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Development of fly ash boards with thermal, acoustic and fire insulation properties

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ABSTRACT

This paper presents an experimental analysis on a new board composed of gypsum and fly ashes from coal combustion, which are mutually compatible. Physical and mechanical properties, sound absorption coefficient, thermal properties and leaching test have been obtained. The mechanical properties showed similar values to other commercial products. As far as the acoustic insulation characteristics are concerned, sound absorption coefficients of 0.3 and 0.8 were found. The board presents a low thermal conductivity and a fire resistance higher than 50 min (for 4 cm of thickness). The leaching of trace elements was below the leaching limit values. These boards can be considered as suitable to be used in building applications as partitions.

1. Introduction

Today, coal still remains a major source for energy production worldwide. The use of coal in power plants generates fly ash as well as bottom ash in high quantities. The approximate total annual coal ash production in the world is in the range of 600–800 million tons (Duminga et al., 2014). Coal ashes contain heavy metals and metalloids, i.e. arsenic (As), lead (Pb), zinc (Zn), nickel (Ni), copper (Cu), manganese (Mn), cadmium (Cd), chromium (Cr) and selenium (Se) at trace levels (Pandey et al., 2011) and it can be a problem in order to be re-used.

Several options are available for reuse of coal combustion ashes which gives additional economic benefits. These include the use in civil construction (Kizgut et al., 2010) in waste-water treatment, for the recovery of metals and for the production of materials like zeolites. As brought out earlier, worldwide usage of ash is 15% of its total production (Hui et al., 2009). This proportion is still considerably low compared to the current rate of production of fly ash (1.65–2.20 million tons day^{-1}). Further, in 2013, fly ash usage remained below 2008 levels for a fifth consecutive year in the face of decreasing coal use and general economic stagnation. This is due to eight years of dramatic growth in coal ash beneficial use (American Coal Ash Association, 2015). Hence, it is important to search for fly ash usage options in new sectors.

The protection of the environment should be promoted by the recovery (reuse or recycling) of waste materials. In many cases, recycled materials must compete with low-cost products. However, when the properties of the ashes make its use possible in specific, high added value applications, these products can successfully compete with products made from primary materials, and reduce the environmental costs of waste disposal. Some of the commercial raw materials used for fire partitions in buildings and industrial installations have a chemical composition and properties like those found in fly ashes. For example, the density of fly ash can be as much as one-third less than that of the cement (Bentz, 2010). Mortars with a high fly ash content may exhibit a reduced thermal conductivity, making them more insulating than conventional mortars.

Building and construction works have the largest single share in global resource use and pollution emissions. In developed countries, the built environment is responsible for around 25–40% of total energy use, 30% of raw material use and 30–40% of global greenhouse gas emissions (ISOVER, 2015).

Thermal insulation is the easiest and most efficient way to limit global climate change and carbon emissions today. When used appropriately, savings of up to 50% can be achieved, and higher energy efficiency is possible with higher levels of insulation. Thermal insulation reduces energy consumption of heating and cooling systems, reduces costs and adds comfort and hygiene (EPA, 2015).

Sound insulation in buildings is necessary to minimize the amount of sound transmitted and to reduce the harmful effects it has on people. In short, disturbing noises are a consequence of

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urbanization and are a threat to our health and comfort. Sound insulation is needed in hospitals, schools, offices, etc. to ensure peaceful conditions and productivity. In other environments, studio or work, for example, low noise levels are the most important requirements (García Rodriguez, 2006).

Fire insulation acts as a barrier to restrict the harmful effects of fire on life, safety and property. Active fire protection systems play an important role, but after the start of a fire there is the risk of mechanical failure and the active protection systems will not work properly (Leiva et al., 2012). Therefore, in addition to active prevention measures, structural measures should be taken to slow the spread of fire throughout the building and to neighboring buildings while allowing the evacuation of people. Fire insulation with fire resistant partitions, restricts the propagation of fire. Thus, fire growth is restricted, financial losses can be prevented and an opportunity for firefighters to intervene is gained.

The aim of this work is to develop materials with good insulating properties, which contain a high amount of fly ash, minimizing the land-filling of this waste and decrease other environmental problems such as noise, fires in buildings and incorporate information on leaching of potentially harmful trace.

2. Materials and methods

2.1. Materials

For this study, fly ashes from combustion of Colombian coal in Los Barrios Power Plant (Cádiz, Spain), without any previous treatment have been used. The ashes were collected during two days, with two samplings per day. All the collected ashes were mixed before the analysis and the manufacture of pieces for the different tests. All the samples were manufactured within three months of ash collection.

The chemical composition of the ash is shown in Table 1. These ashes can be classified as F-class ash ($SiO_2 + Al_2O_3 + Fe_2O_3 > 70\%$ wt), according with the ASTM C618 (2012).

With regard to the particle size of the fly ash, the Table 2 shows its size distribution, where most of the particles have a size less than 63 μm.

Gypsum (G) was used as binder because it presents a good fire resistance and acceptable mechanical properties. The commercial gypsum meets the European standards (EN 13297-1, 2009).

Vermiculite was used as an additive. Vermiculite is a hydrated silicate containing magnesium, aluminum and iron and it has a flaky structure. Vermiculite is often added to mortars used for fire protection (Vilches et al., 2005a; Leiva et al., 2012). The vermiculite used in this study is a commercial vermiculite (VERLITE) from Asturias (Spain) having 84.9% of particles below 1.41 mm-size.

Polypropylene fibers of 2–4 cm long and 20–50 μm in diameter was used to increase the mechanical resistance to bending and fissuring in the mortar (Cifuentes et al., 2012).

2.2. Methods

2.2.1. Board preparation

The goal was to come up with a product composed mainly of ash. From the previous work carried out at laboratory scale (Leiva et al., 2012; Arenas et al., 2011), it was concluded that fly ashes are potentially suitable for developing a sound absorbing and fire resistance material with high proportion of ashes as fine aggregate (80%).The final composition of the boards was acquired using an optimization process in which three main objectives were taken into account: (1) fly ash must be the major component (>50% wt), (2) the need for certain minimal mechanical properties, defined by what the products were ultimately expected to be used for (3) acceptable insulating (acoustic, thermal and fire) properties. According to these accounts and the previous studies (Arenas, 2014), the final selection of the composition is shown in Table 3.

Table 2
Particle size distribution of the ash.

Size (μm)	>300	125	100	65	<65
Distribution (%)	1.4	5.8	4.1	8.5	80.2

Table 3
Composition (wt%) of the paste.

Component	Ash	Gypsum	Vermiculite	Fiber
Proportion (wt%)	60	30	9.5	0.5

The solid components shown in the above table were placed in a concrete mixer and were blended until a homogeneous mixture was achieved during 5 min. Then water was added to the mixture and again was blended until a homogeneous paste was obtained.

The paste obtained was placed in molds. The specimens were taken out of the molds after 24 h and left to cure at ambient temperature for 30 days (average temperature: 20 °C; average relative humidity: 45%). This paste was used to make test pieces of different shapes and sizes following the acoustic, thermal, fire and mechanical tests standards.

2.2.2. Physical and mechanical properties

With the aim of characterizing the physical and mechanical properties of the product, the following tests were carried out:

2.2.2.1. Physical properties. The density (ρ) of the mortar was measured by weight and volume (dimensions) measurements. Four specimens were tested.

The pH of the board was measured according to European standards (EN 102035, 1998). A sample of 2 g was taken from the plate and was dissolved into 20 g of water. After 5 min, the pH of the solution was measured. Four specimens were tested.

Water absorption capacity (A) and Water content (Wc) were measured according to European standards (EN 12859, 2011). Four specimens were tested.

2.2.2.2. Flexural (Rf) and compressive (R_C) strength. The compressive (ASTM E761-92, 2011) and flexural (ASTM C348, 2014) strength of the samples were also evaluated using a compressing test machine (Suzpecar, MEM-102/50 t). The compressive strength tests were performed on 4-cm-high, 3.5-cm-diameter cylinders and flexural strength tests were done on 14-cm-high test probes with a 4 × 4 cm base. Three specimens for each test were used.

2.2.2.3. Surface hardness (D). The potential applications of the plates in construction materials, which might be subjected to impact, lead us to analyze the surface hardness of the material (EN 102031, 1999). The principle of the method described in that

Table 1
Chemical composition of the fly ash (wt%).

Parameter	Moisture	Loss on ignition	CaO	MgO	Fe_2O_3	Al_2O_3	SiO_2	K_2O	Na_2O	TiO_2	SO_3
Composition (%)	0.3	3.5	8.4	1.9	2.4	34.4	45.3	0.6	0.4	1.4	0.5