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POTENTIAL APPLICATION OF MSWI BOTTOM ASH AS SUBSTITUTE MATERIAL IN PORTLAND CEMENT CONCRETE: FILLER OR BINDER

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Abstract

In recent years, the rapid industrialization and urbanization led to the explosive growth of municipal solid waste incineration (MSWI) bottom ashes (BA) production. However, most of them are directly landfilled, which not only brings environmental burden but also results in loss of potential resources. Present researches have proved that MSWI BA could be utilized as a replacement in Portland cement concrete. However, several drawbacks such as volume expansion, leaching behaviour, and relatively lower strength have been reported. In this study, as-received BA was pretreated to remove the metallic aluminium which is responsible for the hydrogen-induced expansion when blended in OPC concretes. Subsequently, the treated BA samples were used as a substitution for cement at the replacement level of 10%. Micronized sand (M300) was selected as reference materials to investigate the role of treated BA in blended cement system, either as filler or binder material. In the experimental program, the hydration process of different mixtures was monitored by isothermal calorimeter and hydration products were determined by X-ray diffraction (XRD) and Thermalgravimetric analysis (TGA). Results showed that the pretreatment effectively removed the metallic aluminum in BA and no severe expansion or strength decrement were detected. The treated BA showed limited reactivity comparing with Portland cement, however, it still worked better than micronized sand as a filler substitution.

1. INTRODUCTION

According to the survey performed by World Bank in 2012 [1], the amount of municipal solid waste (MSW), one of the most typical products of urban lifestyle [2], would be doubled by 2025 (2.2 billion tons per year). The most widely used waste to energy (WtE) process is to

recover the energy in MSW by generating steam and electricity directly through incineration [3, 4]. However, the most important by-product of MSW incineration (MSWI), namely bottom ash (BA), is mainly landfilled at present.

As a result of the increasing landfilling cost and the awareness of resource recovery, MSWI BA is now gaining more attention and regarded as an underutilized material [5]. However, MSWI BA is seldom used directly as a raw material in the industry due to its porous nature and high pollutant content. The primary issue is the leaching problem corresponding to the heavy metal substances and harmful salts in MSWI BA [6-11], which brings a great environmental impact. Numerous studies have been carried out regarding the characterization and potential utilization of MSWI BA in the industry. Several methods of treatment on BA have been proposed to meet the leaching requirement, such as weathering, chemical carbonation and physical stabilization [12].

In more recent years, studies have been carried out to investigate the potential application of MSWI BA. It has been proved that MSWI BA could be used in ordinary Portland cement (OPC) concrete, either as aggregate/filler [13, 14] or cement [15, 16] substitution. However, the application of MSWI BA is quite limited since several significant drawbacks have been frequently reported when used in concrete. For instance, the highly porous and irregular morphology of BA particles [17-20] has been detected, which makes BA easily crushed when used as load-bearing elements. Meanwhile, the relatively low reactivity of MSWI BA has been reported as well, and the addition of BA into concrete resulted in not only the retardation of the hydration process [15, 21] but also the decrement in compressive strength [21-23]. Furthermore, the most undesired issue is the expansion and swelling in concrete structures caused by the addition of MSWI BA. The hydrogen bubbles generated by the dissolution of metallic aluminum content in BA in the concrete mixture was identified as the main cause of the expansion and reduction of strength [14, 16, 22].

According to the present literature, a proper treatment method to improve the properties of MSWI BA is still in scarce before it could be properly used as a substitute material in Portland cement concrete. In addition, the studies corresponding to the hydration properties should be conducted as well to reveal the effect of treated BA samples on the hydration process.

In this study, both chemical and mechanical treatments were performed to reduce the metallic aluminum content in BA samples, followed by a thermal treatment to improve the reactivity of BA. Treated BA samples were then characterized and blended into cement paste to evaluate the effectiveness of different treatment methods. Meanwhile, the hydration process of pastes was measured by the isothermal calorimeter, and the hydration products were detected by XRD and TG analysis.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1. Materials and pretreatment

The MSWI BA used in this research with a particle size of 0-2 mm was provided by a waste-to-energy (Heros Sluiskil B.V.) in the Netherlands. BA was water quenched and underwent a weathering process. Afterward, proper treatment was performed as well to stabilize the leachable substances within the incineration plant. In this research, different types of pre-treatment were conducted to improve the properties of as-received BA. Details of the treating procedures to derive different types of BA samples are given as follows:

- CBA: BA samples were immersed in 1M sodium hydroxide solution with a solid to liquid ratio of 0.1 for 5 days. Subsequently, the BA particles were washed with running water in vacuum filtration and dried at 105°C until a constant mass in a ventilated oven. Finally, an extra grinding process was performed to grind BA into fine powders and control the particle size distribution. The BA derived is labelled as CBA.
- MBA: BA samples were ground in Retsch PM100 planetary ball miller at 250 rpm for 30 minutes so that the metallic aluminum with good ductility could be ground into metal plates and easily sieved out. Afterward, the powder in the grinding jar was collected and the finer fraction was separated with a 63 µm sieve and labelled as MBA.
- MTBA: MBA was thermally activated in a ventilated furnace at 1000 °C for 1 hour and then cooled down to room temperature to generate new reactive phases and remove unburnt organic matters. The sample derived was labelled as MTBA.

CEM I 42.5N Portland cement from ENCI B.V. the Netherlands was selected as the fundamental cementitious material. Besides, micronized silica sand (M300, pure sand with no reactivity) with a similar particle size distribution as CEM I 42.5N cement was used as reference materials for filler substitution.

2.2. Material characterization

The characterization of BA samples was conducted both before and after each type of treatment. The chemical composition was determined by X-ray fluorescence (XRF). Metallic aluminum content was measured by a dissolving test with alkaline solution as described in [24]. The mineralogical composition of BA was checked by X-ray diffraction (XRD).

2.3. Hydration process

The effect of different types of BA on the cement hydration process was evaluated on paste levels by replacing 10% cement powder with treated BA samples in the cement pastes. The water to cement ratio was kept at 0.5 in each group.

The heat evolution in different pastes was monitored by isothermal calorimeter (TAM-Air-314 thermometric isothermal conduction calorimeter). Meanwhile, the cement pastes containing different BA samples were cast into 20 mm cubic specimens and cured in ambient conditions (room temperature, 95% RH). At the age of 28-day, the specimens were crushed into smaller pieces, and hydration process was terminated by immersing crushed specimens in anhydrous ethanol for 24 hours. Subsequently, the specimens were dried in a vacuum chamber and milled into fine powders. The mineralogical phases in 28-day hydration products were detected by XRD. Thermalgravimetric analysis (TGA) was performed as well to estimate the amount of main hydration products, namely portlandite (CH) and non-evaporable water. The mass percentage of portlandite and non-evaporable water in hardened paste powders was calculated according to [25].

3. RESULTS AND DISCUSSION

3.1. Characterization of BA samples

BA samples were characterized both before and after pre-treatment to reveal the effect of different methods on the properties of BA.

Particle size distribution curves of reference and substitute materials used in this research measured by laser diffraction are given in **Figure 1**. An extra grinding process was performed

on treated BA samples to keep the particle size distribution at the same level as the reference materials.

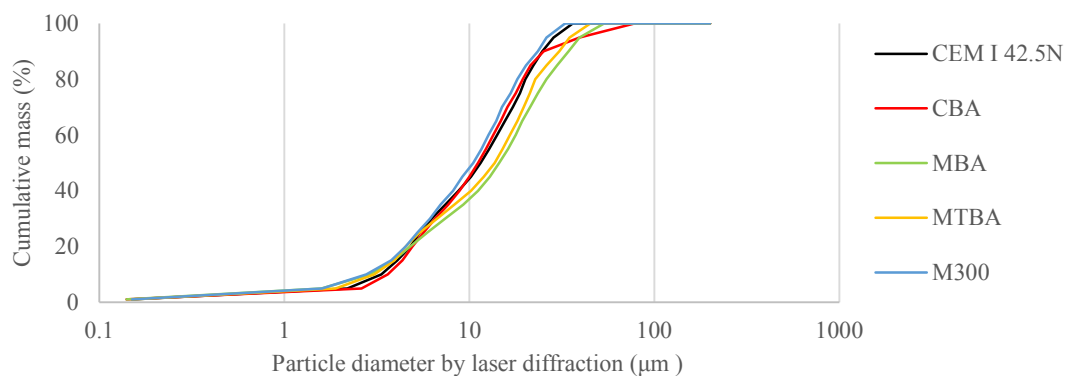


Figure 1: Particle size distribution of reference and substitute materials

As shown in **Figure 2**, the mineralogical compositions of BA samples were detected by XRD. As received BA mainly consists of crystalline phases such as quartz, calcite, magnetite, etc. No significant difference was observed in CBA and MBA. In MTBA, however, much more amorphous phases were detected between 20° and 80° comparing to the narrow peaks referring to crystalline phases in BA, CBA, and MBA. Peaks representing calcite (CaCO_3) vanished after thermal treatment which is due to the decomposition of calcite at high temperature.

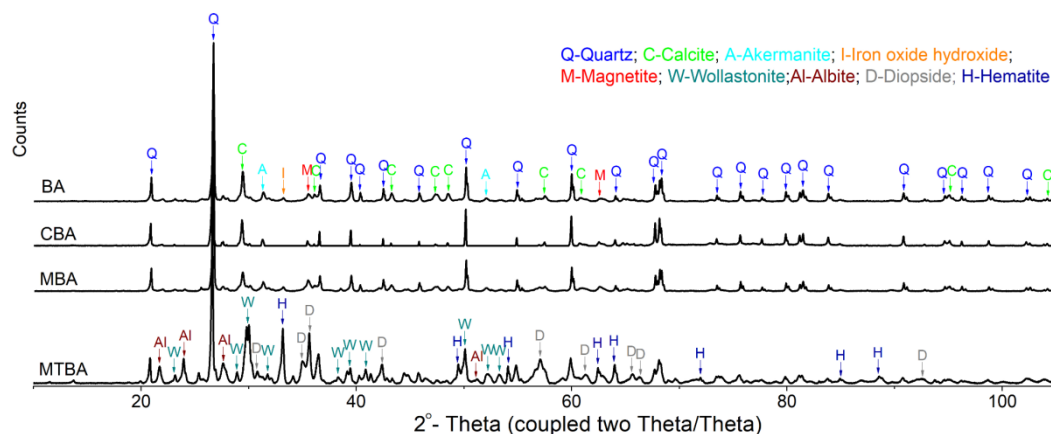


Figure 2: XRD diffractograms of as-received BA and treated BA

The chemical composition of cement and different types of BA samples determined by XRF are given in **Table 1**. Comparing to the reference Portland cement, all BA samples contain much lower content of CaO while the SiO_2 , Fe_2O_3 , Al_2O_3 and MgO are higher than that in cement. All treatments performed in this study did not result in significant changes in the chemical composition of BA. The metallic aluminum content are shown in **Table 1**. The chemical treatment and mechanical treatment effectively reduced the metallic aluminum content in BA by 95% and 84% respectively. Thermal treatment further removed the metallic aluminum by accelerating the oxidation of fine powers at high temperature.

Table 1: Chemical composition of reference cement, as-received BA and treated BA

Chemical composition (wt. %)	CEM I 42.5N	As-received BA	CBA	MBA	MTBA
CaO	64.99	22.39	17.40	18.34	18.70
SiO ₂	17.11	48.44	49.82	50.40	43.67
Fe ₂ O ₃	3.59	12.29	10.58	12.94	13.62
Al ₂ O ₃	3.80	11.66	10.20	9.84	10.08
MgO	1.56	2.47	2.52	2.21	2.40
Na ₂ O	0	0.34	2.96	0.56	0.92
K ₂ O	0.16	0.94	0.79	0.82	0.82
CuO	0.02	0.62	0.52	0.48	0.48
ZnO	0.15	0.90	1.40	0.75	0.77
P ₂ O ₅	0.63	0.84	0.59	0.67	0.74
TiO ₂	0.27	1.30	1.19	1.12	1.20
Cl	0.02	0.16	0.13	0.12	0.03
SO ₃	3.96	1.40	0.36	0.86	0.84
other	2.01	1.02	1.54	0.89	0.96
Metallic aluminum	n.m.	0.80±0.03	0.04±0.03	0.13±0.03	0.06±0.03
n.m.=not measured					

3.2. Hydration properties

Heat flow and cumulative heat curves of different pastes are displayed in **Figure 3**. The paste with CBA was not measured since reactive phases might be already dissolved by chemical treatment.

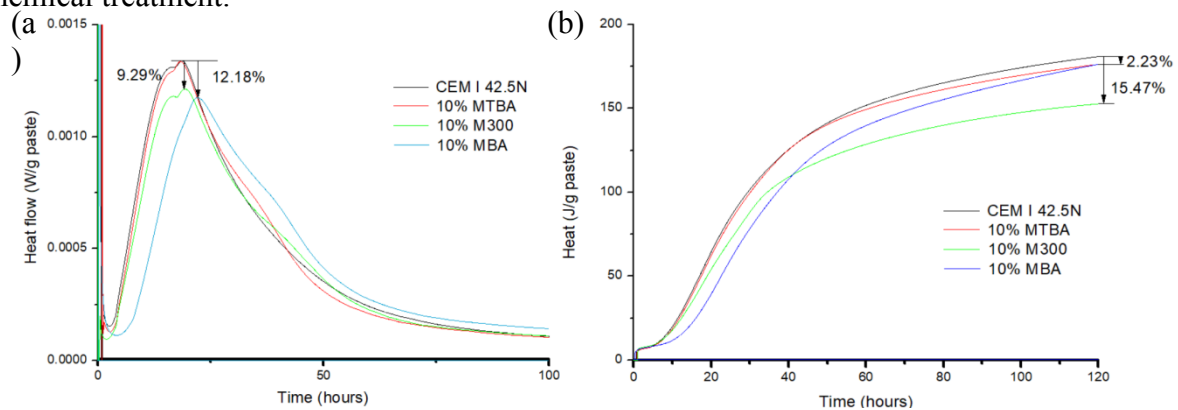


Figure 3: Heat evaluation of paste with treated BA samples. (a) Heat flow (b) Cumulative heat

As shown in **Figure 3 (a)**, there is no significant difference between the maximum heat flow of pure cement and 10% MTBA. However, the maximum heat flow of MBA and M300 decreased by 12.18% and 9.29% respectively. Meanwhile, a remarkable delay of the peak value is observed in the 10% MBA group and the maximum rate of heat release is even lower than 10% M300, which proves that the addition of MBA retarded the early stage hydration. In cumulative heat curve (**Figure 3 (b)**), cement paste with 10% MBA exhibited relatively slow early-stage heat development that the cumulative heat before 40 hours was even lower than

that of 10% M300. However, a reversal occurred at around 40 hours, and after that, the cumulative heat of 10% MBA became higher than that of 10% M300. Therefore, the thermal treatment mainly accelerates the early-stage hydration process.

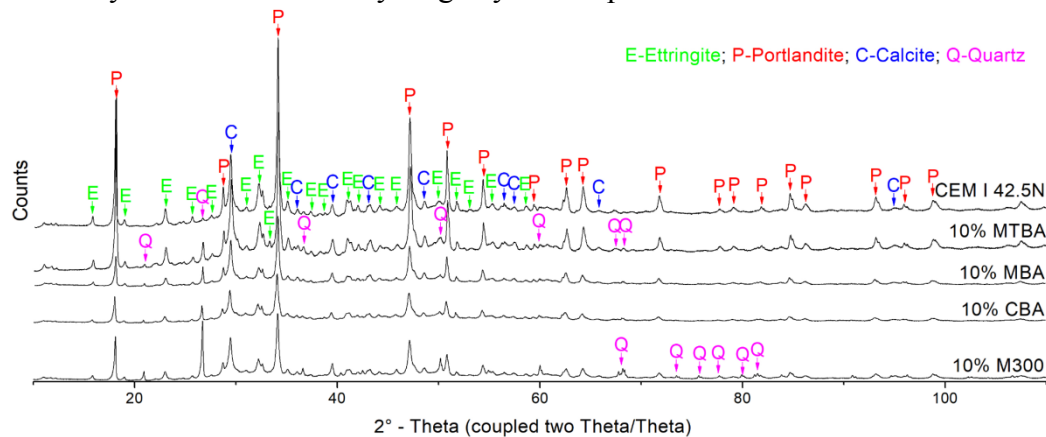


Figure 4: XRD diffractograms of hardened pastes with cement and substitute materials

The mineralogical phases in the hardened pastes were characterized by XRD (as shown in **Figure 4**). The main hydration products detected were ettringite and portlandite distributed over the full XRD detection range. It is also noticed that the profile of cement paste and the paste with 10% MTBA kept almost identical to each other. In pastes with 10% MBA, 10% CBA and 10% M300, dramatic reduction was observed in the intensity of peaks corresponding to calcite, portlandite and ettringite, and some of the peaks even vanished. Accordingly, the addition of MBA, CBA and M300 inhibited the hydration process and less amount of hydration products were generated.

The mass percentage of portlandite and non-evaporable water in hardened paste powders was calculated according to the mass loss along temperature history derived from TGA tests, and the results are given in **Figure 5**. It could be concluded that MTBA is the best cement substitute material in this study with the highest amount of main hydration products. Meanwhile, CBA is the most undesired substitute material in this research which might be attributed to the loss of reactive phases during the chemical treatment. Moreover, MBA exhibited intermediate performance, which is better than micronized sand. The result reveals that MBA could be already regarded as a proper filler substitute material in OPC concrete.

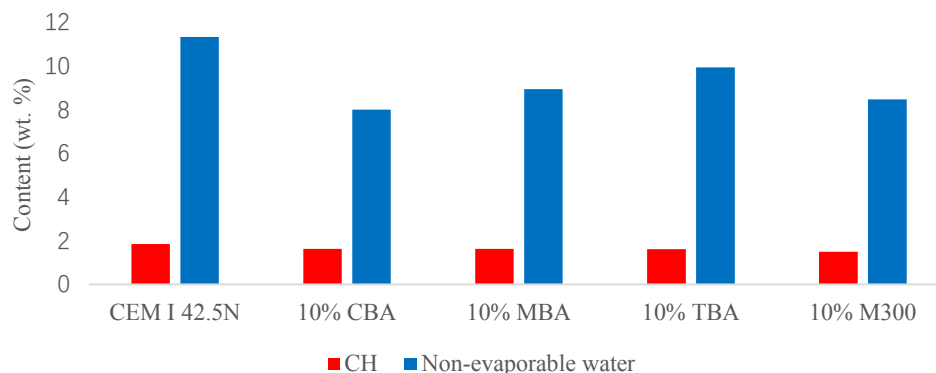


Figure 5: Mass percentage of CH and non-evaporable water in hardened pastes with cement and substitute materials, per unit weight of cement paste

4. CONCLUSIONS

According to the experimental results derived from this study, the following conclusions could be provided :

- Both chemical and mechanical treatments have been proved effective that the metallic aluminum content reduced by 95% and 84% respectively. However, the mineralogical composition characterized by XRD indicates that the soluble amorphous phases might be dissolved during the chemical treatment with alkaline solution.
- More reactive amorphous phases were detected in MTBA, which indicates that thermal treatment increased the reactivity of BA. Meanwhile, according to the result obtained from the metallic Al dissolution test, the thermal treatment further reduced the metallic aluminum content by providing an extreme high-temperature environment which accelerated the oxidization of metallic aluminum powders. MTBA is the best among all cement substitute material derived in this study. However, the thermal treatment might be energy-consuming.
- The hydration product characterized by XRD and TGA reveals that the performance of treated BA samples, when used as substitute material in Portland cement concrete, follows the trend: MTBA > MBA > M300 > CBA. MBA could be regarded as a proper filler substitute material in Portland cement concrete.

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