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High performance of treated and washed MSWI bottom ash granulates as natural aggregate replacement within earth-moist concrete

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ABSTRACT

Municipal solid waste incineration bottom ash was treated with specially designed dry and wet treatment processes, obtaining high quality bottom ash granulate fractions (BGF) suitable for up to 100% replacement of natural gravel in concrete. The wet treatment (using only water for separating and washing) significantly lowers the leaching of e.g. chloride and sulfate, heavy metals (antimony, molybdenum and copper) and dissolved organic carbon (DOC). Two potential bottom ash granulate fractions, both in compliance with the standard EN 12620 (aggregates for concrete), were added into earth-moist concrete mixtures. The fresh and hardened concrete physical performances (e.g. workability, strength and freeze-thaw) of high strength concrete mixtures were maintained or improved compared with the reference mixtures, even after replacing up to 100% of the initial natural gravel. Final element leaching of monolithic and crushed granular state BGF containing concretes, showed no differences with the gravel references. Leaching of all mixtures did not exceed the limit values set by the Dutch Soil Quality Degree. In addition, multiple-life-phase emission (pH static test) for the critical elements of input bottom ash, bottom ash granulate (BGF) and crushed BGF containing concrete were assessed. Simulation pH lowering or potential carbonation processes indicated that metal (antimony, barium, chrome and copper) and sulfate element leaching behavior are mainly pH dominated and controlled, although differ in mechanism and related mineral abundance.

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1. Introduction

One of the sustainability strategies of the European Union (EU) is developing a circular economy. Potential waste and secondary materials are promoted to be re-used or recycled and subsequently applied within comparable or new processes and or applications. Hence, initial waste materials are regarded as potential new resources. This approach will ultimately lower the amount of necessary primary materials and potentially reduce the amount of materials that go into landfills. In relation to this strategy, the EU Construction Products Regulation (CPR 305/2011/EU) has come into force. This EU regulation attempts to obtain more knowledge and junction, creating a generic and level playing field between EU

member states in regard to the re-use application of waste and or secondary materials (related to environmental quality) within processes.

The Netherlands is already facilitating the re-use of many types of secondary materials within construction works by a clear and workable regulation regarding the application of building materials ("SQD) Soil Quality Degree," 2015). In addition, specific actions are initiated by the government to stimulate re-use in a sustainable way. One example is the re-use of Municipal Solid Waste Incinerator (MSWI) bottom ash, where the Dutch industry has signed a 'green-deal' with the central government to improve (towards the year 2020) the physical and environmental quality of the treated ashes. Initiating a more environmental, economically efficient and sustainable bottom ash use in constructions e.g. open granular applications for road base layers and/or secondary aggregate in asphalt and cement concrete applications.

A general, conventionally dry treated MSWI bottom ash is mainly composed non-combustible materials e.g. slag, stone, glass,

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ceramic, sand and metallic metals. Where especially metal recovery is of high economical value regarding the extraction of valuable scarce resources e.g. copper, lead, molybdenum, zinc, aluminum and iron (Allegri et al., 2014). The final mineral ash composition primarily consists of silicon, calcium, iron and aluminum containing structures e.g. quartz, calcite, hematite and ettringite (Chang and Wey, 2006; Chimenos et al., 1999; Funari et al., 2014; Kuo et al., 2013; Tang et al., 2015). The mineral compositions can vary time-to-time between the incinerators in relation to solid waste input and incineration conditions. Additionally, these conditions also effect the abundance and moderate concentrations of heavy metals and salts that are within the ashes (Funari et al., 2014; Margallo et al., 2015).

Treated mineral bottom ashes are to some extent comparable to the most widely used raw concrete aggregates and are therefore possibly useful as mineral additions in various construction material applications (Abbà et al., 2014; Bertolini et al., 2004; Cioffi et al., 2011; Florea, 2014; Forteza et al., 2004; Hassan and Khalid, 2010; Kuo et al., 2013; Pera et al., 1997; Syahrul et al., 2010; Toraldo et al., 2013). As such, a well-designed bottom ash granulate could potentially play an important role in the sustainable progress within Portland cement mixtures, as an aggregate alternative for primary sand and gravel. Additionally, this relative new ash application could stimulate reuse of the relatively fast growing (millions of tons) bottom ash quantities produced world-wide and that are currently and mainly stored in landfill sites (Oehmig et al., 2015).

To the authors knowledge, only a few available recent studies deal with mechanically treated MSWI bottom ash fractions in concrete, where currently no significant and satisfying results have been obtained. Research does show that, overall improved ash-containing concrete performance is obtained with wet treated ashes in comparison with only dry treated (Rubner et al., 2008; Sorlini et al., 2011; Zhang and Zhao, 2014). Where Kuo et al. (2015) and Yang et al. (2012) attribute the difference to the finding that the liquid phase extracts and reduces a large part of the available and potentially disturbing salts, heavy metals and fine particles, present within the ashes. To summarize literature on bottom ash containing concretes compared with the Portland reference systems the following main drawbacks have been observed:

- Strong and substantial decline of fresh concrete workability (Yu et al., 2014; Zhang and Zhao, 2014).
- Severe matrix expansion and cracking by hydrogen gas production (Müller and Rübner, 2006; Yu et al., 2014).
- Cement hydration retardation by abundant disturbing substances (van Eijk, 2001).
- Severe increase of matrix porosity and permeability due to gas bubble formation (Müller and Rübner, 2006; Rubner et al., 2008; Yu et al., 2014).
- Moderate to high loss of mechanical strength (Rubner et al., 2008; Sorlini et al., 2011; Yu et al., 2014; Zhang and Zhao, 2014).

Despite these drawbacks, the mentioned studies also report multiple ash related upsides e.g., relatively good particle distribution for concrete application, equal to slightly lower material density compared to concrete aggregate (Sorlini et al., 2011), moderate to high ash particle abrasion properties, pozzolanic reaction of bottom ash particles (Zhang and Zhao, 2014) and very low economical material costs when applied as granulate.

Knowing both disadvantages and advantages, the authors elaborated a new and promising approach; applying a specially developed dry and wet treatment on the ash before being utilized in earth-moist concrete mixtures. This treatment approach and related concrete design (which will be performed on large scale and real life production pilots) has never been considered.

Until now, all published work focuses on laboratory-scale production by applying relatively wet (high consistency) concrete mixture designs (liquid/binder ratios of ≥ 0.4 – 0.6) instead of dry (low to zero consistency) earth-moist designs. Interestingly, research on the earth-moist concrete production and related products are rarely published (Hüsken and Brouwers, 2008), due to difficulties to produce and simulate this production process at the laboratory scale. In practice, the production requires an extremely high pressure compaction in combination with an ideal particle packing and mixture consistency.

When applying the treated ash, the related earth-moist concrete material properties could trigger an optimized result and consequently ash usage can then be favored. Identifying the potential synergy of this approach: firstly, earth-moist concrete has no slump or measureable workability and consistency is mainly determined by the compaction rate in combination with visual inspection. Hence, workability loss initiated by the ash at its higher water demand is not of influence on the fresh concrete performance. Secondly, the relatively high porosity of earth-moist concrete is able to capture potential hydrogen gas production from the bottom ash, preventing matrix expansion and related crack formation. Thirdly, the dry and wet ash treatment reduces the amount of disturbing substances within the bottom ash, therefore accordingly the potential negative interferences on the cement hydration can be minimized or neglected. Therefore, the following most important parameters (substances) in bottom ash treatment which influence the concrete performances that need to be controlled to obtain valuable bottom ash granulate fractions (BGF) are:

- Recovery of as much of the non-ferrous (aluminum and zinc) and ferrous metallic metals as possible that cause potential concrete expansion, cracking and pop-out problems due to hydrogen formation (Florea, 2014; Rubner et al., 2008).
- Extraction of the majority of fine and coarse unburned organic particles and their released organic structures that potentially disturb cement hydration processes (van Eijk, 2001).
- Reduce the total percentage of very-fine, mainly organic micrometer particles. These particles could interfere with the needed particle packing approach, increase water demand in the mixture, lower fresh concrete workability and retard cement hydration.
- Optimize bottom ash particle-size distribution to obtain an appropriate mineral granulate replacement for natural gravel.
- Reduce the amount of potential leachable salts, heavy metal and organic structures that influence the cement hydration or can leach into soil and groundwater systems (Cornelis et al., 2008; Dijkstra et al., 2006b; Meima and Comans, 1999, 1998; Shim et al., 2003).

Given these characteristics, this research focusses on treatment optimization of raw bottom ash where (1) all of its initial disturbing substances are selectively removed and (2) the (BGF) material is tuned to an ideal particle-size distribution. Furthermore, bottom ash granulates are first produced in a pilot experiment which combines specially designed dry and wet treatment processes. In a second pilot production, pre-fabricated earth-moist concrete elements are produced by replacing various mass percentages (0–100%) of the natural gravel by the BGF.

The overall aims of the present work are:

- Investigate the suitability of the designed bottom ash treatment processes.
- Characterize the initial BGF material properties and their performance within open granular and concrete application.

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