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The Application of Treated Bottom Ash in Mortar as Cement Replacement

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Abstract

The fine municipal solid waste incineration (MSWI) bottom ash (0-2 mm) is pre-treated and used as cement replacement to investigate its effect on the properties of mortar. The chemical and physical properties of the treated bottom ash are characterized, and the metallic aluminum content is determined. The treated bottom ash is used in mortar as cement replacement by 30% wt. The flowability of the fresh mortar with treated bottom ash is determined, and the flexural and compressive strengths of the mortar after different curing times are measured. Finally, the influential factors of the application of treated bottom ash as binder on the properties of mortar are summarized.

Keywords: MSWI bottom ash, treatments, cement replacement, mortar

1. INTRODUCTION

The incineration of municipal solid waste reduces the mass and volume of waste, and decreases the landfilling of solid waste. However, the increasing amount of incineration residues and tax for landfilling promote alternative applications for them [1]. The incineration bottom ash mainly contains stone, bricks, glass, ferrous and non-ferrous matter, as well as unburned material (such as plastic, paper, etc.). Research studies have been done on the potential application of incineration bottom ash in building materials, such as raw material for cement [2,3] or aggregate in concrete [4,5]. Furthermore, there are also studies addressing the pre-treatment of bottom ash to upgrade its properties to make it more suitable to be used in building materials, for instance Cheng [6] investigated the effect of treated bottom ash under different quenching conditions on the properties of blended cement mortar. Pecqueur et al. [7] investigated the properties of the cement treated bottom ash, and addressed the swelling caused by metallic aluminum content. Cioffi et al. [8] used the MSWI bottom ash to produce artificial aggregate which was used in concrete. Lin et al. [9] treated the MSWI bottom ash at 1400 ˚C to produce slag which was used as pozzolanic material in cement. With a continuously increasing consumption of raw materials and increasing environmental awareness, it is encouraging to find ways of using the waste materials as secondary or raw materials in the construction filed.

In this study, the MSWI bottom ash from a Dutch waste-to-energy plant is investigated to be used as a cement replacement in mortar. The bottom ash particles under 2 mm are chosen, and thermal treatment and milling are used as treatments to upgrade the quality of the bottom ash. The properties of bottom ash after treatments are evaluated, and 30% wt. replacement of cement by the treated bottom ash is used. The properties of mortars in fresh and hardened states are measured to study the influential factors of the treated bottom ash.

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2. METHODS AND MATERIALS

2.1. Material

The MSWI bottom ash provided by the waste-to-energy plant (Attero, the Netherlands) is firstly dried, and the fraction of the dried bottom ash particles under 2 mm is selected to be investigated in this study. Thermal treatments and milling are used to upgrade the quality of bottom ash and the differences between the treatments are the temperature and the order of milling and thermal treatment. Four treatments are performed on the bottom ash: method 1 is mill the raw bottom ash using a planetary ball mill to reduce its particle size, and the sample is labelled as BA. Method 2 is thermal treatment on the raw bottom ash particles at 550 ˚C, and then mill the treated bottom ash, the sample is labelled as 5T. Method 3 is firstly mill the bottom ash particles and then the milled bottom ash is thermal treated at 550 ˚C and 750 ˚C in the oven before use, they are labelled as M5T and M7T; Method 4 is firstly thermal treat the bottom ash particles in the oven at 550 ˚C, and sieving the particles under 63 μm after milling, which is labelled as 5T/63. These treated bottom ashes are used as cement replacement in mortar, the binder used is Ordinary Portland Cement CEM I 52.5 R, and sand with a particle size of 0-2 mm is used.

2.2. Experimental procedure and tests

The chemical composition of the treated bottom ash and CEM are determined by X-ray fluorescence (XRF). The helium pycnometer (Micromeritics, AccuPyc Ⅱ 1340) is used to measure the density of the material. The treated bottom ash is mixed with sodium hydroxide solution; the chemical reaction between them is described as:

$$2Al + 2NaOH + 2H_2O \rightarrow 2NaAlO_2 + 3H_2 \uparrow \quad (1)$$

The gas released is collected using a setup, and the amount of metallic aluminum is then calculated according to the ideal gas law. The treated bottom ash is mixed in mortar with 30% replacement of cement by weight, and the mortar sample is mixed according to EN 196-1. The flowability of the fresh mixed mortar is determined using the flow table test according to EN 1015-3. After mixing, the mortar is cast into prism molds (160 mm × 40 mm × 40 mm). After 24 hours, they are demoded and cured in water at room temperature. The compressive and flexural strengths of mortar samples at different curing ages are tested using an automatic strength test machine (AUTOMAX 5, CONTROLS).

3. RESULTS

3.1. Material properties

The main chemical compositions of the used cement and treated bottom ash are shown in Table 1. The treated bottom ash contain higher amount of SiO_2, Al_2O_3, Fe_2O_3 than cement, which is due to the quartz particles, glass matter, ferrous and non-ferrous metals in the bottom ash. The bottom ash also contains higher amount of chloride and sulphate, which mainly come from household residues and industrial wastes. Sample 5T/63 has a lower SiO_2 content and higher CaO, chloride and sulphate than other treated bottom ashes, this may be due to the higher absorption of element of the dust-like layer on the coarse bottom ash particles which is removed during milling. The chemical composition of treated bottom ash indicates its potential to be used as pozzolanic martial in cement based systems [10].

Table 1 Chemical composition of Portland cement and treated bottom ash

Elements (%wt.)	CEM I 52.5 R	BA	5T	M5T	M7T	5T/63
SiO_2	17.39	39.27	37.26	42.10	41.81	26.70
CaO	66.05	21.88	22.56	20.23	20.32	29.96
Al_2O_3	3.88	10.07	10.33	9.80	9.97	11.80
Fe_2O_3	3.64	12.73	12.76	12.19	12.27	9.83
Cl	0.02	0.76	0.77	0.66	0.57	1.11
SO3	4.04	5.68	6.11	5.44	5.31	9.24

3.2. Density

The specific densities of cement and treated bottom ashes are shown in Figure 1. It is shown that the bottom ash has lower density than OPC. The density of bottom ash after thermal treatment increases, which may be explained as the burning of the organic matter. Thermal treatment after milling and higher temperature are more efficient in reducing organic matter. Sample 5T/63 has lower density compared with other treated samples; this may be due to a lower iron content which is sieved out during treatment (Table 1 and Figure 2).

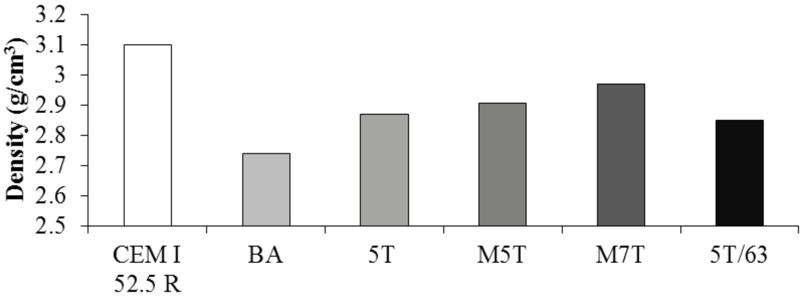

Figure 1. The specific densities of cement and bottom ash samples

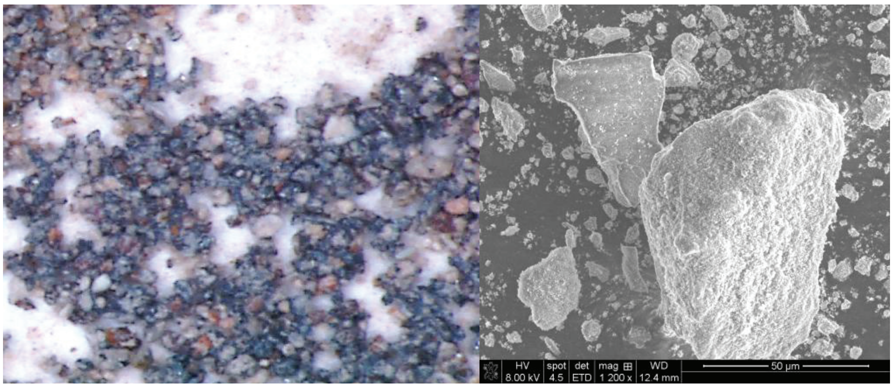

Figure 2. Iron particles picked out by magnet (left) from treated bottom ash particles above 180 µm (mainly the black particles) and treated bottom ash particles (right)

3.3. Metallic aluminum content

The amount of metallic aluminum in bottom ash samples is determined and the results are shown in Table 2. The value is calculated following the reactive stoichiometry as shown in Eq.1. It can be noticed that the metallic aluminum content did not change significantly after the thermal treatment. This may be explained by the fact that the oxidation of metallic aluminum needs higher temperature and the reduction of organic matter. Sample 5T/63 contains less metallic aluminum which can be explained by the sieving out of metallic aluminum during treatment.

Table 2. Metallic aluminium content of bottom ash samples

Sample	BA	5T	M7T	5T/63
Al (% wt.)	0.44	0.48	0.46	<0.2

3.4. Flowability of fresh mortar

The flowability of the fresh mixed mortar is determined and the results are presented in Figure 3. It can be noticed that the replacement of cement with treated bottom ash slightly influences the flowability of the mortars. The mortar with BA has higher flowability than reference, while mortar with 5T has similar flowability with reference. This can be due to the fact that the duration of the milling is not long enough to reduce the bottom ash particle size as fine as cement; therefore the flowability of mortar with BA is larger than reference. As the thermal treatment reduce the organic matters in bottom ash which has higher water absorption, therefore the mortar with thermal treated bottom ashes has lower workability than that of mortar with BA. For mortar with 5T/63, the reduction of the workability is the highest; this may due to the finer particle size compared with the other treated bottom ashes. The influence of the workability can also be due to the particle shape of the treated bottom ashes (Figure 2-right), which are irregular and porous [11].

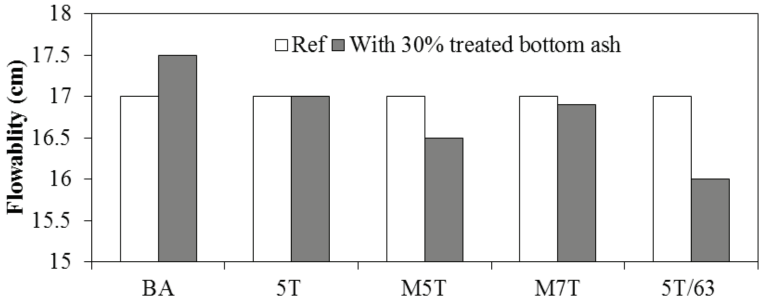

Figure 3. Flowability of mortars with bottom ash additions

3.5. Strength

The flexural and compressive strengths of mortar with treated bottom ash after different curing ages are tested. The strengths of the reference after 1, 3 7 and 28 days are tested in MPa (Table 3), the strengths of the mortar with treated bottom ash at different curing days are shown as the percentage of the reference in Figure 4 and Figure 5.

Table 3. The flexural and compressive strength of reference (MPa)

	1 day	3 day	7 day	28 day
Flexural strength	5.93	6.89	7.47	8.1
Compressive strength	31.69	41.5	48.03	59.75

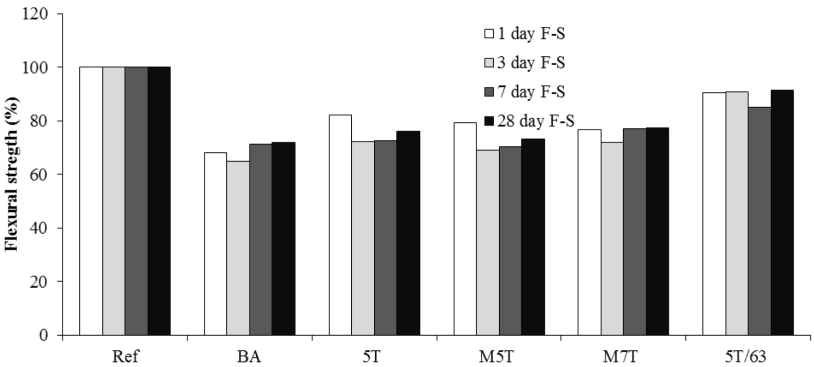

Figure 4. Flexural strength of mortars

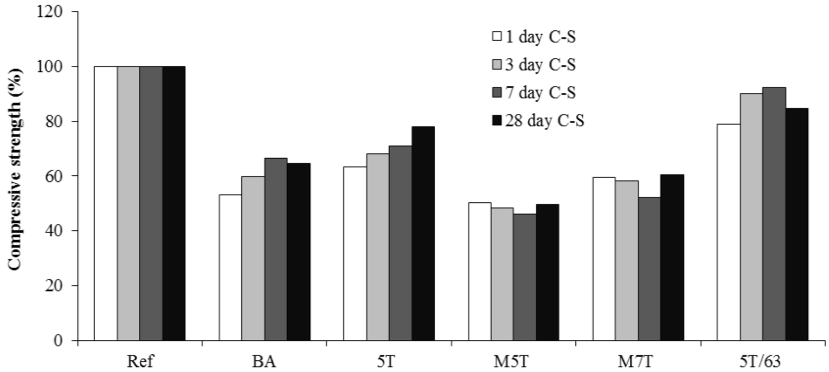

Figure 5. Compressive strength of mortars

As can be noticed in Figure 4 and Figure 5, utilization of treated bottom ashes as cement replacement decreases the strength of mortars at all curing ages for all the mixes. However the decrease of the flexural strength is lower than that of compressive strength for all the mixes. For mortar with BA, the decrease of strengths at all curing age is very high; this could be due to the high content of organic matter and lower pozzolanic properties of raw bottom ash. For mortar with 5T, the strengths decrease at all curing age is less than that of mortar with BA, which is because of the burning of organic matter, resulting in higher pozzolanic properties than BA. For mortar with M5T and M7T, the strength loss is the highest in all mixes, and mortar with M7T has higher strength than mortar with M5T after 28 days. This could be due to the fact that the oxidation of metallic aluminium after treatment prolongs the generation of gas which contribute the inner-crack in mortar (Figure 6); subsequently the strength of the mortar is significantly influenced at all curing age. As the high temperature is more efficient for the reduction of organic content and the decomposition of calcite, the treated bottom ash sample M7T has higher pozzolanic property; therefore the mortar with M7T has higher strength than mortar with M5T.

Figure 6. The fracture surface of mortars (reference and M5T)

For mortar with 5T/63, the decrease of strength is the lowest compared to all other mixes. This can be explained as follows: firstly, the chemical compositions of 5T/63 show it contains more CaO and less SiO_2, and this compositions is closer to that of cement than other samples. Secondly, it contains less metallic aluminum, and the effect of inner-crack on the strength is significantly reduced, so after 28 days of curing the decrease of the strength was not significant. Therefore, it can be noticed that the metallic aluminum content in bottom ash strongly affect the strength of mortars.

4. CONCLUSION

In this study, the treated bottom ash is used to replace 30% wt. of cement in mortar. The properties of mortars in fresh and hardened states are investigated, and the influential factors are studied. The following conclusion can be drawn:

1) The thermal treatment reduces the organic matter, and increases the chemical activity of bottom ash. The treated bottom ash contains less CaO and higher amount of SiO_2, Fe_2O_3 and Al_2O_3than OPC. The density of the treated bottom ash is slightly increased; nevertheless the densities of all the treated bottom ash are less than OPC. The order of milling and thermal treatment affects the oxidation of metallic aluminum which later influences the generation of hydrogen.

2) The replacement of cement by treated bottom ash has a slight influence on the flowability of mortar, and the particle shape and porosity of bottom ash contribute to it.

3) The flexural and compressive strengths of all the mortars with treated bottom ash decrease at all curing ages, and the decrease of the flexural strength is lower than compressive strength. The mortars with M5T and M7T have higher strength loses, because of the inner-crack caused by the generation of hydrogen. The mortar with 5T/63 reaches higher strengths compared with other mixes with treated bottom ashes, with 15% and 8% decrease after 28 days curing for compressive and flexural strength, respectively.

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