom ash and fly ash, and the research on using fly ash alone for road construction is less. In order to prevent heavy metals and other pollutants in fly ash from seeping into soil along with rainwater, fly ash is mainly used in the lower structure layer of roads. The application of fly ash in highway engineering materials will be discussed in the following section.

5.2. Utilization of MSWI Bottom Ash. The content of heavy metals in bottom ash is less than that in fly ash, which has little harm to the environment and has great potential for resource utilization [155]. In developed countries, the bottom ash is often widely used for soil improvement, asphalt concrete aggregate, and road materials, and the utilization rate is as high as 70%–90%. In China, bottom ash is mainly used to make hollow brick and cement concrete aggregate.

5.2.1. Cement Concrete Aggregate. MSWI bottom ash has been widely used as cement concrete aggregate [156–158]. Because of the low heavy-metal content and high strength, the bottom ash is an ideal aggregate substitute. Through research, it is found that the cement concrete product with bottom ash instead of part of aggregate has good performance. However, some chemical components in the bottom

Table 5: Utilization of MSWI fly ash and bottom ash.

	Products	Economic benefits	Leaching toxicity	Pretreatment requirement
Fly ash	Cement raw meal	High	Low	No
	Cement concrete aggregate	High	Low	No
	Ceramic	Middle	Low	No
	Adsorbent	Middle	High	Yes
	Landfill cover material	Middle	High	Yes
	Highway engineering material		See Table 7	
Bottom ash	Cement concrete aggregate	High	Low	No
	Ceramic or brick	Middle	Low	No
	Landfill cover material	Low	Low	No
	Highway engineering material		See Table 7	

ash may affect the performance of cement concrete, such as chlorides and sulfates. Chlorides and sulfates may cause corrosion of steel bars and damage of cement concrete. The metal cations can delay the setting time of cement concrete [159]. Al in the bottom ash will also generate hydrogen due to the alkaline environment formed by cement hydration, which will lead to the existence of bubbles in cement concrete and reduce the product quality [160]. Therefore, pretreatment can be carried out before the aggregate is made to reduce the heavy metal content and improve the product performance.

5.2.2. Ceramic or Brick. Because of its high strength, bottom ash can be used as ceramic or brick raw material [161–163]. Using bottom ash as raw material does not reduce the strength of the product [164]. However, the product performance is controlled by temperature, sintering method, bottom ash gradation, and other influencing factors, and the product performance is not stable due to the complex composition of bottom ash [165]. Pretreatment can be carried out before sintering to improve product performance.

5.2.3. Landfill Cover Material. Because of the low content of heavy metals in the bottom ash, it can be used as the covering material of the landfill site [100, 166, 167]. This is one of the main ways to use bottom ash in the United States. But, the landfill itself occupies a lot of land resources, and the economic benefit is not good [168]. In addition, with the increasing amount of bottom ash and fly ash, the landfill exceeds its bearing capacity.

5.2.4. Highway Engineering Materials. Compared with fly ash, MSWI bottom ash has good strength and low heavy metal content, so it is widely used in highway engineering, including pavement and subgrade materials. Its application in highway engineering will be introduced in detail below.

Developing countries need to further improve and develop infrastructure, and longer mileage of railway and highway transportation facilities will be built in the coming years. These will undoubtedly consume a huge amount of building materials including stone and sand. However, the environment has been seriously damaged due to the excessive exploitation of sand and gravel. Many local governments have formulated relevant policies to limit the further exploitation of natural sand and stone. In this context, MSWI fly ash and bottom ash are encouraged as highway materials.

6. Utilization of MSWI Fly Ash and Bottom Ash in Highway Engineering

6.1. Application in Asphalt Pavement Material. In the aspect of highway engineering utilization, more research is focused on MSWI bottom ash or mixture of bottom ash and fly ash, while less research is focused on using fly ash alone. As the hazardous substances such as heavy metals in MSWI fly ash are easy to leach, it is mainly used in the lower layer structure of the highway to avoid direct contact with rainwater [169]. As heavy metals in fly ash can be solidified by asphalt, it can be used in asphalt mixture [170]. However, pretreatment must be carried out before this to reduce the impact on the environment and improve asphalt mixture quality.

The leaching concentration of heavy metals must be considered when MSWI fly ash is used in asphalt pavement. The performance of Marshall stability, water sensitivity, resilient modulus, fatigue life, and rutting of asphalt mixture with fly ash in the range of 8%–16% designed by Marshall and superior performance asphalt pavements (SUPERPAVE) design procedures is better than that of ordinary Marshall mixture [135, 171]. Compared with cement solidification, the leaching amount is better than that of cement and can meet the requirements of the EPA standard [172]. The leaching concentration of fly ash after asphalt solidification is shown in Table 6. However, the long-term road performance and leaching of asphalt mixture still lack of relevant research.

Compared with fly ash, bottom ash has higher strength and lower heavy metal leaching, so it has been widely used in asphalt pavement. The bottom ash can replace part of the aggregate in the asphalt mixture, indicating that the asphalt mixture has a good road performance [173–175]. Compared with coarse aggregate, bottom ash is more likely to replace fine aggregate. When the bottom ash is used as aggregate, the elastic modulus and tensile strength of asphalt mixture can be improved [176, 177]. When MSWI bottom ash is added as filling material, the elastic modulus, tensile strength, and fracture performance of asphalt mixture can be improved reliably [42, 178–181]. When 20% of bottom ash is added, the

Table 6: Leaching concentration of fly ash after asphalt solidification.

Heavy metal	Content (mg/kg)	Leaching concentration (mg/L)		
		Without solidification	Marshall sample	SUPERPAVE sample
Cu	670	45	4.79	6.21
Cd	276	23	0.97	1.08
Pb	4744	331	0.63	1.05
Zn	10259	622	119.12	67.94
Cr	450	25	3.61	3.46
Ni	68	6	0.95	1.2

performance of hot mix asphalt is the best, which has a good compression performance and antirutting performance. The mixing of bottom ash can also improve the antiwear ability of the surface course and improve the friction force [182, 183]. There have been many practices in the use of MSWI bottom ash in the surface layer, but there is still a lack of relevant research on the field construction and long-term performance testing [184, 185]. In addition, the unburned heavy metals in bottom ash need to be removed by sieving and magnetic separation to improve the quality of products.

6.2. Application in Base and Subbase Material. Because the base is between the surface layer and the subgrade, it will not directly contact with water and soil, so it reduces the risk of heavy metal pollution and is regarded as an ideal recycling method of fly ash and bottom ash [43, 186, 187]. Considering the environmental safety and structural characteristics, fly ash and bottom ash must be pretreated before they are used as base materials [188]. Fly ash and bottom ash are widely used as base or subbase materials, and a large number of studies have been carried out in developed countries such as Holland, Spain, the United States, and France [42].

Fly ash and bottom ash need to be washed, cemented, or melted curing before being used as base materials. The strength requirement of highway base is very high, which mainly adopts cement-stabilized base, asphalt-stabilized base, or granular base [189]. Due to the poor solidification effect of granular base for heavy metals, bottom ash and fly ash are more commonly used in cement-stabilized base and asphalt base.

The properties of cement base are similar to those of cement concrete [74]. Because the base needs to bear a lot of load, the base must have enough stiffness and strength. The application of fly ash or bottom ash in cement stabilized base course can not only replace part of aggregate but also has little influence on the strength of products. However, Cl and Al will affect the quality of the base course, leading to cracks more easily. Due to the higher leaching risk of heavy metals in fly ash, chemical pretreatment is needed, which will increase the cost and put the fly ash at a disadvantage in practice. Therefore, it is a better choice to use bottom ash in base or subbase [190].

The asphalt base course is similar to asphalt pavement, so we will not repeat it here. It should be pointed out that asphalt is not suitable for heavy traffic because its modulus is lower than that of cement-stabilized base. Asphalt base is also more expensive, so its use in developing countries is less.

6.3. Application in Subgrade Material. The cost of subgrade material is relatively low, and the cost must be considered when selecting the appropriate subgrade replacement material. Because the heavy metal in fly ash is easy to leach, it must be pretreated before it is used as subgrade material. After solidification of fly ash cement, its strength can meet the requirements of subgrade, and the amount of heavy metal leaching is less [191]. In addition, fly ash can be directly used as subgrade material to waterproof subgrade. Once the leakage occurs, heavy metals will directly enter the soil and groundwater, thus polluting the surrounding environment [188, 192].

The mechanical properties and leaching characteristics of bottom ash are better than those of fly ash, and it has better applicability in road construction [193]. The shear strength, elastic modulus, and bearing ratio of bottom ash are close to those of sand. When the bottom ash is mixed with sand or soil, the strength of the mixture can also be improved [182, 191, 194]. Bottom ash has been widely used as a subgrade filler, and the strength, stability, and durability are good [186]. If it is washed before it is used as subgrade filling material, the chloride and other soluble substances can be reduced, so as to reduce the impact on the surrounding environment [195]. Considering that the price of bottom ash is relatively cheap, the bottom ash is an ideal subgrade material.

6.4. Comparison of Economic and Environmental Benefits of Different Layers. Generally, the structure which is closer to the surface needs to bear the greater load and has to meet higher requirements for the strength and durability. Therefore, road surface materials are often more expensive than base and roadbed materials. Under the premise of meeting relevant requirements, the closer application of fly ash and bottom ash will get more economic benefits if they are used in the top layers. In addition, pretreatment is also a very important factor affecting economic benefits. If the pretreatment means are too complicated or too expensive, it will greatly increase the cost of the project. Compared with fly ash, the bottom ash has very little leaching of heavy metals, and it can be washed or left untreated. Also, the strength of bottom ash is higher than that of fly ash, so it can replace aggregate more. The comparison of economic and environmental benefits is shown in Table 7.

For the environment, the surface layer and the base layer are the easiest to leach because they are more easily exposed to water. Therefore, fly ash and bottom ash are used in places

Table 7: Comparison of economic and environmental benefits.

	Layers	Economic benefits	Environmental benefits	Pretreatment requirement	Application extent
Fly ash	Asphalt surface course	High	High	No	Middle
	Base or subbase	Middle	Middle	Yes	Narrow
	Subgrade	Low	Low	Yes	Narrow
Bottom ash	Asphalt surface course	High	High	No	Wide
	Base or subbase	High	High	No	Wide
	Subgrade	Middle	High	No	Wide

that are not in direct contact with water and soil to prevent polluting the environment. Fly ash is often not used in the top layer or subgrade. During the pretreatment process, secondary pollution may also be caused. Suitable materials need to consider both economic and ecological benefits.

7. Recommendations and Outlook

Due to its good mechanical properties and low heavy-metal leaching, MSWI bottom ash is widely used in highway engineering materials. MSWI bottom ash has been widely studied and applied in subgrade filling and cement-stabilized macadam aggregate. However, considering its side effect on the quality of asphalt mixture, it is seldom applied in asphalt pavement.

Considering the cost of natural aggregate, MSWI bottom ash as aggregate has a wide prospect in cement-stabilized macadam, especially in developing countries. This is conducive to reduce the cost of highway and promote the development of MSWI to alleviate the ecological problems caused by MSW.

However, due to concerns about heavy-metal leaching, MSWI fly ash is rarely applied in highway engineering. Considering that most of the road surface is impermeable, the application of MSWI fly ash in cement-stabilized macadam has certain potential. In addition, aquifuges can be set to prevent the leaching of heavy metals. Cement is beneficial to play a role in solidification of fly ash to reduce its environmental pollution. However, due to the particle size of fly ash, it can only be used as fine aggregate or mineral powder. The large-scale utilization of fly ash depends on the support of government policies.

8. Conclusions

The main conclusions are as follows:

(1) MSWI fly ash and bottom ash are huge in quantity and have certain toxicity. Therefore, it is necessary to find suitable utilization methods to reduce land occupation and environmental pollution.

(2) The main components of MSWI fly ash and bottom ash are SiO_2, CaO, and Al_2O_3. However, compared with fly ash, bottom ash has higher SiO_2 and CaO content and lower heavy-metal content; thus, it has higher strength and less heavy-metal leaching.

(3) The main pretreatment methods are separation, solidification/stabilization, and heat treatment. Among them, the separation needs chemical reagents, but heavy metals can be extracted. Solidification/stabilization can reduce the leaching of heavy metals and improve the strength of MSWI fly ash and bottom ash. Although heat treatment has a good effect on reducing the heavy metal leaching, it needs energy consumption and waste gas treatment.

(4) MSWI fly ash is mainly used in cement concrete aggregate, ceramic, adsorbent, fertilizer, and highway engineering materials. MSWI bottom ash is mainly used in cement concrete aggregate, ceramic, landfill covering material, and highway engineering material. Among them, using fly ash and bottom ash as cement concrete aggregate has a good economic benefit, and using as ceramic raw material has a good effect on limiting heavy-metal leaching.

(5) Considering its low strength and serious leaching toxicity, MSWI fly ash is seldom used in highway engineering, especially in the top layer and subgrade. MSWI bottom ash has high strength and less heavy-metal leaching; thus, it can be used in all surface layers and has good economic and environmental benefits.

Data Availability

The data that support the findings of this study are available from the corresponding author, YC Huang, upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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