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Technical and environmental performance of lower carbon footprint cement mortars containing biomass fly ash as a secondary cementitious material

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ABSTRACT

This study evaluated the mechanical and environmental properties of cement mortars containing fly ash from biomass combustion as a secondary cementitious material.

Cement mortars with 20 and 40% wt. replacement of Portland cement with fly ash from two types of installations were tested for their compressive strength and leaching behaviour.

Substitution of 20% Portland cement with wood fly ash complied with the reference standard for compressive strength of 42.5öMPa at 28ödays. Replacement rates of 40% developed a lower strength (30 and 33.5öMPa), but were still suitable for applications. The pulverized fuel ash perform substantially worse. We conclude that the biomass fly ash from fluidized bed combustion performs as a functional secondary cementitious material in cement, whereas the functionality of pulverized fuel fly ash is insufficient.

The release of environmentally relevant elements from all the tested specimens fulfilled the Dutch leaching criteria for reuse. During second life as a granular construction material the release of Ba, Cr, Mo and V increased to a level of concern. However, this release was found to be similar to that of existing blended cements and was controlled by cement chemistry.

The technical performance of cement mortars was influenced by the type and ratio of fly ash mixed with cement. However, the environmental performance was driven by the cement matrix that controlled the release of contaminants.

Using biomass fly ash as a secondary cementitious material can reduce the carbon footprint of concrete by 40% while maintaining good technical and environmental performance.

1. Introduction

Cement is an essential ingredient for concrete that is currently the most used construction material worldwide with an annual output, in 2009, of 2.8 Gtons (WBCSD – World Business Council for Sustainable Development, 2009). For traditional cement production, different raw materials such as limestone and clay need to be mined, blended in specific proportions, ground and heated at high temperature in a rotary kiln. This process is energy and resource intensive and results in considerable CO_2 emissions due to the decomposition of calcium carbonate (limestone) into calcium oxide and the combustion of fossil fuels during the heating of the mixture. The global average gross CO_2 emission per ton of cement is estimated to be around 900 kg, accounting for 5–8% of total human atmospheric CO_2 emission (Habert et al., 2010). Over the last years, many efforts have been made to reduce the carbon footprint of the cement industry, including: i) improving the energy efficiency of the kilns; ii) replacing fossil fuels with alternative energy sources such as animal residue, sewage sludge and waste oil; iii) substitution of the traditional Portland cement with alternative cementitious materials, such as blast furnace slags and coal combustion fly ash.

The substitution of traditional cement with biomass fly ash is progressively being investigated due to the growing use of biomass for sustainable energy production and the corresponding large amount of biomass fly ash produced (Berra et al., 2015; Rajamma et al., 2015; Siddique, 2012). Besides reducing greenhouse gas emissions due to lower energy and raw materials consumption, the addition of biomass ash to cement could result in the beneficial effects of avoiding the landfilling of the biomass combustion residues. On the other hand, some potentially dangerous substances present in the biomass ash might be released in the environment during different life stages of cement containing fly ash. At present, the use of fly ash as a mineral admixture in concrete is regulated by the European standard EN 450-1 (2005). In practice, this standard precludes the use of any material not derived from coal combustion. This prerequisite, limits the use of

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biomass ash in cement because coal-fired power plants can use only up to 20% biomass to replace coal. At this percentage, the characteristics of the fly ash from co-combustion of coal and biomass (normally clean wood) is dominated by the coal-ash and can be used in the same applications. Higher percentages of biomass ash generally lead to a higher content of alkali and phosphorus (Boersma, 2011; Sarabèr, 2014; van Loo and Koppejan, 2008). The elevated levels of these constituents make the biomass ash unsuitable for the established application of coal fly ash according to EN-450. In many countries most of the biomass ash is still landfilled (van Eijk et al., 2012). However, several researchers have demonstrated that biomass fly ash can be effectively used as cement replacement to produce concrete with acceptable strength and durability performances (Cheah and Ramli, 2011). The effects of biomass ash on the technical cement properties can vary depending on the physical-chemical properties of the ash. These properties are determined by the type of biomass feedstock combusted (i.e., ash forming elements present in the biomass and their mode of occurrence) (Obernberger et al., 1997; van Lith et al., 2006), the thermal conversion technology adopted (i.e., pulverized fuel combustion, fluidized bed, grate stoker) and the flue gas cleaning system (Sarabèr, 2014; Tarelho et al., 2015).

A general observation is that strength properties of cement and concrete mixtures decreases with increasing wood ash contents but, when pozzolanic activity is present, strength increases with age (Siddique, 2012, 2008; Wang et al., 2008). Normally this observation is attributed to the low hydraulic activity of biomass fly ash with consequential dilution of active phases contained in cement (Cheah and Ramli, 2013; Rajamma et al., 2015). The maximum replacement ratio at which acceptable compressive strength is maintained is around 10–20% of total binder weight (Cheah and Ramli, 2012, 2011; Corinaldesi et al., 2016; Rajamma et al., 2015; Rajamma, 2009). Lothenbach et al. (2011) also stated that fly ash with a high Calcium content can contain reactive crystalline phases such as dicalcium silicates which can contribute to strength development by forming hydrated products. Therefore, we focus on ashes with a relatively high Ca content to study the cement performance in combination with higher replacement rates (20–40%).

Most studies have focused mainly on the technical performance of cement containing biomass ash. To date, little is known about the environmental compatibility of products containing biomass ash when exposed to different utilization scenarios (Berra et al., 2011). Fly ash from biomass combustion can contain significant amounts of hazardous elements (Saqib and Bäckström, 2015) even if the fuel is regarded as clean fuel (Pels et al., 2004). Other studies have shown that the use of alternative materials in cement (e.g. coal fly ash, blast furnace slags) can affect the potential release of hazardous substances from these products (Kosson et al., 2009, 2014; van der Sloot et al., 2008). Thus, when biomass ash is used in cement, part of the contaminants could be released from the product during its service life (e.g., application of material in intact structures) and potential second life applications (e.g., reuse of recycled concrete aggregates as road sub-base) (Engelsen et al., 2017, 2012, 2010; van Zomeren et al., 2015). Release of contaminants might threaten the environment and restrict re-use of biomass ash in products.

In this study we evaluate both the technical and environmental performance of blended cement mortars containing different replacement ratios of biomass fly ash. Combination of different leaching tests is employed to assess the potential impact of cement containing biomass ash under different application scenarios. Results from this work could form a basis to assess the sustainability of cement containing biomass ash in a wider perspective, beyond energy and raw material savings. The testing and assessment approach that is presented here, may also support the development of a more circular use of cementitious materials in multiple life cycles.

2. Materials and methods

2.1. Biomass fly ash

Three biomass fly ashes (i.e. FA1, FA2 and FA3) were investigated in this study. The samples had a particle size < 1 mm and were stored dry in the laboratory. Sample FA1 originates from a circulating fluidized bed installation that combusts a mixture of clean wood and either cacao husks, molasses or other clean biomass streams that were occasionally added. The sample FA1 was collected from the electrostatic precipitator. Sample FA2 originates from the combustion of wood pellets in a pulverized fuel installation and was collected from the electrostatic precipitator.

Sample FA3 was sampled from a bubbling fluidized bed incinerator. The fuel consisted of a mixture with an equal share of recovered paper sludge from the de-inking step of the paper recycling process and recovered waste wood. The fly ash was collected from the electrostatic filter (90% by mass) and the textile bag filter (10% by mass) flue gas cleaning system. The investigated biomass ashes cover a fairly wide range of commonly used biomass fuels and conversion technologies and can, therefore, be considered representative for future biomass ash use in cement products.

2.2. Preparation of blended cement mortars

Cement mortar samples were prepared by dry mixing of Portland Cement CEM I 42.5N with biomass fly ash in accordance with the European standard EN 196-1 (2005). Both 20% and 40% (by total binder weight) of the Ordinary Portland cement (OPC) was replaced with biomass fly ash. Table 1 shows the mix design of the cement mortars. All specimens were prepared with a water-binder weight ratio (w/b) of 1:2 and a sand-binder ratio of 3:1. Rectangular blocks (160 × 40 × 40 mm) were casted and removed from the mold after 24 h of curing. Next, the molds were cured for 28 days in a controlled temperature and humidity room (20 °C and 95% humidity). After 28 days of curing, the specimens were subjected to compressive strength (EN-196-1, 2005) and leaching tests.

2.3. Leaching tests

The release of inorganic elements from the pure biomass ashes, the 20% blends, 40% blends and the reference was measured by means of three leaching tests: tank leaching test (FprCEN/TS, 2013), parallel batch extraction test at different L/S ratios (EPA, 2012) and the pH dependence leaching test (EN 14429, 2015). Selection of an appropriate combination of leaching tests to characterize the environmental performance of cement mortars during a determined use or second life scenario was based on the physical form of materials (i.e. granular or monolithic) and the anticipated application conditions. The tank leaching test (FprCEN/TS, 2013) is suitable for an intended use scenario

Table 1
Composition and sample IDs of the studied cement mortar recipes. The percentage of replacement of traditional Portland cement (OPC reference) by fly ash (FA1, FA2 or FA3) refers to the total binder weight.

		Reference	20_Blends	40_Blends
Portland Cement (CEM I 42.5-N)	wt%	22.2	17.8	13.3
Fly Ash[a]	wt%	–	4.4	8.9
Sand	wt%	66.7	66.7	66.7
Water	wt%	11.1	11.1	11.1
Sample ID	sample code	OPC reference	20_FA1 20_FA2 20_FA3	40_FA1 40_FA2 40_FA3

[a] Different types of FA were used (i.e. FA1, FA2 and FA3).