Accelerated carbonation of municipal solid waste incineration bottom ash for alternative aggregate production

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ABSTRACT

Municipal solid waste incinerated bottom ash (MSWI-BA) is a byproduct from waste incineration process, which is used mainly as replacement of sand and natural aggregates in road foundations and concrete pavements. Usually, MSWI-BA undergoes a maturation treatment before being used by exposing it to the atmosphere for a period of minimum 18 weeks. This study investigates an accelerated carbonation process for MSWI-BA maturation, which aims to enhance both its engineering properties and its environmental sustainability. The results demonstrate significant improvements in shortening treatment duration without compromising physical properties such as density and water absorption while concurrently reducing greenhouse gas emissions through CO_2 sequestration. These findings have established that accelerated carbonation could be an effective maturation technique for MSWI-BA, thus offering new insights for its practical implementation in waste management and resource recovery strategies.

KEYWORDS: *municipal solid waste incinerated bottom ash, accelerated carbonation, accelerated maturation, aggregates, concrete.*

1. Introduction

Municipal solid waste incinerated bottom ash (MSWI-BA), which makes up 80% of the residual waste after combustion, is the main by-product of municipal solid waste incineration. The European Union produces 19 million tonnes of MSWI-BA annually (CEWEP, 2017). Due to its similar density and particle size distribution, MSWI-BA is often used as a substitute for natural sand and aggregate (Dhir et al., 2018a; Courard et al., 2002). Before utilization, MSWI-BA typically undergoes natural aging, where it is stored in stockpiles for at least 18 weeks and sometimes up to 6 months. During this period, natural carbonation and leaching processes occur, leading to the formation of carbonates, mainly calcite, and reducing the content of heavy metals. This results in a significant decrease in pH from 12 to around 10 (Dhir et al., 2018b; Arm et al., 2011). Accelerated aging mimics these chemical reactions but at a faster rate by optimizing conditions such as temperature, relative humidity, and moisture content to stimulate the reactions. To potentiate the accelerated carbonation of MSWI-BA, the materials can be placed in a CO_2 enriched controlled environment chamber which can shorten the treatment duration from months to days (Lin et al (2015a). This study explores the potential of accelerated carbonation as a method for stabilizing MSWI-BA.

2. Materials and methods

2.1 Raw materials

The MSWI-BA used in this investigation was collected from the waste incineration plant of Thumaide (IPALLE) directly after the incineration process. Its granular fraction is between 0 and 20 mm (BA0-20) with a moisture content of around 20% (wt.%). A portion of the MSWI-BA was wet sieved to obtain a granular fraction between 0 and 2 mm (BA0-2) with a moisture content of around 45% (wt.%).

2.2 Accelerated carbonation experiment

The accelerated carbonation was carried out in CO_2 incubator maintaining a volume concentration of 12% CO_2 at atmospheric pressure. The temperature and relative humidity inside the incubator were kept at 30±1 °C and 60±3%, respectively.
The experiment was carried using two approaches:

- Approach A: the MSWI-BA was conditioned in a climate chamber at a temperature of 30±1 °C and relative humidity of 60±3% until its weight stabilised (4 days). The moisture content of the samples decreased from 20% to 2% for both BA0-20_A and BA0-2_A before starting the accelerated carbonation.
- Approach B: the carbonation was carried out directly without any type of pre-conditioning (BA0-20_B and BA0-2_B).

Samples were collected after being carbonated for 1, 2, 4, 8, 24, 48 and 168 h where $CaCO_3$ content, CO_2 uptake, pH value and moisture content were measured.

2.3 Method analysis

After accelerated carbonation, the MSWI-BA samples were crushed using grinding disc up to d <300 µm. The calcium carbonate content of the samples was calculated by means of thermogravimetric analysis (Netzsch STA Jupiter 449). A quantity of 30-40 mg milled was weighed in a sample pan heated from 40 to 1000 °C under a nitrogen atmosphere at a heating rate of 10 °C/min. The CO_2 uptake (in g/kg of MSWI-BA) was calculated from weight loss recorded by the microbalance between 500 and 800°C (Chang et al (2015)) during the decarbonation reaction (1). The calcium carbonate content is calculated from the stoichiometry equations (2).

$$CaCO_3 \rightarrow CaO + CO_2 \quad (1)$$

$$CaCO_3\ (\mathrm{wt.\%}) = CO_2\ (\mathrm{wt.\%}) \times \frac{MW_{CaO}(\mathrm{g/mole})}{MW_{CO_2}(\mathrm{g/mole})} \quad (2)$$

where MW_{CaO} (g/mole) is the molecular weight of CaO and MW_{CO2} (g/mole) is the molecular weight of CO_2.
pH was measured on a solution with a liquid-to-solid ratio (L/S) of 1, using crushed MSWI-BA (<300 µm) and deionized water was prepared. This solution is then homogenized using a magnetic stirrer for 30 minutes.
The physical properties including density, water absorption and wear resistance (Micro-Deval) of fresh, carbonated and traditionally aged MSWI-BA were measured using the standards procedures NBN EN 1097-6 (2022) and NBN EN 1097-1 (2023).

3. Results and discussions

3.1 $CaCO_3$ content

Figure 1 illustrates the evolution of calcium carbonate content in fresh bottom BA0-20 and BA0-2 over carbonation duration. For the BA0-20, the $CaCO_3$ content rises proportionally with storage time, reaching a plateau at 4 hours for approach A and 8 hours for approach B. Beyond these points, $CaCO_3$ content stabilizes. Notably, approach B exhibits a more pronounced increase in $CaCO_3$ content compared to approach A.
For BA0-2, the $CaCO_3$ content increases with time up to 8 hours for approach B and remains constant afterwards. However, with approach A, there is no observed gain in $CaCO_3$ content even after 7 days of carbonation.

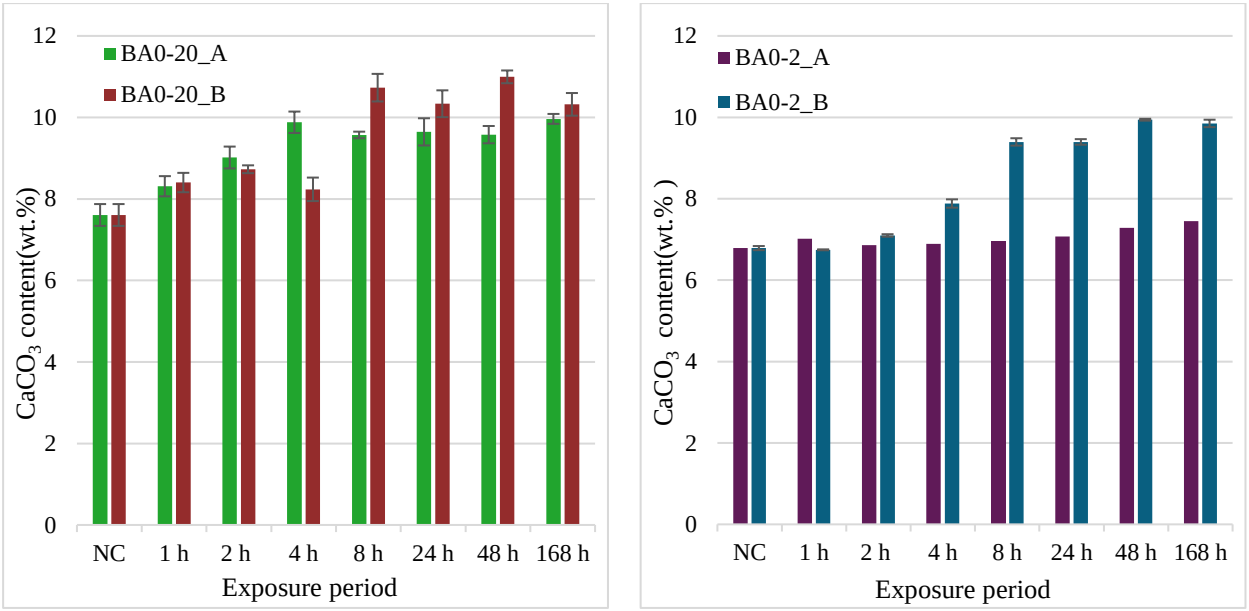

Figure 1: $CaCO_3$ content of BA0-20 (left) and BA0-2 (right) after different exposure periods to accelerated carbonation.

3.2 CO_2 Uptake

The evolution of the CO_2 uptake was represented in a similar way to the evolution the $CaCO_3$ content. Figure 2 shows that the CO_2 uptake of BA0-20 rises proportionally with time, reaching its maximum value at 4 hours for approach A and 8 hours for approach B. Beyond these points, CO_2 uptake stabilizes. Notably, approach B exhibits a more pronounced increase in equivalent CO_2 uptake where it reached almost 14g/kg of MSWI-BA compared to approach A (only 10 g/kg). A similar behavior is observed for BA0-2, where the CO_2 uptake increases with time up to 8 hours for approach B, after which the results remain constant. However, with approach A, the gain in CO_2 uptake was negligible compared to approach B even after 7 days of carbonation. The results were similar to those obtained by Lin et al (2015a), Lin et al (2015b) and Yoa et al (2022).

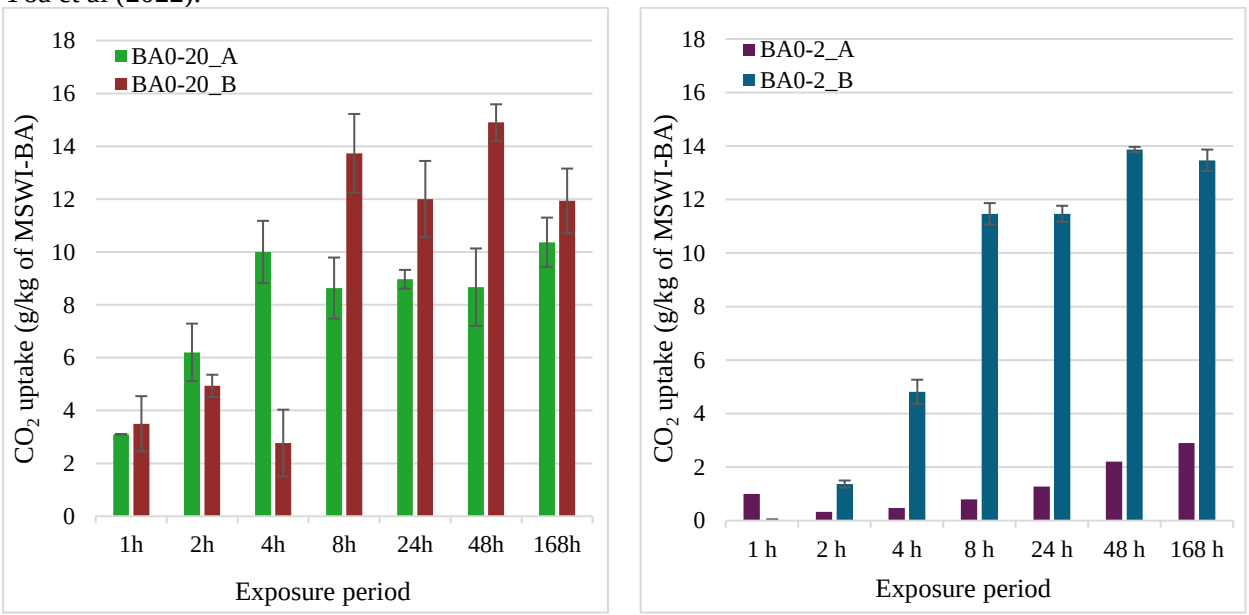

Figure 2 : CO_2 uptake of BA0-20 (left) and BA0-2 (right) after different exposure periods to accelerated carbonation.

3.3 Influence of moisture content

In order to understand why approach B was more effective than approach A, the evolution of the degree of carbonation (DoC) and the actual moisture content (WC) as a function of the exposure period for both BA0-20 and BA0-2 were checked. Figures 3 show that the evolution of the degree of carbonation is greater when the water content is between 10 and 15% for the BA0-20_B and between 10 and 30% for BA0-2_B. This is in line with previous findings by Lin et al (2015b) on the effect of the initial moisture content on the efficiency of the accelerated carbonation process of BA. This means that a minimum but limited moisture content is needed for carbonation process.

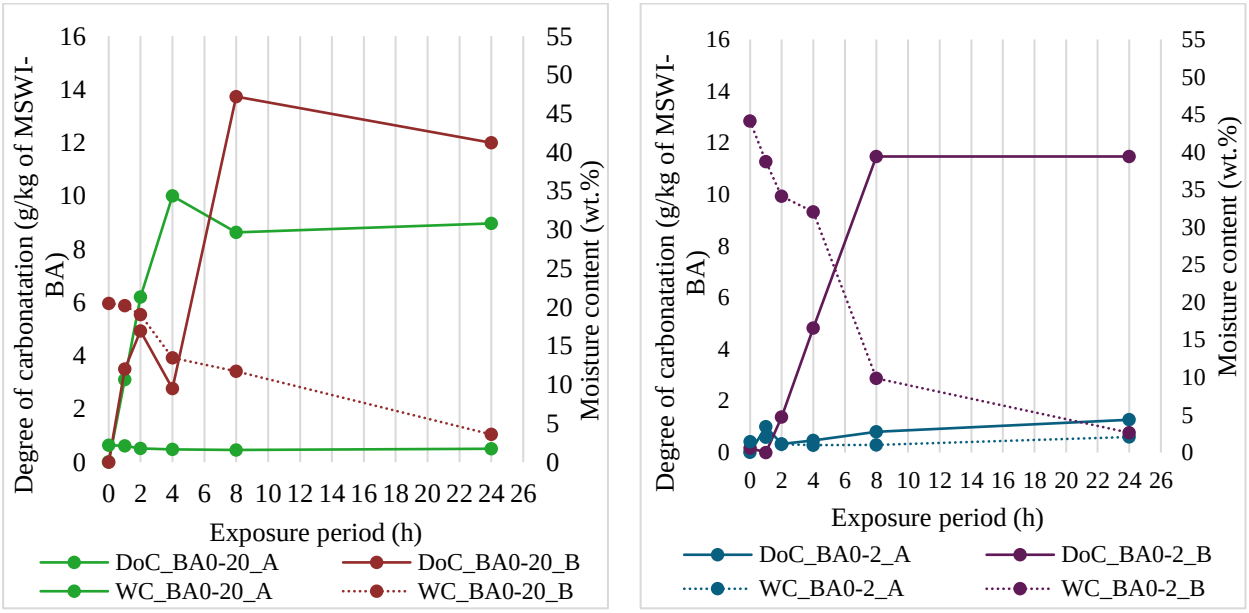

Figure 3: Evolution of the degree of carbonation and the moisture content of BA0-20 (left) and BA0-2 (right) during accelerated carbonation.

3.4 pH evolution

Equivalent results were obtained regarding the evolution of pH as figure 4 shows that the pH of the MSWI-BA decreased more significantly with carbonation using approach B over approach A, for BA0-20 and BA0-2 as well. In both cases, using approach B successfully descended the pH of MSWI-BA from 12 to 10 similar to the pH value of traditionally maturated MSWI-BA (Dhir et al (2018b), Arm et al (2011)) which aligns with previous studies done by Lin et al (2015a).

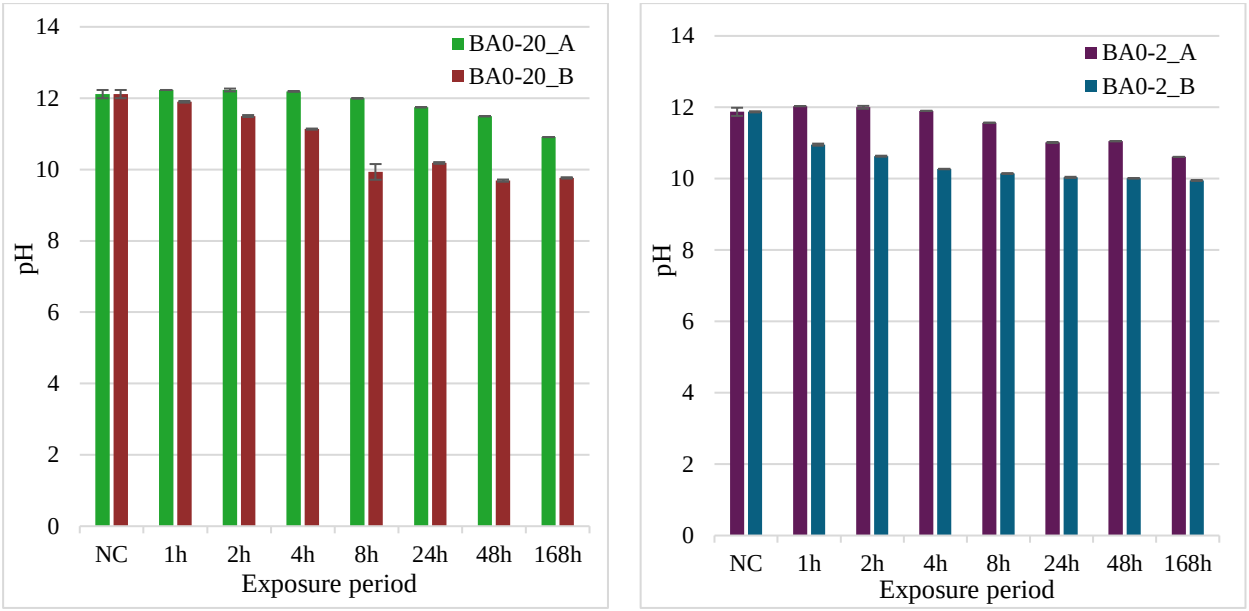

Figure 4: pH measurements of BA0-20 (left) and BA0-2 (right) after different exposure periods to accelerated carbonation.

3.5 Physical properties

Table 1 and 2 show the physical properties of fresh, traditionally maturated MSWI-BA and also MSWI-BA maturated by accelerated carbonation in controlled environment chamber using approach B for a duration of 24h. Results show improvement of the density of carbonated MSWI-BA fines aggregates compared to the fresh and the maturated samples: this is due to the transformation of most of the CaO into calcite although this didn't reflect in any decrease in water absorption capacity. For the coarse aggregates, neither the carbonation nor the maturation significantly affected the density or the water absorption capacity. This is mostly due to the fact that most of the carbonatable content is present in the fine fraction of the MSWI-BA aggregates (Lin et al (2015a)). This was reflected on the wear resistance test which was concluded on the coarse aggregates fraction as we can see that the carbonation nor the maturation process has any significant effect on the results.
Considering that the majority of the results mentioned in table 1 and 2 were in the same range as the ones obtained in the literature by Dhir et al (2018a), Becquart & Abriak (2013) and Descamps et al (2011) on the properties of traditionally maturated MSWI-BA, it's safe to say that neither the accelerated carbonation nor the traditional maturation treatment has any significant effect on the physical properties of MSWI-BA.

Table 1: Density and water absorption capacity of fines and coarse MSWI-BA aggregates under different treatment conditions compared to literature results (Dhir et al (2018a)).

		Fresh	Carbonated	Maturated	Literature
Fines MSWI-BA aggregates	**Density (kg/m^3)**	1840	2145	2239	2150-2850
	Water absorption (%)	6.9	7.3	8.24	2.2-17.3
Coarse MSWI-BA aggregates	**Density (kg/m^3)**	2280	2360	2239	1860-2680
	Water absorption (%)	2	2.4	4	7.2-15

Table 2: Wear resistance of MSWI-BA under different treatment conditions compared to literature results (Becquart & Abriak (2013); Descamps et al (2011)).

	Fresh	Carbonated	Maturated	Literature
Wear resistance (wt.%)	21	24	21	18-31

4. Conclusions

This study attempts to explore the carbon capture in MSWI-BA using accelerated carbonation and its effect on the maturation process and the physical properties of MSWI-BA. Fresh MSWI-BA was carbonated using different approaches to assess their effect on the carbonation process and pH variation. The following conclusions could be drawn according to the experimental results:

- For both fractions studied, moist carbonation (approach B) was more effective regarding carbon capture and pH stabilisation and more practical since no pre-conditioning was required.
- Regarding the type of treatment used (accelerated carbonation or traditional maturation) there was no significant improvement in the physical properties of MSWI-BA.

While this study covered the effect of accelerated carbonation on the physical properties of MSWI-BA, additional studies are required in order to investigate the effect of accelerated carbonation on chemical properties and the leaching of MSWI-BA which are the main obstacles limiting its use as secondary materials.

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