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

Kui-Hao Chuanga,⁎, Chien-Hsing Lub, Jyh-Cherng Chenb, Ming-Yen Weyc

a Department of Safety Health and Environmental Engineering, Central Taiwan University of Science and Technology, Taichung 406, Taiwan, ROC
b Department of Environmental Engineering, National Chung Hsing University, Taichung 402, Taiwan, ROC
c Department of Safety Health and Environmental Engineering, Feng Chia University, Taichung 407, Taiwan, ROC

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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 (SiO2 and Al2O3), while FA contains the flux substances (i.e. a mixture of Fe2O3, Na2O, MgO, K2O, 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 landfills.

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.
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 inferences 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

<table>
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<tr>
<th>Formulation</th>
<th>M65</th>
<th>M70</th>
<th>M75</th>
<th>F65</th>
<th>F70</th>
<th>F75</th>
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<tr>
<td>Mechanical-bed bottom ash (wt%)</td>
<td>65</td>
<td>70</td>
<td>75</td>
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<td>–</td>
<td>–</td>
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<tr>
<td>Mechanical-bed fly ash (wt%)</td>
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<td>10</td>
<td>5</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Fluidized-bed bottom ash (wt%)</td>
<td>–</td>
<td>–</td>
<td>65</td>
<td>70</td>
<td>75</td>
<td>–</td>
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<tr>
<td>Fluidized-bed fly ash (wt%)</td>
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<td>–</td>
<td>15</td>
<td>10</td>
<td>5</td>
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### Table 2

<table>
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<tr>
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<th>Al$_2$O$_3$ (%)</th>
<th>CaO (%)</th>
<th>Fe$_2$O$_3$ (%)</th>
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<td>F75</td>
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*Fluxing compounds: Fe$_2$O$_3$, CaO, MgO, K$_2$O, and Na$_2$O.

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 pial comprised 100 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 filtered 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.
when the sintering temperature was 1150 °C. The rest of the residues were white with porous surfaces and released white powder after sintering. This indicated that the cohesiveness of the LWAs produced using the MB residues was low when sintered below 1100 °C. The surface color of the LWAs of series F gradually became deep brown with increasing sintering temperature, and their surfaces became denser than those of the surfaces of the series M LWAs. The sintered materials formed using the FB residues softened and adhered to the gasket when sintered at a high temperature (1150 °C) and thus remained spherical.

3.2. Properties of sintered LWAs

Bloating is the main process by which sintered aggregates turn into LWAs. Hence, the chemical composition of the aggregates and the sintering temperature are the primary factors controlling this process [20]. In this study, we compared the differences between blended mixtures of FA and BA from the two types of furnaces, while increasing the amount of added residue to 80%. The results indicate an increased applicability of FA and BA from different furnaces in the manufacturing of LWAs, based on the fundamental characteristics of the fabricated LWAs. Fig. 2 shows the bloating indices of the LWAs produced using the residuals from the MB and FB incinerators at sintering temperatures of 950–1150 °C. For all the samples, no bloating occurred at 950 °C. The LWAs from series F showed more volume expansion for the same ratio of BA and FA than that obtained for the LWAs from series M at a sintering rate of 1000 °C/15 min. The LWAs produced from MB ashes showed better bloating properties because the temperature was increased to 1050 °C. Sample F65, which was formed using 65% FB BA, 15% FB FA, and 20% RS, showed the highest bloating index at 1100 °C. This sample had a high content of glassy materials and a sufficient amount of fluxing, which allowed for the generation and entrapment of gas bubbles within the solid matrix. The Fe₂O₃ in the foaming agent decomposed into Fe₃O₄, releasing O₂ during sintering and leading to a significant increase in the LWAs volume. When heated at 1150 °C, the LWAs produced using different ratios of MB BA and FA showed volume contraction ratios ranging from −6.7% to −10.0%. Further, LWAs could not be produced using the FB ashes at this temperature because of the phenomena of bloating and collapse.

Fig. 3 shows the changes in the densities of LWAs formed using MB and FB residues in different ratios. The bulk densities (0.9–2.0 g/cm³) were within the EN 13055-1:2005 limits. The densities of aggregates
formed using the FB incinerator residues decreased with increasing sintering temperature. The incorporation of 80% FB residue with the RS resulted in volume expansion, producing a minimum bulk density of 0.9 g/cm³ for sample F65, which contained 65% BA and 15% FA and was sintered at 1100 °C. LWAs could not be formed from the FB incinerator residues at a temperature of 1150 °C because the resulting aggregates were very soft. Thus, no specimens were analyzed in this case. For a firing temperature of 1100 °C, the bulk density of LWAs formed from MB incinerator residues also decreased with increasing temperature. However, shrinkage occurred when the temperature reached 1150 °C, causing an increase in density. Overall, the density of the aggregates formed using MB residues was lower than that of the aggregates formed using FB residues. However, the effects of the materials used were evaluated further through parameter tests.

Cheeseman and Virdi have stated that the LWAs should possess low water absorption (WA) rates [29]. LWAs with low WA rate have minimum maintenance requirements and show high durability [30]. The recommended WA rate is generally less than 20%. The WA capacities of the fabricated LWAs are shown in Fig. 4; these values were measured using LWA samples dried for 24 h. The WA rates of the LWAs produced using the residues from the FB incinerator were in agreement with the suggested values, while those of the LWAs produced using the MB incinerator residues were significantly higher, when sintering was performed at temperatures below 1100 °C. The presence of high concentrations of SiO₂ in the FB residues resulted in ready vitrification, which limited water absorption [31]. On the other hand, the WA rate was high for the MB residues probably owing to the presence of particles with open pores (Fig. 1). Moreover, the MB residues had relatively higher Ca content, which also increased water absorption. Further, the WA rate of the LWAs produced using the MB residues decreased upon increasing the sintering temperature to 1150 °C, because vitrification was promoted at higher temperatures [32,33]. The benefits of adding FB FA during the manufacturing of LWAs, which include a decrease in the weight as well as energy savings owing to the relatively lower sintering temperature (1100 °C), were clearly evident in the case of the series F LWAs.

The difference in the sample weight before and after sintering is defined as the loss of ignition (LOI). The LOI values of the different LWA samples are shown in Fig. 5. The aggregates produced using the MB and FB residues showed weight losses of 12.4–15.4% and 1.5–4.0%, respectively. These results indicated that the residue loss of the LWAs manufactured from the FB residues were similar, irrespective of the addition ratio and sintering temperature used. The residues from the FB incinerator contained large amounts of nonvolatile substances, such as Si, which resulted in the LOI being lower than that for the LWAs made from MB incinerator residues. The significant difference in the LOI values of the samples was based on the residues from the two incinerators. Therefore, quenching and tempering (i.e. addition of Si and Al) had to be performed for the residues obtained from the MB incinerator prior to sintering. On the other hand, the residues from the FB incinerator could be used directly without any pretreatment. This reduced the material and production costs associated with the quenching and tempering processes.

The compressive strength of structural and nonstructural LWAs is a suitable index for evaluating their usability once they meet the physical and chemical conditions listed in the reuse standards [34,35]. Fig. 6 shows that the compressive strength of sample F70 increased as sintering temperature was raised. Further, the compressive resistance increased upon increasing the amount of FB BA used, as determined after sintering at 950 °C and 1000 °C. Samples F65 and F75 had the highest compressive strengths, of 42 and 57 MPa, respectively, at 1050 °C. The compressive strength of the samples produced using the MB incinerator ash remained 10 MPa when sintering was performed at temperatures lower than 1100 °C. Nevertheless, for a sintering temperature of 1150 °C, the compressive strength of the fabricated LWAs was measured to be 42–50 MPa. These results suggested that low temperatures (< 1100 °C) are not appropriate for the sintering of the residues from MB incinerators. High-compressive-strength LWAs could only be produced at high temperatures (1150 °C). However, this also resulted in increased bulk density, which is a disadvantage with respect to the use of MB residues in LWAs.

Since the LWAs based on samples F70 and F75 sintered at 1050 °C exhibited high compressive strengths, the chemical compositions of these LWAs were investigated in greater detail (Table 4). The LWAs
Based on MB residues exhibited higher CaO contents. Thus, the higher WA rates of these LWAs could be attributed to their higher Ca contents than the suggested value; this also accounted for their minimum compressive strengths. The LWAs based on FB ash had higher SiO2 and Fe2O3 contents, which enhanced their compressive strengths. These observations explain why LWAs based on FB ash showed better physical properties, such as bloating index, bulk density, WA, LOI, and compressive strength, than those of LWAs based on MB ash.

### 3.3. Evaluation of stabilization effect

To confirm whether the contamination is transferred from solid phase to liquid streams, we analyzed the leaching behaviors of the incinerated FA and BA samples to determine the leaching of toxic substances.

#### Table 4

<table>
<thead>
<tr>
<th>Item</th>
<th>M65</th>
<th>M70</th>
<th>M75</th>
<th>F65</th>
<th>F70</th>
<th>F75</th>
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<td>9.6</td>
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<tr>
<td>CaO (%)</td>
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<td>5.7</td>
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<tr>
<td>Fe2O3 (%)</td>
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<td>9.0</td>
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<td>Na2O (%)</td>
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<td>SO3 (%)</td>
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<tr>
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<td>TiO2 (%)</td>
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<td>1.9</td>
<td>0.6</td>
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</tbody>
</table>

Fig. 6. Compressive strengths of LWA samples at different sintering temperatures.

References

[16] A. Bloise, M. Catalano, E. Barrese, A.F. Guisari, N. Bursi Gandolfi, S. Capella, experimental results showed that all the LWAs produced under the conditions investigated herein agreed well with the leaching standards. The flux and foaming agents from the MB incinerator had higher proportion of calcium (51.8–53.6%) than the agent from the FB incinerator, because a greater amount of calcium hydroxide was added to the APCDs in the MB incinerator as an acid gas adsorbent. Compared to the MB incinerator, the FB incinerator allows for significant energy savings, because its residues can be used to produce LWAs with higher compressive strengths at lower temperatures. These LWAs also exhibited lower LOI and WA values than the LWAs produced using MB incinerator residues. In addition, the properties of the former products agreed with the recommended standards and the suggested values. Based on an analysis of the chemical compositions of the sintered LWAs, it was concluded that those manufactured using FA and BA obtained from the FB incinerator retained greater amounts of SiO2 and Fe2O3, resulting in better physical properties of the LWAs. On the other hand, the LWAs produced from the ash of the MB incinerator contained more CaO, which was the most likely reason for their low compressive strength and high WA rate. Thus, the sintering temperature and chemical composition of LWAs are the primary factors affecting their physicochemical properties. Since silica sand was added to the FB incinerator as a medium, the silicon contents of the incinerated FA and BA were relatively high. In addition, the operational mode of the FB incinerator resulted in even burning, leading to reduced heavy metal leaching from the corresponding LWAs. Therefore, the BA and FA from these incinerators can be reused directly without any pretreatment.

Acknowledgements

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