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Co-combustion and its impact on fly ash quality; full-scale experiments

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ABSTRACT

As second part of an extensive study on the relation of co-combustion of biomass and fly ash quality, co-combustion fly ashes were investigated from full-scale co-combustion experiments in the Netherlands using agricultural biomass, meat and bone meal, paper sludge and municipal sewage sludge as secondary fuel. The fly ash was investigated in relation to its performance for use in concrete. It was shown that the quality of co-combustion fly ash can be explained from the characteristics of the fuel and the combustion process. Further, it was shown that also fly ash obtained from high co-combustion percentages is able to meet the basic requirements of the European standard for fly ash in concrete (EN 450). Whether an individual co-combustion fly ash does so, depends on the nature of the co-fired fuel and especially on the amount and nature of its inorganic matter.

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1. Introduction

1.1. General

For the past 15 years or so, co-combustion of secondary fuels in coal fired power plants has been an issue of growing importance, as it plays an important role in the reduction of the emission of fossil CO_2. Therefore, the Dutch power companies and the government have agreed to reduce these emissions by signing the covenant “Coal-fired power plants and CO_2 reduction”. The power companies committed themselves to reduce emissions by 3.2 Mton CO_2 on average during the budget period 2008–2012 by replacing coal with biomass. The capacity of power generation with biomass input corresponded to 503 MW_e of the total capacity of 3875 MW_e of the coal fired power plants in the Netherlands At the moment (2014) there is a new commitment between the power sector and the Dutch government, whereby co-combustion will continue to play an important role to reach the 2020 goals namely 20% renewable energy and 30% less greenhouse gas emissions (reference year: 1990).

An important aspect of co-combustion is the quality of the fly ash as it is a valuable resource for the concrete industry. Fly ash is able to replace a significant part of cement in concrete. This replacement has a positive influence on costs, sustainability (less primary materials, reduction of carbon foot print) and enhanced durability. Further, fly ash is used as raw material (mineral source) for the production of blended cements (Portland fly ash cement), Portland clinker (half product of cement) and as raw material for asphalt fillers. Disposal of fly ash in the Netherlands is forbidden according to the Dutch national Waste Management Plan [1]. Moreover, since several years the demand for fly ash is higher than the production in the Netherlands.

Fly ash quality is related to its properties which depend on three aspects, namely fuel (especially its mineral matter), conversion technology and removal technology. The mineral matter in secondary fuels may be different from that in coal due to the different origin, which means that fly ash properties may also be influenced by co-combustion. It implies that to continue the use of fly ash from co-combustion with a guaranteed quality and performance, understanding the influence of co-combustion on fly ash properties is necessary. The goal of this research is to investigate the effects of co-combusting high percentages of biomass from different origins on the properties of the generated fly ash and its performance for use in concrete.

Practical experiences (mainly from the period 1995–2000) with fly ash from co-combustion with a maximum of 10% (on basis of mass fuel input) [2] were positive. In 2001 it became clear that co-combustion would further increase. Therefore more fundamental knowledge was necessary to be able to assess the consequences for the use of the thereby generated fly ashes in concrete and cement industry. This knowledge was generated by first investigating fly ash from co-combustion experiments at pilot-scale [3], which was followed by investigation of fly ashes from

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full-scale co-combustion experiments at several Dutch coal-fired power plants.

The experiments were performed using different biomasses, namely municipal sewage sludge, meat and bone meal, paper sludge and several other biomasses. The generated fly ashes were investigated for its properties and its performance for use in concrete. The results of this investigation are described in this article. First results were presented at several conferences [4,5].

The investigation in fly ashes from full-scale trials consisted of three steps, namely

– Performance of co-combustion experiments and collection of fly ash samples
– Chemical, mineralogical and physical characterization of generated fly ashes.
– Assessment of the performance of co-combustion fly ashes when used in concrete. The requirements of the present European standard for fly ash in concrete (EN 450-1) regarding chemical, physical and performance properties are used as starting point for the assessment. These requirements are listed in Table 1. Requirements regarding maximum variety of fineness and particle density are not listed in the table as these cannot be assessed using fly ash from individual experiments.

1.2. Background information co-fired biomass

Biomass is defined as biological material derived from living or recently living organisms. The ash forming matter in biomass can be divided generally into four groups:

– inherent in biomass, organically associated,
– inherent in biomass, inorganically associated,
– inherent in biomass as salts, ionically bound,
– not inherent in biomass due to contamination, mainly inorganically associated.

Several approaches can be used to classify biomass and other secondary fuels for power generation. From the point of view of ash properties, the following classification [6,7], which is based on ash composition, is most practical:

1. Wood and woody biomass. Examples are wood pellets, wood waste from commercial logging and harvesting and mill residues.
2. Herbaceous and agricultural biomass. This can be herbaceous and other annual growth materials as straw, grass, maize and leaves, but also agricultural residues like olive residue, cacao husks and rice husks.
3. Aquatic biomass like algae.
4. Biomass from animal origin, mainly manure and meat and bone meal.
5. Biomass, contaminated with mineral matter from anthropogenic origin like sewage sludge, paper sludge, solid recovered fuel (SRF) and demolition wood.

These classes are described more in detail in the following, except for aquatic biomass as it was not used in our tests.

1.2.1. Wood and woody biomass

Fifteen mineral elements are essential for growth in higher plants. These can be divided (based on average concentration) in primary macronutrients (N, P, K), secondary macronutrients (Ca, Mg, S) and micronutrients (Fe, Mn, Zn, Cu, B, Mo, Cl, Ni, Co). The macronutrients are present at concentrations of 0.2–5% or even higher, while micronutrient may be present at levels of 0.1–100 mg/kg [8]. The concentration of these elements in plants depends on several factors like the specie, season of year, part of the specie and soil conditions. Furthermore, it is influenced by the way of harvesting, processing and pre-treatment.

Ca, Mg and K are mainly organically associated. E.g. Mg is a compound in chlorophyll ($C_{55}H_{70}O_6N_4Mg$ and $C_{55}H_{72}O_5N_4Mg$) and K is dissolved in the cytoplasm of cells [9]. Phosphorus is a very important element for plant growth. It is a component of lipids, DNA and of ATP (adenosine tri phosphate), which is an essential compound in the energy regulation of organisms. Reproductive parts of plants often contain often relative high concentrations of potassium and phosphorus as a supply before the uptake from the soil starts when new plants starts to grow from the seeds [10].

Contamination with soil during harvesting may increase the amount of ash (forming matter), by increasing the amount of minerals like quartz, clays, feldspar, limestone etc.

The percentage of ash forming matter in wood is relatively low. Woods of temperate zones contain 0.1–1.0% m/m, while those of tropical and subtropical zones contain up to 5% ash [11]. There is a certain dependency of the ash content and ash composition of the location within the tree. The highest ash forming matter is in the needles or the leaves. The sequence of decreasing ash forming matter is subsequently bark > tiny roots > twigs > roots > branches > stem. However contamination with soil during harvesting may influence this sequence. The main components are Ca, K and Mg. In many woods to 50% of the ash content is Ca. In general, bark has high Ca contents related to sapwood. Mineral deposits in wood consist mostly of calcium carbonate, calcium oxalate or silicate. Silicon occurs in plants mainly in the form of silicic acid ($Si(OH)_{4\ aq}$) and precipitated as hydrated amorphous silica

Table 1
Requirements for fly ash (category N) according to EN 450-1.

Property	Unit	Requirement
Loss on ignition (LOI) (class A)	% m/m	≤5.0
Fineness, passing 45 μm	% m/m	≥60[a]
Soluble phosphate (as P_2O_5)	mg/kg	≤100
Total phosphate (as P_2O_5)	% m/m	≤5.0
Initial setting	min.	2C[b]
Sum $SiO_2 + Al_2O_3 + Fe_2O_3$	% m/m	≥70
Reactive SiO_2	% m/m	≥25
Activity index after 28 days and 91 days	%	≥75 and ≥85
Total content of alkalis (as Na_2O equivalent)	% m/m	≤5.0
Reactive calcium oxide (as CaO)	% m/m	≤10.0
Sulfate content (as SO_3)	% m/m	≤.0
Free calcium oxide (CaO)	% m/m	≤1.5
Soundness[c]	mm	≤10
Magnesium oxide (MgO)	% m/m	≤4.0
Chloride (Cl^-)	% m/m	≤0.10

[a] In the standard it is declared as ≤40% may retain on sieve 45 μm.
[b] Initial setting of fly ash cement paste shall not be more than twice as long as the initial setting time of the test cement alone.
[c] If the content of free lime is greater than 1.5% by mass, the fly ash must be tested for conformity to the requirement for soundness.

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