

Development of Acoustic Barriers Mainly Composed of Co-Combustion Bottom Ash

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ABSTRACT

The environmental problem of acoustic pollution is gaining increasing importance for our society. Furthermore, the accumulation of bottom ash and the need for waste management are becoming more and more pressing. This study presents sound absorption and environmental results (leachability EN 12457-4, NEN 7345, and radioactivity tests) for a new product consisting mainly of coal and petcoke co-combustion bottom ash (80 wt %) mixed with Portland cement type II. The combination of three different bottom ash particle size fractions to manufacture a product of 16 cm-thickness which can be used as a panel or noise barrier has been investigated. The acoustic results are similar or even better than those found in porous concrete used for the same application, the mechanical properties are acceptable and the final material presents no environmental risk according to this study.

1. INTRODUCTION

Noise is becoming an increasingly significant concern because of its negative impact on human health. Urban traffic noise is one of the most pervasive types of noise pollution. On densely traveled roads the equivalent sound pressure levels for 24h can reach up to 75-80 dB [1]. Changes in the Regulations have led to the creation of programs under the European Directive on the Assessment and Management of Environmental Noise [2] which are likely to lead to growth in the use of noise barriers as a way of reducing traffic noise.

Conventional barriers are generally designed to reflect a large proportion of traffic noise, which creates a problem when a minimization of sound reflection towards noise sensitive areas adjacent to the highway is required. In addition, in the case of residential and other developed areas on both sides of trafficked roadways, pairs of parallel traffic noise barriers are usually set up. However, the multiple reflections occurring between the barriers may end up causing significant degradation of the single barrier screening performance [3][4]. Therefore, there is a need for traffic noise barriers which absorb noise. These concerns have to lead to major developments in the field of sound absorbing materials [5].

One of the most common materials used for highway noise barrier applications is a combination of lightweight concrete with a hard backing consisting of standard concrete [6]. Lightweight concrete is proportioned by gap grading the coarse aggregates and either eliminating or minimizing the sand volume in the matrix to develop a network of interconnected pores within the material. As a result, the pores inside the material absorb sound energy through internal friction [7].

Many experimental studies have been conducted in the past to develop efficient sound absorbing porous concrete using recycled aggregates as an alternative to normal aggregates [8][9]. This is due to the fact that as industrial wastes continue to accumulate, they are becoming a major problem for the environment as well as for public health. Moreover, the decrease of natural resources is also becoming a problem.

In Spain, over 12% of primary energy consumption came from coal in 2006 [10], thus large amounts of by-products from coal power plants have been generated. Among them, the uses of fly ash in cement and concrete as a natural pozzolan have been reported in many published articles [11][12]. However, relatively few detailed studies have been conducted using bottom ash as a replacement material in the production of cement and concrete [13][14].

The objective of this study is to design a product composed mainly of bottom ash, reusing all grain particle sizes, so that it can be applied in the field of road noise barriers. The best combination of bottom ash particle grain sizes has been studied in order to achieve the greatest acoustic insulating behavior of the product. An environmental study, including leachability and radioactivity tests, has been carried out to analyze its viability as an outdoor construction element.

2. EXPERIMENTAL WORK

2.1 Materials

In this study, bottom ash (BA) from the co-combustion of coal and pet-coke (70/30) in a Spanish power plant has been studied. In addition, ordinary Portland cement type II (CPII) (CEM II/B-L 32,5 N according to EN 197-1 [15]), fine aggregate (Fine) and coarse aggregate (Coarse), in the form of natural river sand and crushed granite were used.

The chemical composition of the different materials, according to ASTM D3682-01 [16], is shown in Table 1, and Figure 1 shows the solids grain size distribution of course materials.

Parameter	BA (%)	CP II (%)	Fine (%)	Coarse (%)
SiO ₂	52.32	13.83	96.21	85.73
Al ₂ O ₃	25.14	3.53	0.76	4.96
Fe ₂ O ₃	9.23	2.26	0.22	2.92
MnO	0.07	0.06	<0.01	0.04
MgO	1.84	0.70	<0.01	0.30
CaO	2.37	59.33	0.13	0.46
Na ₂ O	0.66	0.08	0.05	1.14
K ₂ O	3.72	0.48	0.30	0.99
TiO ₂	1.45	0.19	0.12	0.23
P ₂ O ₅	0.25	0.06	0.01	0.06
SO ₃	0.03	1.68	0.02	0.03
Loss on ignition (750°C)	1.07	15.50	0.3	0.95
Specific gravity (g/cm ³)	2.2	3.1	2.8	2.7

Table 1. Chemical composition (%wt)

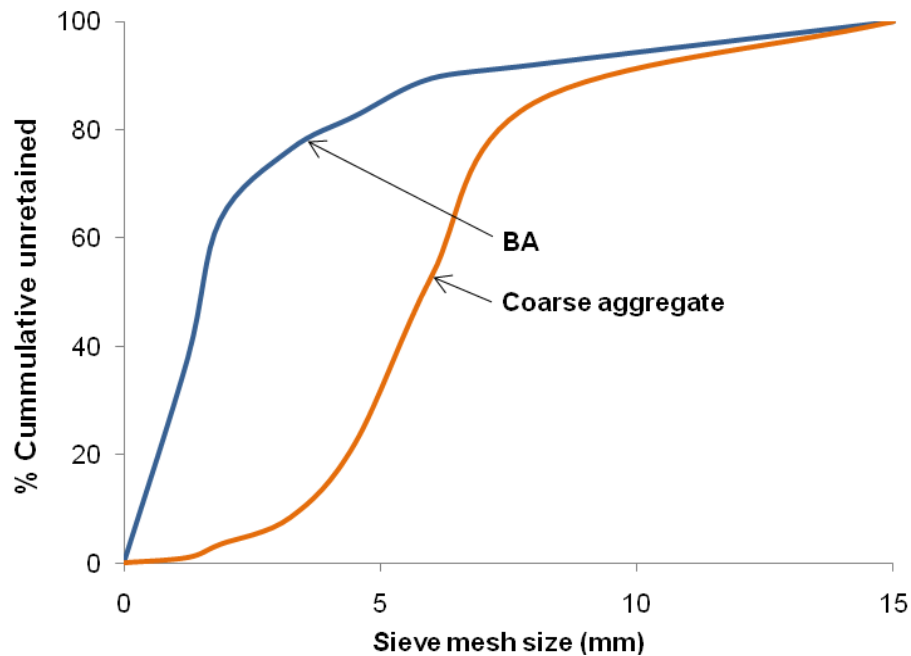


Figure 1. Solids grain size distribution (%)

As shown in Table 1, the sum of the percentages of SiO_2 , Al_2O_3 and Fe_2O_3 reaches 87.7 % in the bottom ash, indicating that it can be classified as an F-type ash as prescribed by ASTM C 618 [17]. The calcium content of the bottom ash is very low. The fine and coarse aggregates are fundamentally composed of SiO_2 ; all other analyzed components remaining insignificant.

As can be seen in Figure 1, BA presents a higher proportion of fine particles than coarse aggregate, which are mainly composed of larger particles.

2.2 Preparation of test specimens

Our goal was to create a product composed mainly of coal bottom ash, elaborated with all grain particle sizes, and good sound absorption characteristics. For this reason, 16 cm-thick specimens were manufactured, from 80% BA- 20% CII mortar and combining three different particle sizes. In order to compare the properties of these materials, specimens made from porous (PC) and standard (SC) concrete were also manufactured. Tables 2, 3 and 4 show the compositions of the mortars and their different combinations.

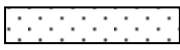
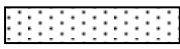

	% BA	% CII	Particle size (mm)	Pattern
BA-C	80	20	$\phi > 5$	
BA-M	80	20	$5 > \phi > 1.25$	
BA-F	80	20	$1.25 > \phi$	

Table 2. Mix proportion (wt% of BA mortars

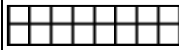

	% Coarse aggregate	% Fine aggregate	% CII	Pattern
PC	80	-	20	
SC	30	50	20	

Table 3. Composition (wt%) of porous and standard concrete

The solid components shown in the tables above were placed in a concrete mixer and were mixed until a homogeneous mixture was achieved. Then, water was added to the mixture and it was mixed again until a homogeneous paste was obtained. When the mixing was completed, the paste was placed in moulds and was compacted twice using a vibration table when half-full and full. The pastes were then taken out of the moulds after 24 hours and left to cure at ambient temperature for 27 days (average temperature: 20°C; average relative humidity: 95%).

2.3 Test Methods

2.3.1 Acoustic properties

When a sound wave strikes a material, a portion of the sound energy is reflected back, another portion is absorbed by the material while the rest is transmitted. The absorption coefficient, α , is the ratio of the absorbed energy to the total incident energy and the reflection coefficient, r , is the ratio of the reflected energy to the total incident energy.

To determine the acoustic properties of the products prepared, the sound absorption and reflection coefficients were determined by the impedance tube method [18] in samples 16 cm thick. The circumferential edge of the test sample was carefully sealed with vaseline, as recommended by the ISO 10534-2, to ensure a good fit between the sample and the tube. A preliminary study was carried out in the impedance tube to analyze the influence of the fit, as in previous studies [8]. Each value represents the average value obtained after testing three samples. The Noise Reduction Coefficient (NRC) was then obtained by calculating the arithmetic mean of the absorption coefficients at 250 Hz, 500 Hz, 1000 Hz and 2000 Hz, in order to make some comparisons.

2.3.2 Physical and mechanical properties

Open void ratio has been measured because this property is related to the acoustic behavior of the products. The method of vacuum water saturation has been followed in the determination of open void ratio ($VR\%$). The samples were oven-dried at $105\pm 5^\circ\text{C}$. Subsequently, they were weighed (W_1) and left under water in a vacuum vessel until saturation was reached. After 24 hours they were removed and weighed again (W_2). The open void ratio was calculated by $VR(\%) = V_W/V_S \cdot 100$, where V_W is the volume in the sample occupied by water and V_S is the total volume of the sample. The volume of water can be found as $V_W = (W_2 - W_1)/\rho_w$, where ρ_w is the density of water.

Density and compressive strength have been measured in order to carry out an exhaustive characterization of the best final product. 10 cm-side cubic test specimens were manufactured. The density (ρ) of the mortar was measured by

weight and volume (dimensions) measurements. The compressive strength (R_c) of the test samples was performed based on ASTM C39/C39M-05e2 [19], using a compressive test machine (Supezcar, MEM-102/50t). Each result was obtained by testing three specimens.

2.4 Environmental study

In order to facilitate its use as a construction material, the product developed in the present study must guarantee a low toxicity level, which is often assessed through a leachability study. The study involved subjecting the different materials to the EN 12457-4 leaching test [20], at a liquid to solid ratio of 10 L/kg, as well as subjecting the product to one of the most commonly used leaching tests for monolith samples in the waste management field in Europe, the NEN 7345 diffusion test or tank leaching test [21]. Leachate metal analysis was carried out using Atomic Absorption Spectrophotometry and Inductively Coupled Plasma techniques.

The radioactivity of the test samples was measured using a well-type HPGe detector from Canberra with a relative efficiency of 30% and crystal volume of 160 cm³. The samples obtained were collected into a cylindrical holder and sealed with paraffin film. Each sample was measured for at least 25 days after the sample was prepared to establish secular equilibrium between ²²⁶Ra and ²³²Th and their respective radioactive progeny. The ²²⁶Ra and ²³²Th contents were measured through the photopeaks of their daughters: ²¹⁴Pb (1.760 MeV) and ²⁰⁸Tl (2.614 MeV), respectively, while the ⁴⁰K content was measured directly via its 1.460 MeV peak.

3. RESULTS AND DISCUSSION

3.1 Acoustic behavior

First, the influence of the BA particle size on the acoustic behavior of the products was investigated. Figure 2 shows the sound absorption and reflection coefficient variation of the products made from different BA particle sizes.

As can be seen in Figure 2, the sound absorption coefficient increases when the BA particle size is larger. This fact is explained by the void ratio results for SOL. BA-C (VR=37%), SOL. BA-M (VR=28%) and SOL. BA-F (VR=11%). Smaller particle sizes leave less void space between particles and this produces a lower VR in the product. The sound absorption of a porous material is related to the

energy loss by friction produced in the walls of its holes. Consequently, SOL. BA-C presents the highest values of the sound absorption coefficient for all the frequency ranges.

The variation of the reflection coefficient is inversely proportional to the sound absorption coefficient. Therefore, lower reflection coefficients are obtained for larger particle size products. In this case, SOL. BA-F presents the best values of the reflection coefficient compared with the other BA products. In general, a product which presents bad sound absorption behavior will probably be a good reflective material.

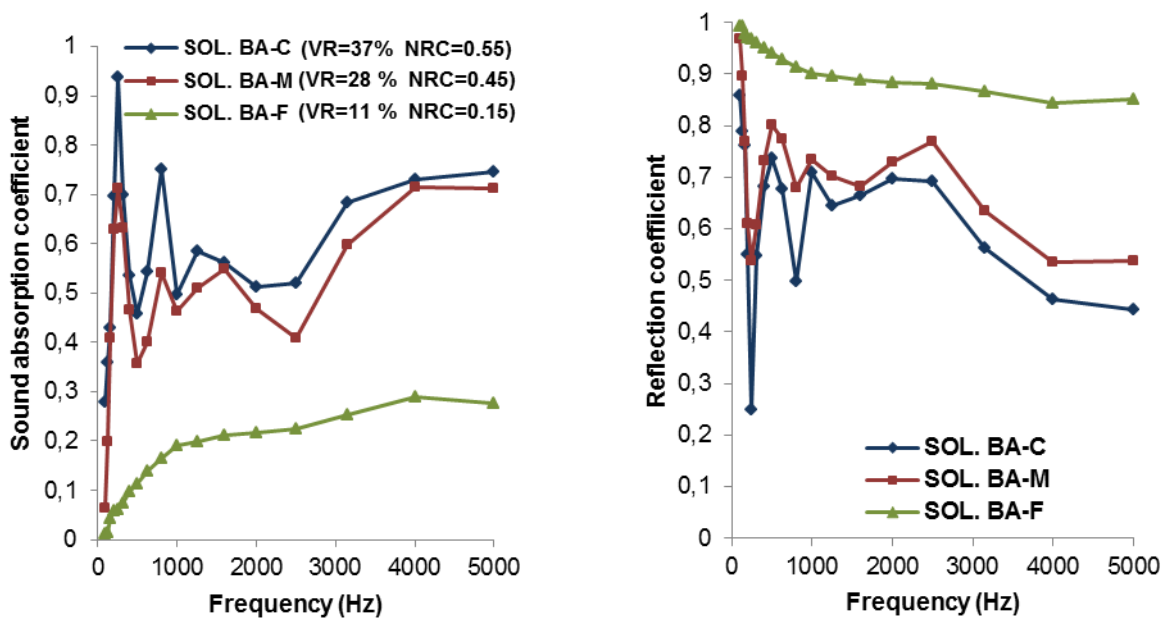


Figure 2. Sound absorption and reflection coefficients for BA products of different particle sizes

In the field of noise barriers, the sound absorption of an acoustic product is considered more important than the sound reflection. However, our goal was to develop a product elaborated with the entire range of BA particle sizes (using the BA as it is produced), although not all of them have the same influence on the acoustic behavior of the product.

Therefore, the next stage of this research consisted in manufacturing a composite product using two or three layers prepared using different BA particle size fractions to be used as a sound absorbing barrier, as indicated in Table 4. The aim was to

analyze the influence of having BA-F in the last layer of SOL. BA-C or SOL. BA-M specimens, to conform SOL. BA-CF or SOL. BA-MF products as shown in the diagrams included in Table 4.

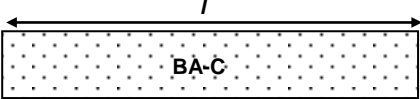


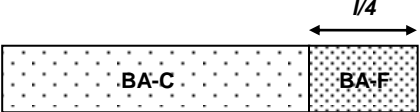

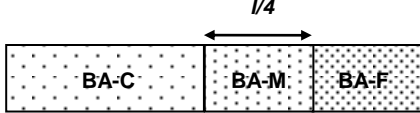
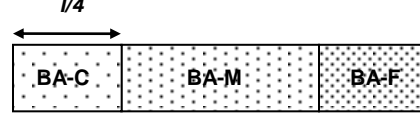
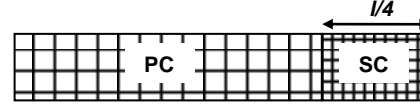
Product name	Combination diagram
SOL. BA-C	
SOL. BA-M	
SOL. BA-F	
SOL. BA-CF	
SOL. BA-MF	
SOL. BA1	
SOL. BA2	
REF	

Table 4. Combination diagrams of different product solutions

The improvement of the sound absorption coefficient in the medium and high frequency ranges for SOL. BA-CF and SOL. BA-MF products are presented in Figure 3. As can be seen, for low frequency (<250 Hz), the measurements are quite similar to those obtained without adding BA-F, however, more differences can be observed for medium and high frequencies (250-5000 Hz). According to the

literature [22] for low frequencies and 10-16 cm product thickness, the speed of the sound wave inside the porous layer is very low. As a result, the energy loss by friction is minimal whether they have a reflective layer or not. On the other hand, for medium and high frequencies, when the sound wave hits the reflective wall it changes its direction so that absorption is increased not only because the friction losses become higher, but also because the reflected and direct waves are coupled. This behavior could explain why some peaks are displaced, and have increased or decreased [22].

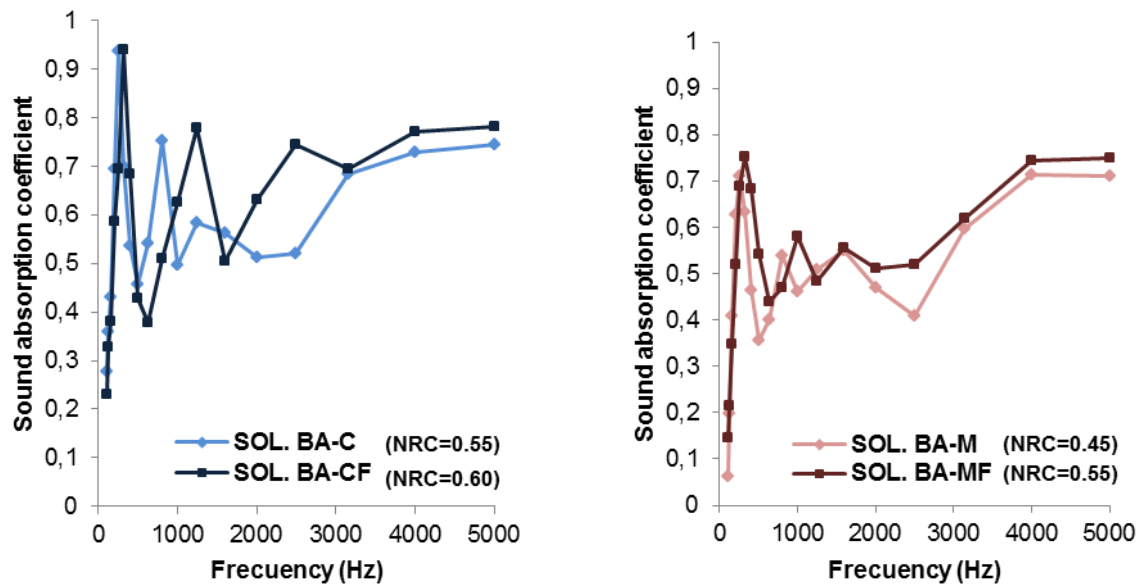


Figure 3. Comparison of sound absorption coefficient in single-layer (BA-C and BA-M) and double-layer products (BA-CF and BA-MF)

Taking into account the results obtained after the second stage, to manufacture an acoustic product elaborated with all the BA particle sizes, the finest material of BA should be used in the last layer of the product (opposite the sound front). In this way, it will probably improve the sound absorption at medium and high frequencies, but will not affect the behavior at low frequencies.

Finally, to completely define the acoustic product achieving our goal of using all the BA fractions, it is necessary to identify the composition of the top layers of the acoustic product. This task was accomplished in the last research phase. The best combination of BA-C and BA-M is given by having BA-C in the incident noise face of the product followed by BA-M, because SOL. BA-C is the layer which showed the best sound absorption coefficient results.

Figure 4 presents the sound absorption coefficient curves for SOL. BA1, SOL. BA2 and for a reference product (REF) made from porous and standard concrete as a conventional acoustic barrier.

The reference product presents the lowest sound absorption coefficient values as can be seen in Figure 4. The combination of both BA mortars has been found to exhibit better sound absorption behavior. According to the results, SOL. BA1 is the best combining solution for the acoustic product in accordance with the sound absorption coefficient. Wider layers of BA-C give better sound absorption coefficient values, because BA-C is the most porous layer, so the energy loss by friction is greater. Compared with BA-CF, although SOL. BA1 presents lower values for the more important peaks, its average sound absorption coefficient (NRC) is higher.

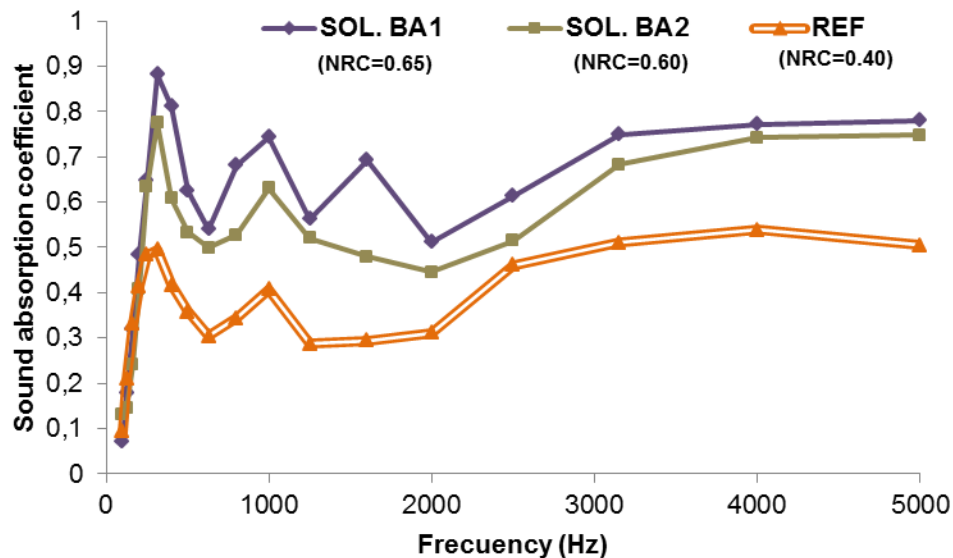


Figure 4. Sound absorption coefficients for SOL. BA1, SOL BA2 and REF

3.2 Physical and compressive strength

Density and compressive strength measurements have been carried out on the best BA acoustic product (SOL. BA1 product), in order to achieve a more complete characterization. Table 5 shows the results obtained.

	Density [kg/m ³]	Rc [MPa]
SOL. BA1	1470	5.1

Table 5. Density and compressive strength of the optimized BA product

The density of the BA product is within the usual values found in similar products used for noise barrier applications. Concrete noise barriers show densities of around 2000 kg/m³. Other acoustic materials made from industrial wastes, such as crumb rubber also show high densities ($\rho = 1800\text{-}2100 \text{ kg/m}^3$) [23], but ceramic formulations obtained using a slag from aluminum recycling process and dust from marble manufacturing present lower densities (800-1200 kg/m³) [24].

Regarding compressive strength, the values measured for SOL. BA1 are similar to those obtained for individual BA-C, BA-M and BA-F in previous research [25]. The compressive strength measured is higher than that found for a porous concrete with the same density, which is around 3 MPa [8].

3.3 Environmental study

The Introduction to the EN 1794-2 standard [26] indicates: “While performing their primary function, road traffic noise reducing devices should not pose hazards to road users or other people in the vicinity or to the environment at large”. EN 1794-2 establishes that road traffic noise reducing devices must specify any physical or chemical condition which could cause environmental problems. This regulation also mentions: “They (the noise reducing devices) should be made from materials which do not emit noxious fumes or leachates as the result of natural or industrial processes or as the result of fire”. In the case of coal bottom ash (and in general when recycled materials are used) the main environmental problem could be the release of heavy metals into the environment through leaching. However, when leachability was assessed, neither standard leaching tests nor any pollutant concentration limits restricting their use in this kind of application could be found.

Therefore, the bottom ash was submitted to the EN 12457-4 [20] test, a leaching test commonly used in the Waste Management field. Moreover, the same test was applied to the other individual components used in this study such as CPII and coarse aggregates. Table 6 shows the leachate results obtained for BA and CA compared with the limits stated by two Spanish standards, the Order on Valorization of Slags from Catalonia (OCVE) and that of the Basque Country (PV).

Although these standards are related to metallurgical slags used in pavement base courses, they can be used as guidance.

The leaching results for BA and CA are always below the limits stated by OCVE. When a comparison with PV order is made, Se and Cd limit concentrations are exceeded. However, the high detection limit of the analytical method used for measuring Se and Cd does not allow for the drawing of any conclusions regarding the accomplishment of the PV limits. BA and CA leaching results are similar to each other except in the case of V where a greater concentration in the leachate of BA has been detected.

	BA (mg/kg)	Coarse aggregate (mg/kg)	OCVE limit (mg/kg)	PV limit (mg/kg)
Hg	<0.005	<0.005	0.01	-
Se	<0.025	<0.025	0.1	0.007
Sn	<0.01	<0.01	-	-
Pb	<0.01	<0.01	0.5	-
Ba	0.037	0.23	20	17
Cd	<0.01	<0.01	0.04	0.009
Sb	<0.01	<0.01	0.06	-
Co	<0.01	<0.01	-	-
Cr	0.01	<0.01	0.5	2.6
V	0.37	<0.02	-	1.3
As	0.11	<0.05	0.5	-
Mo	0.04	<0.02	0.5	1.3
Ni	0.032	0.05	0.4	0.8
Zn	<0.01	0.18	4	1.2
Cu	<0.01	<0.01	2	-

Table 6. Leaching test EN-12457 results compared with the metal concentration limits stated in the Order on Valorization of Slags from Catalonia (OCVE) and that of the Basque Country (PV)

Given the scarcity of standards existing in Spain regarding the reuse of secondary materials in the building industry, the Dutch regulations stated in the Decree of Soil Quality (DSQ) 2007 [27] have also been considered. The DSQ contains rules related to the use of different materials in construction aimed at preventing pollution of the soil and surface waters. Unlike leaching test EN-12457-4 (which

can be considered the most unfavorable leaching conditions), the NEN 7345 diffusion test or tank leaching test is the test prescribed by DSQ for bound or shaped materials. Thus, Table 7 shows the results of the leachability study carried out to SOL. BA1 and standard concrete (SC) specimens compared with DSQ limits.

As shown in Table 7, leaching test results for SOL. BA1 are under the DSQ limits in all cases. The same result was obtained for SC. Therefore, no leaching problems are expected for the use of the acoustic product made from BA developed in this study according to DSQ.

	SOL. BA1 (mg/m²)	SC (mg/m²)	DSQ limit (mg/m²)
Hg	≤0.1	≤0.1	1.4
Se	≤0.7	≤0.4	4.8
Sn	≤1.5	≤0.3	50
Pb	≤0.8	≤0.3	400
Ba	13.1	≤0.9	1500
Cd	≤0.2	≤0.1	3.8
Sb	≤1.3	≤0.4	8.7
Co	≤0.2	≤0.1	60
Cr	16.8	3.4	120
V	4.8	2.6	320
As	≤2.8	0.1	260
Mo	≤0.4	1.7	144
Ni	≤0.2	≤0.7	81
Zn	≤2.7	≤0.1	800
Cu	≤0.2	≤0.2	98

Table 7. Leaching test NEN 7345 results compared with DSQ limits

The radiological safety of building materials based on combustion waste is ensured by complying with limitations set out by international recommendations and national legislation [28-32]. In Spain, as previously mentioned in the leaching tests section, there is no legislation for this kind of product. International recommendations [30] allow the selection of an effective dose increment constraint in the range 0.3-1.0 mSv/y for prolonged exposure to natural radiation by a

member of the public. The effective dose takes into account, in addition to the energy absorbed by the body due to exposure to radiation, the relative biological harm and the susceptibility to harm of different biological tissues.

The activity concentrations of radionuclides ^{226}Ra , ^{232}Th , and ^{40}K in the samples of SOL. BA1 and CPII tested are presented in Table 8. Results show that the activity concentrations of radionuclides are higher in BA than in CPII. In any case, the activities of the different radionuclides are below the European recommendations for standard concrete and aerated concrete (European Commission Radiation Protection, 1999).

Activity concentrations (Bq/kg)	SOL. BA1	CPII	Radiation Protection 112 limits	
			Concrete	Aerated concrete
Ra-226	66	4	260	260
Th-232	60	7	190	290
K-40	741	29	1600	1600
I	0.407	0.058	< 1	

Table 8. Activity concentrations (Bq/kg) of radionuclides ^{226}Ra , ^{232}Th , ^{40}K and the activity concentration index, I.

For practical purposes, the evaluation of the compliance of a specific building material with the limits of international recommendations is carried out using the activity concentration index “I”. This index is expressed in terms of activity concentrations of the three major natural radionuclides: ^{226}Ra , ^{232}Th , and ^{40}K , according to the equation:

$$I = C_{\text{Ra-226}}/300 + C_{\text{Th-232}}/200 + C_{\text{K-40}}/3000$$

Where $C_{\text{Ra-226}}$, $C_{\text{Th-232}}$, and $C_{\text{K-40}}$ are the activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in $\text{Bq}\cdot\text{kg}^{-1}$ in the building material tested. To comply with the regulations (based on the annual dose increment constraint of 0.3 mSv/y) the activity concentration index calculated for the product tested must comply with the criterion: $I \leq 1.0$. The results of Table 8 confirm a potential for industrial use of BA because “I” is under this criterion.

4. CONCLUSIONS

The main goal of this experimental study was to develop a product composed mainly of coal bottom ash presenting good noise absorption characteristics. The co-combustion BA studied is used as produced, first separating three particle size fractions and making them a composite product using the fractions in three different layers. In the course of this study, the following conclusions were reached.

- The grain particle size of BA is related to the acoustic behavior of the product made from BA. The best sound absorption coefficients have been measured in products made from the larger BA particle sizes. On the other hand, good reflective properties have been found in the products made from the finest particles.
- Combining the finest BA particle sizes in the last layer of a two-layer product along with other BA particle sizes in the incident noise face, achieved an improvement of the sound absorption coefficient of the composite product, especially at medium and high frequencies.
- The combination of the three different BA particle size fractions so that the whole BA can be recycled in this kind of application has been optimized from a sound absorption point of view. The product is composed of a wide layer containing the larger BA particles in the incident noise face of the product, followed by the material made using the medium BA particle size and finally, the finest BA particle size material. The BA product thus developed presents better sound absorbing behavior than a porous concrete reference product.
- The optimized BA acoustic product presents density and compressive strength properties similar to those found in barriers made of conventional or recycled products.
- From an environmental point of view, the BA product developed has presented no significant problems regarding both leaching and radioactivity according to some general regulations.
- Coal and pet-coke co-combustion bottom ash can thus be recycled as road noise barriers in view of the results obtained. The product made of 80% BA shows similar properties to other conventional materials used in this application.

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