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New methodology for assessing the environmental burden of cement mortars with partial replacement of coal bottom ash and fly ash

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ABSTRACT

This paper assess the mechanical an environmental behaviour of cement mortars manufactured with addition of fly ash (FA) and bottom ash (BA), as partial cement replacement (10%, 25% and 35%). The environmental behaviour was studied by leaching tests, which were performed under several temperature (23 °C and 60 °C) and pH (5 and 10) conditions, and ages (1, 2, 4 and 7 days). Then, the accumulated amount of the different constituents leached was analysed. In order to obtain an environmental burden (EB) value of each cement mixture, a new methodology was developed. The EB value obtained is related to the amount leached and the hazardous level of each constituent. Finally, the integral study of compressive strength and EB values of cement mixtures allowed their classification. The results showed that mortars manufactured with ordinary Portland cement (OPC) and with coal BA had similar or even better environmental and mechanical behaviour than mortars with FA. Therefore, the partial replacement of cement by BA might be as suitable or even better as the replacement by FA.

1. Introduction

Concrete and steel are currently the most widely used construction materials. The main component of concrete is cement, which main constituent is clinker. The manufacture of clinker consumes non-renewable resources, both in the fuels and in the raw materials themselves, and releases CO_2. The partial replacement of clinker by additions, like coal combustion residues, minimizes these disadvantages. Furthermore, the use of additions in the cement manufacture modifies the microstructure of the hydrated pastes. In general, the use of additions in cements causes denser hydration products and a more closed porous network than that of Ordinary Portland Cement (OCP). This results in more durable construction materials. (Menéndez and de Frutos, 2009, 2011). From the point of view of wastes, construction materials have normally been used for their inertia and stabilization, avoiding CO_2 gas emissions or reducing the leaching of dangerous substances (Maeda et al., 2011; Lima et al., 2012).

The European standard EN 197–1, 2011 limits both the type and the amount of additions that can replace clinker in cement manufacture. Among these additions, some are industrial by-products, that is, wastes recycled in the production of cement. One of the by-products most commonly used in cement and concrete manufacture is fly ash (FA) from coal-pulverized power plants, which are fine particles collected by electrostatic or mechanical precipitation. Coal power plants also produce bottom ash (BA), which are coarse and glassy particles that fall to the bottom of the furnace and conglomerate. FA represents between 70% and 90% of the coal ashes produced in power plants, while coal BA represents between 10% and 30% (Siddique, 2010). The European production of FA and BA in 2008 was 37.5 MT and 4.8 MT, respectively (ECOBA, 2008). Despite the amounts produced coal BAs have not been used yet as cement additions.

There are differences between FA and BA, both in chemical and physical composition. The chemical composition of coal BA contains lightly more heavy metals than FA. However, BA radioactivity content (e.g. ^{226}Ra, ^{232}Th, ^{40}K, ^{238}U and ^{210}Pb) is lower than that of the respective FA (Karangelos et al., 2004; Puch et al., 2005; Lu et al., 2006). Regarding their physical properties, BA particles are denser and coarser than FA particles (Siddique, 2010; Bai and Bashaer, 2003).

The properties of FA as addition to cement have been widely studied due to they are included as authorized additions to cement in replacement amounts of up to 50% (EN 197–1, 2011 and RC-08, 2008). It can be deduced from these studies that the addition of FA produces properties similar to or even better than Portland

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cement (Papadakis, 1999, 2000). One of the main improvements is the lower demand of water and less heat in the hydration process (González et al., 2009). As regards coal BAs, they have only been used in some applications in the construction industry, mainly as an aggregate to concrete in the manufacture of blocks and as filling material, for example, in the foundations of road construction (ECOBA, 2008; Siddique, 2010; Lee et al., 2010).

Although BA is not considered an addition to cement (Cheriaf et al., 1999), several authors have tested their pozzolanic properties and the compressive strength of cement mortars with partial replacements of BA and these studies have obtained satisfactory results. Jatuapitakkul and Cheerarot (2003) studied the pozzolanic properties and the mechanical strength of mortars manufactured with coal BA, reporting that the pozzolanic activity appears at 28 days of hydration, improving this property with a suitable grind. This fact was also observed by Jatuapitakkul and Cheerarot (2003) and Sanjuan and Menéndez (2011). Good mechanical properties of mortars were observed by Canpolat et al. (2004) and Argiz et al. (2013) when cement was replace for FA, BA or a mixture of both up to 25%. Suitable strength was also observed when cement with 25% replacement was used in the manufacture of concrete (Jatuapitakkul and Cheerarot, 2003). Canpolat et al. (2004) studied the effects of the addition of zeolite and BA or FA in different proportions in Portland cement, reporting that the majority of the cements studied showed compressive strength greater than the CEM I 42.5 cement, according to the European Standards.

However, some suitable pozzolanic and mechanical properties are not enough qualities for reuse these ashes as secondary construction materials (Chatveera and Lertwattanaruk, 2011; Kayhanian et al., 2012). The protection of the environment, especially those aspects related to air, water and soil quality, as well as human health, are essential requirements expressed in the European Construction Products Directive (CPD, 1989). More specifically the CPD focuses on the leaching of dangerous substances from construction materials to the water, which is an especially concern when secondary materials are used (van der Sloot et al., 1997). Therefore, construction materials must be tested with regard to their leaching properties.

Leaching process is influenced by both the characteristics of the material and environmental factors. The multiple variables involved in the process have resulted in multiple types of testing methods, originally used to characterised wastes or wastes stabilized in matrix (e.g. cement matrix). From the point of view of the own material, it can be classified as monolithic or granular. The release of constituents from monolithic materials are mainly controlling by diffusion process while the release of constituents from granular materials are due to percolation (van der Sloot et al., 1997; van der Sloot and Dijikstra, 2004; Barna et al., 2005; Tiruta-Barna et al., 2005).

Cement based materials often behave as porous monoliths. There are different testing methods for monolithic material and several authors using different methods have studied the leaching of dangerous elements from materials made of FA from Municipal Solid Waste Incineration (MSWI). Aubert et al. (2007) used the French Standard NFX 31–211 regulation as testing method in order to obtain the behaviour of the dangerous elements contained in these materials. Sinyoung et al. (2011) and Chai et al. (2009) used the EA NEN 7375, 2004 “tank test method” in order to evaluate the leaching behaviour of chromium, a heavy metal with negative effects on the environment. This method was also used by Ginés et al. (2009) to study this type of addition compared to BA produced in the same process. Cinquepalmi et al. (2008) developed a method for the leaching behaviour of the chemical elements based on the results obtained from the “sequential leach test on monolithic specimens” developed by Kosson et al. (2002).

Table 1
Chemical composition of cement and ashes (%).

Chemical composition	OPC	Fly Ash (FA)	Bottom Ash (BA)
Loss of ignition (LOI)	3.60	3.65	1.85
Insoluble Residue (RI)	2.14	1.03	0.31
Free lime	0.12	0.11	0.07
SiO_2	17.74	54.20	49.97
Al_2O_3	3.49	27.17	26.95
Fe_2O_3	3.42	6.23	8.34
CaO	58.92	6.89	8.28
MgO	1.51	1.16	1.12
K_2O	0.84	0.67	0.78
CO_2	2.11	2.78	0.00
TiO_2	0.23	1.79	2.25
Na_2O	0.20	0.17	0.14
P_2O_5	0.09	0.97	0.95
SO_3	2.88	0.11	0.11
SrO	0.10	0.21	0.29
Cr_2O_3	0.00	0.04	0.05
ZnO	0.03	$\leq$0.01	0.01
Mn_2O_3	0.03	0.05	0.05
Cl	0.01	0.01	0.02

Despite multiple existing test methods, they are not able to assess the complete impact of the material considering proportionally the different hazards of each leached substance. While methods like that used in the French Standard NFX 31–211 regulation are focuses on not to exceed a limited value of several substances, other are occupied on study the complex leaching process calculating leaching parameters like diffusion coefficients (EA NEN 7375, 2004).

In this paper, a methodology was developed to assess the environmental burden of several cement materials by establishing a single value for each one starting from a usual leaching test. This value, denominated Environmental Burden (EB), is related to the relative amount and the hazard level of each substance leached. The methodology was applied to several cement mortars with different proportions of partial replacement of FA and BA from coal fired power plants in order to study the usability of BA as addition to cement from the point of view of environmental impact. Then, the EB values obtained were faced to the compressive strength results to classifying the cement mixtures taking into account both the mechanical and environmental behaviour.

2. Experimental

In this work, mechanical and leaching behaviour of different cement mixtures with FA and BA were studied. First, the compressive strength of cement mortars were tested according to established limits. Then, the leaching test of cement mortars were studied in different test conditions. Finally, a new methodology was developed and applied to the cement mortars studied in order to evaluate and classify them according to their mechanical and environmental behaviour.

2.1. Raw materials and sample preparation

The cement used was an OPC classified as CEM I 42.5 type. FA and BA were collected from the ENDESA – Carboneras power plant (Almería-Spain) because of the satisfactory chemical and physical properties of that FA. This power plant has a power production of 1,158,900 kW and uses coal from South Africa (90%) and Colombia (10%).

The main components of these raw materials was determined by X-ray fluorescence using a Bruker, S8 The Insoluble Residue (RI) was analysed through the sodium carbonate method and the