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Reuse of bottom ash and fly ash from mechanical-bed and fluidized-bed municipal incinerators in manufacturing lightweight aggregates

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ABSTRACT

This study involved the reuse of residues, including fly ash (FA) and bottom ash (BA), from municipal solid waste (MSW) incineration and reservoir sediment (RS) to make lightweight aggregates (LWAs) and to evaluate the effects of the incinerator type, material mixing ratio, and preparation conditions on the properties of the resulting aggregates. The MSW incineration ashes were mixed in three different ratios (65% BA + 15% FA, 70% BA + 10% FA, and 75% BA + 5% FA) with reservoir sediment and were sintered at temperatures of 950–1050 °C. The ash samples were obtained from an incineration plant equipped with fluidized-bed (FB) and mechanical-bed (MB) furnaces. The ash from the FB incinerator could be turned into LWAs at a relatively low temperature (1000 °C). Compressive strength measurements indicated that these aggregates were stronger than those manufactured using the ash from the MB incinerator. The BA and FA from the FB incinerator showed good chemical stabilities due to the operating conditions of the incinerator, suggesting that they are suitable for fabricating LWAs. Thus, the thermal synthesis of LWAs from mixtures of incineration residue and RS is a highly effective method for the recycling/disposal of MSW incinerator ash.

1. Introduction

Incineration technology has the advantages of reduction and stabilization and is becoming a popular and important option for treating municipal solid waste (MSW). However, solid residues are produced in significant amounts (10–15% of the total MSW volume) during the incineration process. Approximately 910,000 t of incinerator BA and 290,000 t of FA are produced daily in Taiwan [1]. BA is the non-combustible residue from MSW incineration and is used widely as a civil and construction material [2–4]. In contrast, FA is classified as a hazardous waste because of the presence of high concentrations of heavy metals and dioxins [5,6]. Although FA has limited use, subjecting it to a thermal treatment has been proposed as an environmentally stable technique for reusing it in the manufacture of building materials. MSW BA contains desirable vitrification compounds (SiO_2 and Al_2O_3), while FA contains the flux substances (i.e. a mixture of Fe_2O_3, Na_2O, MgO, K_2O, and CaO) necessary for generating high-quality lightweight aggregates (LWAs) [7–12]. Thus, several studies have explored the possibility of utilizing MSW incineration ashes for LWA production as an alternative recycling technique to landfilling.

LWAs are porous and granular materials and have the additional benefits of light weight, low water absorption, good thermal characteristics, and high durability. Accordingly, LWAs are used in architectural construction, geotechnical fills, insulation materials, and gardening. LWAs are primarily manufactured by sintering at elevated temperatures through processes including heating, vitrification, and foaming. The raw materials are first crushed and mixed with various other materials, for example clay, cement, and sand, in different proportions, and the blend is then pelletized with water and sintered at a high temperature for a short period to produce a hardened, high-porosity material [13,14]. Many studies have demonstrated that vitrification results in fixation of the heavy metals and hazardous materials present into the silicon crystals [15,16], thus reducing the risk of heavy metal leaching [17,18]. Adding the residue from MSW incineration can reduce the sintering temperature for forming LWAs [19], with the reported temperature being 1000–1200 °C.

The type of furnace used, composition of the feed waste, operational conditions, and other parameters affect the physicochemical characteristics of MSW incineration ash. The main compositions of MSW incineration ash determine its bloating properties, and hence, those of the resulting LWAs during the subsequent thermal treatment. FA from mechanical-bed (MB) MSW incinerators is considered hazardous

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because the degree of leaching of heavy metals may exceed the regulation limits; on the other hand, FA from fluidized-bed (FB) MSW incinerators is considered nonhazardous because it meets the regulation standards. FB incinerators are generally operated at lower combustion temperatures than MB incinerators, with a fluidized medium (SiO_2) being mixed uniformly in the former.

There have been numerous studies on the recycling of the MSW incineration FA generated in mechanical incinerators, which involve using it as the raw material for manufacturing LWAs [20–23]. Hwang et al. manufactured LWAs by incorporating 10–50% MSW incineration FA (mixture of scrubber ash and cyclone ash) with RS [24]. They found that MSW incineration FA can only be used as an additive and that its maximum content should be less than 30%. However, there are few reports on the feasibility of recycling BA and FA from different types of MSW incinerators by using them in the manufacture of LWAs. In an earlier study [25], we had mixed fly ashes from MB and FB incinerators with RS and used the resulting mixtures as raw materials for producing LWAs, with the maximum content of the ashes being as high as 15%. Liu et al. have also reported that the mass ratio of basic and acidic oxides can be a useful parameter for optimizing the characteristics of the thus-produced LWAs [26].

The BA from FB incinerators contains Si-Al compounds in high concentrations and can also be used in the production of LWAs to reduce the amounts of vitreous materials needed. FB incinerators allow direct reuse of the residues. However, there are not many reports on the reuse of FB BA and FA for LWA production. If BA is used for vitrification or if its viscosity is low, RS can be used as a binder to facilitate the formation of a small sphere. However, the effects of the mixing ratio of FA and BA from FB incinerators on the physicochemical properties of the produced LWAs need to be explored further.

In this study, we explored the reuse of MSW residues (containing FA and BA) from FB and MB incinerators in the manufacture of LWAs by combining with RS under thermal conditions. We also studied the influences of the composition of the MSW residues and the sintering temperature on the microstructure and properties of the LWAs produced. The results of this study should aid efforts to reuse FA and BA from different types of incinerators and provide useful information regarding the recycling and cotreatment of MSW incineration residues.

2. Materials and methods

2.1. Raw materials used

MSW incineration FA and BA samples were obtained from different incinerators, while RS from northern Taiwan was used as a binder to produce LWAs. The MB incinerator capacity was 1350 t/day, and its operational temperature was 1100 °C. The MB incinerator was equipped with a semidry scrubber (containing calcium hydroxide and activated carbon), a fabric filter, and a cyclone as the air pollution control devices (APCDs). On the other hand, the FB incinerator was operated at 850–950 °C and had a capacity of 400 t/day. It was equipped with a fabric filter as the APCD. The feeding waste from the two incinerators was nonhazardous MSW. FA was collected from APCDs and mixed thoroughly until combined well. Afterwards, the incinerator BA, FA, and RS were dried at 105 °C for 24 h.

2.2. Production of lightweight aggregates (LWAs)

LWAs were fabricated using the incineration BA, FA, and RS in the ratios listed in Table 1. The mixture was blended by hand using approximately 30% deionized water to form spherical pellets with diameters of 16 ± 1 mm. The pellets were first dried (at 105 °C for 24 h) [20], and then heated at a rate of 2 °C/min in a programmable high-temperature furnace. The collected aggregates were then sintered again at temperatures of 950–1150 °C in increments of 50 °C for 15 min. Table 2 shows the chemical compositions of the LWAs, corresponding to the different mixing ratios of the materials from the two furnaces. The inorganic components were analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-AES, ICAP 9000, Jarrell-Ash).

Table 1
Mixing proportions used in this study.

Formulation	M65	M70	M75	F65	F70	F75
Mechanical-bed bottom ash (wt%)	65	70	75	–	–	–
Mechanical-bed fly ash (wt%)	15	10	5	–	–	–
Fluidized-bed bottom ash (wt%)	–	–	–	65	70	75
Fluidized-bed fly ash (wt%)	–	–	–	15	10	5
Reservoir sediment (wt%)	20	20	20	20	20	20

Table 2
Chemical compositions of various LWA mixtures before sintering.

Reference	SiO_2 (%)	Al_2O_3 (%)	Fluxing[a] (%)	CaO (%)	Fe_2O_3 (%)
M65	27.4	9.7	40.1	53.6	13.6
M70	28.1	9.8	40.4	52.7	14.3
M75	28.7	10.0	40.7	51.8	14.9
F65	29.8	10.2	37.2	41.7	18.0
F70	29.9	9.8	38.6	41.7	18.9
F75	30.0	9.4	40.1	41.8	19.8

[a] Fluxing compounds: Fe_2O_3, CaO, MgO, K_2O, and Na_2O.

2.3. Characterization of LWAs

The characteristics of the manufactured LWAs were evaluated. Samples were tested six or more times and the measured values were averaged. The properties of the LWAs (Table 3) were evaluated by mechanical and physical measurements.

2.4. Leaching properties of LWAs

The toxicity characteristic leaching procedure (TCLP) is a batch test developed by the United States Environmental Protection Agency (USEPA) to assess the leachability of toxic metals from wastes [27,28]. The leachability of the fabricated LWAs was determined according to the USEPA Method 1311 using an acetic acid solution (pH 2.88) as the leaching fluid. Each leaching phial comprised100 mL of TCLP extraction fluid and 5 g of solid, and the leaching vials were rotated end-over-end at 30 ± 2 rpm for 18 h. The leachate was then filtrated with a 0.45 μm membrane filter. The concentrations of all the metals in the leachate were analytically derived via ICP-AES.

3. Results and discussion

3.1. Effect of synthesis parameter on LWAs morphologies

The appearances of the LWA samples produced using BA and FA from the FB and MB incinerators and the RS in different ratios are shown in Fig. 1. The color of the fired LWAs of series M was light brown

Table 3
Physical properties of the fabricated LWAs and the evaluation methods/equations used.

Properties	
Morphology	Observe out / in layer directly
Bloating index	Measure by using a pachymeter
Density	UNE-EN-1097-6
Water absorption	UNE-EN-1097-6
Loss of ignition	NIEA R216.02C
Compressive strength	$\rho=2.8p/\pi x^2$, x: distance between the plates (cm), p: pressure recorded to crush the pellets (N)