Fuel 118 (2014) 272–280

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

An evaluation of bottom ash from plant biomass as a replacement for cement in building blocks

B. Carrasco [a,*], N. Cruz [b], J. Terrados [a], F.A. Corpas [b], L. Pérez [b]

[a] Department of Graphics Engineering, Design and Projects, University of Jaén, Polytechnic School of Linares, 23700 Linares, Jaén, Spain
[b] Department of Chemical, Environmental and Materials Engineering, University of Jaén, Polytechnic School of Linares, 23700 Linares, Jaén, Spain

HIGHLIGHTS

- Addition of bottom ash from biomass in cement-based material is investigated.
- The mechanical properties were studied following EN standards.
- The best results were obtained with mixtures with a 1:1 weight ratio.

ARTICLE INFO

Article history:
Received 31 July 2012
Received in revised form 27 September 2013
Accepted 30 October 2013
Available online 12 November 2013

Keywords:
Biomass
Bottom ash
Cement
Sustainability
Building block

ABSTRACT

This paper presents the results of research on the effect of adding bottom ash from the combustion of plant biomass to construction material, substituting the ash for Portland cement in proportions ranging from 10% to 90% in mass. After determining the physical, chemical, and mineralogical character of the raw materials, sample building blocks were formed through compression at 20 MPa. The experimental program included a wide range of testing methods such as mechanical strength, XRD, porosity, microstructure, freeze–thaw, thermal conductivity, and environmental safety (heavy metal leachability).

The results demonstrate that the addition of bottom ash increases the material's porosity, thereby decreasing its thermal conductivity and compressive strength. The mixture with a 1:1 Si/Ca ratio shows the best mechanical characteristics (61.11 MPa) with acceptable thermal conductivity value (0.773 W/mK) and could potentially be used in products such as building blocks, since partially replacing the cement with ash produced samples based on criteria of the EN standards. Heavy metal concentration in the leachates of the bottom ash and samples formed are far lower than those recommended in the Spanish legislation (OM AAA/661/2013) and US-EPA standard.

1. Introduction

Community Directives 2008/98/CE on waste and 2010/31/CE on energy efficiency [1] establish measures for preventing and reducing the environmental impact of waste production and management, as well as for the fostering efficient, rational energy technologies that are sustainable in environmental terms. In this research to develop new materials that derive value from the by-products of industrial processes becomes crucial, while also providing an excellent opportunity for the development of new applications initiatives and new sites of use.

In recent years, the use of biomass to generate heat and electrical energy has increased substantially in the European Community, becoming the highest-growth renewable energy. According to the EU's energy predictions, the contribution of this energy is expected to grow to 236–255 Mtep by 2030, an increase of up to 210% in its current market share. In Spain, biomass represents 5.21% of the total energy consumed [2]. Promotion of this technology has led to a sharp increase in the production of combustion waste, especially ash, which is classified as non-hazardous on the European List of Waste [3]. As a result, there is growing interest in finding ways to use this material as a resource with added value.

Ash produced by the process of biomass combustion can be divided into bottom and fly ash. Bottom ash is produced on the grate in the first combustion chamber of the boiler. This portion of the ash is often mixed with impurities from the biomass, such as sand, stone, and dirt [4].

Fly ash is produced by dragging ash from the base of the furnace. It gathers primarily in multi-cyclones placed behind the combustion unit and in electrostatic, ceramic, or bag filters, which are usually placed behind the cyclones.

The chemical characteristics of the ash depend on the type of biomass burned, as well as the transformations that occur during the combustion process at the different temperatures to which

* Corresponding author. Address: Polytechnic School of Linares, C/Alfonso X, 28, 23700 Linares, Jaén, Spain. Tel.: +34 953648538; fax: +34 953648533.
E-mail address: bhurtado@ujaen.es (B. Carrasco).

0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.10.077

they are subjected [5]. This ash is thus a highly heterogeneous product whose composition consists primarily of a few main components: silica (SiO_2), alumina (Al_2O_3), calcium oxide (CaO) and carbon (C). Other components are present in lower proportions. Bottom ash usually accounts for 60–90% of the total ash generated [6].

Disposing of ash as a by-product of biomass combustion is a growing economic and environmental burden. The lack of legislative regulation in most countries encourages its removal to dumps.

Based on both the physical and the chemical properties of biomass ash, bottom ash could be used instead of dumped. Possible applications include its use in fertilizers and land improvement for agriculture and forests, as well as in cements and concretes, ceramic products and construction materials [7–11].

Although extensive research has been conducted recently on industrial by-products and other waste in cement-based materials [12–19], very little of this research treats the effect of the bottom ash from biomass on these materials. Yet using these by-products reduces cost and minimizes the environmental impact of waste disposal and cement production.

The goal of the present study is to consider the viability of using bottom ash from plant biomass to replace cement in cement-based material for use in construction materials (building blocks). Determining the feasibility of substitution involves assessing the effect that adding different proportions of ash has on the physico-mechanical properties of these materials and studying their environmental impact (heavy metal leachability).

2. Materials and methods

2.1. Materials

The materials used were boiler bottom ash (as a source of silica), a by-product of combustion in a steam boiler with a vibrating grate from the biomass power plant Bioeléctrica in Linares (Valoriza, of the Sacyr Vallehermoso group), located in the province of Jaén (Andalusia, Spain) and commercial Type II Portland cement S-L 32.5. The 15 Mw biomass plant uses as fuel a mixture of biomass composed of olive pomace (40%) and agricultural residue (cleared underbrush, olive and fruit tree trimmings, and energy crops (60%)).

2.2. Experimental method

To achieve our research goal, we performed physical, chemical, mineralogical, and microstructural characterization of the materials used before beginning the experiment.

The moisture content of the materials was determined using EN 103300:1993 [20], and their pH using a PCE-PH20S pH-meter.

Particle size distribution was performed using sieve granulometry following EN 933-1:2012 [21] for bottom ash and a laser beam from a Malvern Mastersizer 2000 for the Portland cement.

Thermal behavior was obtained by TGA/DTA analysis using a Mettler Toledo 850 device and subjecting the samples to a heating process at a speed of 20 °C/min from room temperature to 1000 °C.

Real density was measured in an AccuPyc 1340 using helium gas and the specific surface area (BET) by obtaining the N_2 adsorption–desorption at 77 K in a Micromeritics ASAP 2000 Analyzer. We determined the specific surface area (BET) by obtaining the N_2 adsorption–desorption isotherms at 77 K with a Micromeritics ASAP 2000 Analyzer.

The carbon, hydrogen, nitrogen, and sulfur content were determined using elemental analysis in a Thermo Finnigan FlashEA1112 CHNS-O.

The chemical composition was obtained using X-ray fluorescence in an S4 PIONEER sequential wavelength-dispersive X-ray fluorescence spectrometer (WDXRF).

The leachability of heavy metals in the bottom ash was analyzed using the toxicity characteristic leaching procedure according to EPA method 1311(TCLP) [22]. The concentrations in the filtrate were determined using Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES Agilent 7500).

The crystalline phases present in the ash were determined using X-ray powder diffraction in a PANalytical X'Pert PRO MPD diffractometer with CuK1,2 radiation (1.5406 Å) and High Score Plus software. The microstructural analysis was performed by scanning electron microscopy (SEM) using a JEOL SM 840 microscope.

After characterization of the bottom ash and the Portland cement, the appropriate mixtures for the samples were designed.

The bottom ash was dried in an oven at 105 °C and milled in a ball mill until homogeneous particle size was obtained. To reduce agglomeration, the particles were sieved through a 100 μm mesh prior to incorporation in the cement blends.

The next step was to mix the sources in solid state, using a mixer. Nine series were prepared (numbered 1–9), with 16 samples (60 × 30 × 10 mm) weighing 50 g for each homogenized mix (a total of 144 samples) shaped in a Mega KCK-30 hydraulic press. The samples were formed in a cylindrical mold with a rectangular opening by applying uniaxial loads of 20 MPa for 30 seconds. The dimensions of the samples conformed to the specifications of EN standard 772-16:2011 [23].

The blends contained proportions of Si/Ca ranging from 1:9 to 9:1. Two additional control series were prepared using the base materials, with bottom ash and Portland cement constituting 100% of the dry mass, respectively. The proportion of water to mixture was optimized to obtain the consistency necessary for subsequent shaping (Table 3). The mixtures were labeled bottom ash (CF) and Portland cement (CM).

The samples obtained were then subjected to a curing process by placing them in water for 28 days (at 20 °C), in accordance with EN standard 12390-2:2009 [24]. After another drying period, in an oven at 105 °C until stable mass was reached, the samples were tested using EN standards to determine their physical, mechanical, and thermal properties. They then underwent mineralogical and microstructural analysis.

Standard tests EN 772-13:2001 [25] and EN 772-21:2011 [26] were used to evaluate the apparent density and water absorption for all of the series.

Six samples were tested for compressive strength in accordance with Standard Test Method EN 772-1:2011 [27] in a Suzpecar CME 200 SDC Press. All of the samples were subjected to a normal, progressively increasing force, with the load applied to the center of the upper surface of the sample at a speed not exceeding 20 MPa/s to breaking. The compressive strength of each sample was obtained by dividing the maximum load by the average surface area of the supporting faces and is expressed in MPa with an error of 0.1 MPa.

Based on analysis of the test results from all sample series for apparent density, water absorption, and compressive strength and determination of the decision parameters for using the samples as building blocks, the series that fulfilled the dual goal of high values for compressive strength and higher proportion of industrial by-product (bottom ash) were subjected to 25 freezing–thawing cycles, following standard test EN 12372:2002 [28]. The samples that showed exfoliation, fissures, or chipping were rejected. Resistance to freezing–thawing cycles was tested on 6 samples (18 h of freezing, 8 hours of thawing) using a freezer. The samples were saturated by immersion in water for 48 h prior to the freezing–thawing cycles.