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Turning municipal solid waste incineration into a cleaner cement production

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ABSTRACT

The incineration of Municipal Solid Wastes (MSW) presents the added advantage of recovering energy from the wastes' residual calorific content. However, the process also generates by-products of ash and carbon emissions. This study evaluates the feasibility of using the outputs of energy, ash, and carbon dioxide in the making of a cementing material through novel steps tailored to allow replicating the process within an incinerator facility. The cementing material was synthesized using more than 85% ash residues and a clinkering temperature of 1000 °C, congruous to the operating conditions of a typical incinerator. Cement so produced is cleaner than traditional Portland cement for not being intensive in resource, energy and carbon footprints. It exhibited no hydraulicity but could be rapidly activated by carbon dioxide. Benched against Portland cement, paste specimens recorded an average compressive strength of 53 MPa and a CO_2 sequestering uptake of 6.7 wt. % after undergoing only 2 h of carbonation activation. Mineral analyses identified the active cementing components to be chloro-ellestadite ($Ca_{10}(SiO_4)_3(SO_4)_3Cl_2$) and belite ($Ca_2SiO_4$), which upon reacting with CO_2 rapidly formed a hardened binding matrix. Standardized leaching tests deemed the clinker product stable. This work presents first step of a broader scope to ultimately turn MSW incineration into a cleaner cement production, where locally-sourced heat, ash, and emitted CO_2 can be used to generate products for building applications.

1. Introduction

Globally, the generation of municipal solid waste (MSW) is estimated to range between 1 and 2 billion tons per year (Hoornweg and Bhada-Tata, 2012). Incineration is a widely implemented solid waste management approach, especially in localities with limited land-space and high population densities (Stehlik, 2009). However, the process generates considerable amounts of unstable by-products, namely, bottom ash and fly ash; with fly ash posing a greater challenge for containing leachable heavy metals, chlorides, and organic contaminants (Erol et al., 2007; Tang et al., 2018). On the other hand, the bulk of fly ash's composition also makes it a rich mineral source for silica and lime, and potentially well suited as a raw feed material for cement production (Tang et al., 2018; Lederer et al., 2017). By the same token, the high clinkering temperatures of cement-making can effectively destroy the fly ash's toxic organic contaminants (e.g. dioxins, furans), and also stabilize heavy metal components via structural incorporation in the generated clinker phases (Rincó et al., 1999; Ferreira et al., 2003; Cheng et al., 2007; Lederer et al., 2017).

Efforts have been made to produce environmentally-friendly cementitious materials from blends containing partial amounts of MSW incineration ash (Kikuchi, 2001; Shih et al., 2003; Ferreira et al., 2003; Saikia et al., 2006; Singh et al., 2008; Shi et al., 2009; Wu et al., 2011; Guo et al., 2014; Lederer et al., 2017). Kikuchi (2001) demonstrated the viability of producing a clinker material from a mix of MSW ash, sewage sludge, and limestone at 1400 °C, where the raw meal contained up to 40% MSW ash. Likewise, Saikia et al. (2006) obtained a cement similar to the composition of OPC by replacing 48% of the raw clinker mix with MSW fly ash and processing within the 1300–1400 °C range. Singh et al. (2008) generated a hydraulic alinite-based cement (belonging to the $CaO–SiO_2–Al_2O_3–MgO–Cl$ system) from raw formulations containing 20–60% of both MSW fly ash and bottom ash fired between 1100 and 1200 °C. More recently, Guo et al. (2014) succeeded in the synthesis of a calcium sulfo-aluminate (C$A) cement at 1200 °C from a raw mix containing 30% MSW fly ash. C$A cements contain ye'elimite ($Ca_4Al_6O_{12}(SO_4)$) and belite as the major clinker phases,

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and, according to an in-depth LCA analysis by Hanein et al. (2018), they present the most promising and realistic sustainable alternative to OPC.

The abovementioned examples all associate embodied carbon footprints, albeit lower than OPC, for their partial sourcing/processing of virgin raw materials and use of energy during synthesis. The need for high temperatures to generate clinker phases implies that large-scale production would likely require kiln operations like ones used in conventional cement making.

Also known as waste-to-energy (WTE) facilities, incinerators are in fact mini power-plants that make the most of the calorific content of MSW to generate heat, which in most cases is eventually converted into steam and/or electricity to supply the plant's energy demand and contributing to the local power grid. In other words, energy in the form of heat is of abundance within an incinerator facility. Considering that traditional incinerators achieve heat conversion efficiencies of 20–30% (Pan et al., 2015), dissipated heat could potentially be harnessed for direct in-situ clinkering of ash residues and the production of waste-derived cements at point source. Peak combustion temperatures within an incinerator normally range between 800 and 1200 °C (Kalyani and Pandey, 2014), which may not be enough to generate all high-temperature calcium-silicate phases found in Portland cement, but perhaps sufficient in forming belite or other low-energy cementitious phases.

Belite is inherently latent hydraulic, or non-hydraulic in the specific case of the γ−polymorph (Odler, 2000), exhibiting latent to no binding ability when reacted with water in either case. However, introducing carbon dioxide into the equation can overcome this practical limitation, where carbonation has not only been shown to address belite's hydraulic latency, but even activate the binding strength of the non-hydraulic γ−polymorph. Young et al. (1974) first demonstrated how β-C_2S could react with CO_2 in the presence of water to rapidly form $CaCO_3$ and C−S−H − the crucial reaction product responsible for strength and other physico-mechanical developments in concrete (Valls and Vazquez, 2001). The reaction is given in Eq. (1). Bukowski and Berger (1979) also showed how non-hydraulic γ−C_2S and even $CaSiO_3$ (wollastonite) could be activated by carbon dioxide, where 16 h of carbonation achieved strength values higher than 28-day hydrated OPC for both mortar and paste specimens. Qian et al. (2016) synthesized a clinker material at 1300 °C comprised mainly of rankinite ($Ca_3Si_2O_7$) and pseudowollastonite ($Ca_3(Si_3O_9)$), both of which were non-hydraulic but hardened via accelerated carbonation.

$$2(CaO\cdot SiO_2) + yH_2O + (2-x)CO_2 \rightarrow xCaO\cdot SiO_2\cdot yH_2O\ [C{-}S{-}H] + (2-x)CaCO_3 \quad (1)$$

With carbonation's demonstrated ability to engage and/or activate cementitious components and other minerals (Jang et al., 2016), the exploitation of this mechanism may present new grounds for targeting the synthesis of waste-derived clinker systems that embody even lower energy footprints than demonstrated by previous works. Furthermore, carbonation has also been shown to contribute to waste stabilization. The precipitation of calcium-carbonate crystals during carbonation densifies the processed microstructure, imparting a reduction in porosity and a better retention of contaminants and toxic heavy metals that may be present (Lange et al., 1996). Moreover, carbonation lends a pH neutralizing effect, which in its own right decreases the solubility/mobility of certain regulated metals (Li et al., 2003). It has been popularized as an effective technique for stabilizing heavy-metal-laden wastes (Fernandez-Bertos et al., 2004).

The purpose of this paper is to demonstrate the practical viability of producing a cleaner cement material exclusively from MSW incineration residues at a synthesis temperature of 1000 °C, equivalent to an incinerator's operating conditions. Cementing material synthesized at this temperature will likely be non-hydraulic, where carbonation will be employed to activate the binding strength. Optimum stoichiometric mixtures and clinkering regimens were investigated using fly ash and air pollution control (APC) waste-lime as the respective principal sources of silica and lime. Building on this work, future realization would ultimately associate the use of incineration heat as clinkering energy, and stack-recovered CO_2 as the carbonation activator. To that effect, an MSW incinerator facility would become a cleaner operation, in addition to a self-sustaining cement production. The intention is not to contend with traditional cement-making, but rather demonstrate the novel manner by which a cleaner and valorizing incineration process could be achieved. The cement so produced does exhibit various environmental advantages over previous works in that lower virgin raw materials are required; lower clinkering temperatures adopted − particularly to facilitate point-source processing within an incinerator facility; no fossil-fuel burning necessitated; a zero embodied carbon footprint ensured due to being mostly waste-derived; and a carbon sequestering opportunity presented.

2. Materials and methods

2.1. Materials

The two MSW incineration residues, fly ash and waste-lime, used in this study were collected from the Quebec City Municipal Incinerator (Quebec, Canada) on three separate occasions over a span of two years. At the facility, fly ash was recovered from the Heat Recovery Steam Generator (HRSG) and Electrostatic Precipitator (ESP) systems, while waste-lime was collected further downstream from the baghouse assembly. Lime is normally used to neutralize the acidity of the flue-gas and contain SOx, chlorines, and other contaminants entrained in the flue-gas. At the end of its service life, the expended lime undergoes an in-house washing step prior to disposal. The facility generates around 7000 tons of fly ash and 3500 tons of waste-lime per year. These are then disposed of in specialized landfills. Supplementary raw materials in this study include ground silica sand (<25 μm) and Graymont® hydrated-lime, which served as the additives for fine compositional adjustments when preparing the raw clinker mixes. Ordinary Portland cement (OPC) was used as the commercial reference for performance comparisons.

2.2. Material preparation

Waste-lime was collected in the form of wet cakes from the incinerator. These were dried at 105 °C for 24 h and then pulverized. The fly ash was received in powder form and had a wide particle size range. The coarse portion comprised charred flakes and incompletely burnt material (mostly paper fragments). To ensure compositional and dimensional homogeneity, this residue was passed through a 212 μm sieve to remove the minor non-representative coarse portion. The passing portion was then ground to fine powders by a ring-and-puck vibratory mill. The final powder size was approximated by the Blaine fineness number using a standard air permeability apparatus (ASTM C-204). The fineness values obtained were: $307 \pm 29\ m^2/kg$ for fly ash; $331 \pm 38\ m^2/kg$ for waste-lime; and $384 \pm 35\ m^2/kg$ for the OPC benchmark reference.

2.3. Compositional analysis

The compositions of the fly ash, waste-lime, produced clinker,