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Experimental study of a noise reducing barrier made of fly ash

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ABSTRACT: Although fly ash is commonly used as an additive to cement, large amounts of this material are disposed in landfills. To mitigate, it would be interesting to develop new products in which fly ash can be easily used and required in large quantities. In this work, fly ash is added to manufacture eco-friendly materials with acceptable acoustic and non-acoustic properties and a low cost. We built a barrier composed of fly ash (60 wt.%), type II Portland cement (25 wt.%), vermiculite (14.5 wt.%) and polypropylene fibers (0.5 wt.%). The barrier complied with the mechanical requirements of European standards. The sound absorption coefficient and the airborne sound insulation were determined in a reverberation room, and the barrier was classified as A2 and B3. No leaching problems were observed.

KEYWORDS: Fly ash; Sound absorption; Airborne sound insulation; Heavy metals.

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RESUMEN: *Estudio experimental de una barrera acústica compuesta de cenizas volantes* . Aunque las cenizas volantes se usan comúnmente como una adición en la fabricación del cemento, grandes cantidades se siguen depositando en vertedero. Para mitigar este problema, es interesante desarrollar nuevos productos en los que las cenizas volantes se puedan usar fácilmente en grandes cantidades. En este trabajo, se emplean cenizas volantes para fabricar materiales con una alta absorción acústica, con propiedades mecánicas aceptables y un bajo coste. Se ha construido una barrera compuesta de cenizas volantes (60% en peso), cemento Portland tipo II (25% en peso), vermiculita (14.5% en peso) y fibras de polipropileno (0.5% en peso). La barrera cumplió con los requisitos mecánicos establecidos de las normas europeas. El coeficiente de absorción acústica y el aislamiento acústico en el aire se han determinado en una sala de reverberación, y la barrera se clasificó como A2 y B3. No se han observado problemas de lixiviación.

PALABRAS CLAVE: Cenizas volantes; Absorción acústica; Aislamiento acústico en el aire; Metales pesados.

1. INTRODUCTION

Noise pollution can cause health problems to people, particularly when it is due to close proximity to overcrowded roads or highways. It is estimated that 40% of the population of the European Union (EU) is exposed to road traffic noise with an equivalent sound pressure level above 55 dB(A) during the day and 30% of the population is exposed to it at night (1). A way of reducing traffic noise is the use of noise barriers (2). Conventional barriers are generally designed by using non-porous materials, so that a great proportion of the noise is reflected. Nonetheless, a problem is created when a minimization of sound levels is required on both sides of the road, since traffic noise barriers should absorb the noise and not reflect nor transmit it.

Waste is a problem from an environmental, social and economic point of view. Nowadays, a large amount of waste is generated and, consequently, great efforts are required to reduce, prevent and/or reuse it. The European Waste Directive (3, 4) promotes the recycling, reuse and extracting of valuable substances from waste, minimizing the disposal of waste in landfills and the consumption of natural raw materials. Thus, types of waste that used to be considered disposable in the past have potential value as a resource today.

In the last few years, construction materials composed of industrial waste (e.g., tyres, plastics, aluminium slags, marble dusts, foundry sands and recycled expanded polystyrene from recycling tetrabriks and other types of packaging) with interesting acoustical properties (2, 5) have been developed.

Although the recycling of industrial waste into raw materials has increased in recent years, low recycling rates are observed. In addition, few recycled construction materials have similar or better properties compared to commercial products. The key challenges are: (I) there is a lack of technical regulations on the use of waste in specific building materials; (II) many different chemical compounds, including dangerous ones (e.g., heavy metals) may be present in the waste depending on the production process involved; (III) prototypes and tests are required at semi-industrial scale to compare the properties of commercial and recycled materials; and (IV) some waste materials need previous treatments (e.g., sieving, gridding), which increases the final cost of the recycled material and hampers its financial viability.

Despite the reduction of coal consumption in favor of renewable energies, coal still provides 15% of global primary energy production in Spain and 37% in the United States. In 2018, only around 58% of fly ash (FA) was reused in the USA (6), primarily as a concrete constituent, supplementary cementitious material, road construction soil amendment and structural fill (6) and, more recently, to develop geopolymers (7). New applications should be developed to promote and maximize the utilization of the unused fraction of FA.

The sound absorption coefficient of barriers mainly composed of fly ash was analyzed by using a Kundt tube at laboratory scale in a previous study (8). The results showed that a sound absorbing barrier composed of fly ash (60 wt.%) had a similar sound absorption to that of typical acoustic barriers.

The main aim of this study was to develop a prototype of a sound absorbing barrier following a low-cost and simple manufacturing procedure similar to that of concrete noise barriers that can satisfy the requirements for road traffic noise reducing devices.

2. MATERIALS AND METHODS

2.1. Materials

Fly ash was obtained from traditional pulverized coal combustion. Portland cement, vermiculite and polypropylene fibers were also used.

We used type II Portland cement (PCII) with 32.5 MPa compressive strength according to EN 197-1 (9). We used PCII because it was the most economically efficient cement. Although its mechanical properties were below 42.5 MPa, according to a previous study (8), mechanical properties of materials with 32.5 MPa cement are appropriate.

Vermiculite is a hydrated silicate that contains iron, magnesium and aluminium and has very low specific density (0.15 g/cm^3). Materials used to manufacture sound absorbing devices usually contain vermiculite (10, 11). The vermiculite used in this study was a commercial product (VERLITE) manufactured in Asturias, Spain, with 85 wt.% and particle size below 1.4 mm. Polypropylene fibers range from 20 to 50 μm in diameter and 40 mm in length. They were added to enhance flexural strength (12).

Table 1 shows the chemical composition, specific gravity and loss of ignition (LOI) of FA and PCII. The chemical composition was determined according to the ASTM D3682-13 standard test method (13). The main components in FA are SiO_2, Al_2O_3 and Fe_2O_3. FA can be classified as an F-type ash in accordance to ASTM C 618-17 (14) that has a low content of K_2O; MgO, Na_2O and CaO.

Specific gravity was determined according to the EN 1097-7 standard (15). The specific gravity of the fly ash (2.7) was lower than that of PCII (3.1).

Figure 1 shows the particle size distribution of FA, where most of the particles had a size ranging between 0.2 and 100 μm, although the prevalent particle size ranged between 5 and 30 μm. Fly ash had a slightly lower particle size than PCII.

We performed a leaching test of the fly ash in accordance with EN 12457-4 (16) to determine any risk to the environment or human health due to the leaching of heavy metals. We compared the results obtained (Table 1) with the European Landfill Directive (17). The Directive establishes three different categories: inert, hazardous or non-hazardous. As shown on Table 1, FA can be classified as non-hazardous waste, with molybdenum content slightly above the inert waste limit. Note that this leaching test reproduces unfavorable conditions but does not adequately represent the behavior of the final construction material.

2.2. Barrier composition

Previous studies (8, 11) have determined the optimal fly ash/cement/vermiculite ratio to develop a material with high sound absorption - by using an impedance tube - and acceptable compressive strength using the highest possible amount of fly ash. In this study, we built a semi-industrial scale prototype based on the best dosage previously determined in (8) and tested it in an accredited laboratory. We also characterized other acoustic and non-acoustic parameters in much greater detail.

We concluded that 60 wt.% of fly ash is appropriate for developing an adequate sound absorbing porous material. We also used 14.5 wt.% expanded vermiculite to increase open porosity. We added a dosage of 0.5 wt.% polypropylene fibers to increase the mechanical properties based on a previous study (18). The composition of the barrier is presented in wt.% in Table 2. However, the same values are very different when they are expressed in v/v% because of the specific densities of their components. Vermiculite (% v/v) = 76.1; FA (% v/v) = 17.2; PCII (% v/v) = 6%. The purpose of showing the values in wt.% rather than v/v% in Table 2 was to show the mixing dosage and allow researchers to reproduce these results.

2.3. Barrier manufacture

The solid components (i.e., fly ash, cement, vermiculite and fibers) were added in a vertical mixer and were rotated for 5 minutes. Next, water was poured into the mixer and rotated for another 15 minutes.

Due to the different particle size distribution of cement, fly ash and vermiculite, the mixture could be considered a mortar. This mortar was used to cast test specimens of different sizes and shapes for the different acoustic, mechanical and fire tests. They were demolded 24 hours later and cured for 27 days (relative humidity: 45%, temperature: 20 ºC). The intention was to manufacture the panels in a similar way as they are made in situ on the road. Higher relative humidity (e.g., submerging the samples in a water bath) could yield better mechanical properties

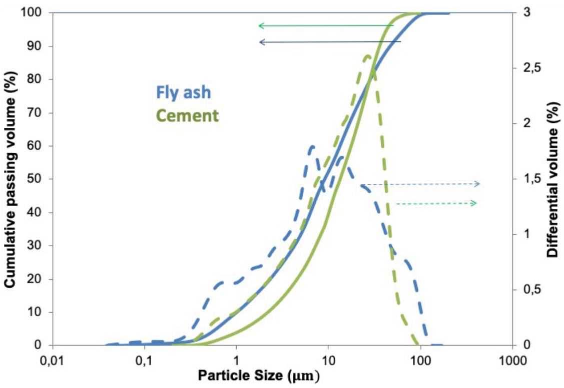

Figure 1. Particle size distribution of fly ash and cement.

Table 1. Chemical compositions of PCII and FA (wt.%) and results of the leaching test (EN 12457-4). Comparison with the European Landfill Directive.

	FA	PCII	Leaching test (mg/kg)	FA	Inert	Non- hazardous	Hazardous
SiO_2	45.3	13.83	**Hg**	<0.01	0.01	0.2	2
Al_2O_3	34.4	3.53	**Se**	<0.03	0.10	0.5	7
MgO	1.9	0.7	**Ba**	0.32	20.00	100	300
Fe_2O_3	2.4	2.26	**Pb**	<0.03	0.50	10	50
Na_2O	0.4	0.08	**Cr**	0.17	0.50	10	70
CaO	8.4	59.33	**Cd**	<0.03	0.04	1	5
TiO_2	1.4	0.19	**Mo**	0.97	0.50	10	30
K_2O	0.6	0.48	**As**	0.21	0.50	2	25
SO_3	0.5	1.68	**Ni**	<0.01	0.40	10	40
LOI	3.5	15.5	**Cu**	<0.01	2.00	10	50
Specific gravity	2.72	3.10	**Zn**	<0.01	4.00	20	50

TABLE 2. Composition of the barrier.

	Fly ash (% wt)	Portland cement (% wt)	Vermiculite (% wt)	Fibers (% wt)	Water/solid ratio
FA barrier	60	25	14.5	0.5	0.5

but did not influence the acoustic properties of the barrier.

2.4. Test methods

The barrier characterization (non-acoustic and acoustic) was conducted in compliance with the European standards for road traffic noise reducing devices. The legislation framework comprises EN 1793-1 (19) for acoustic characterization, and EN 1794-1 (20), EN 1794-2 (21) and EN 1794-3 (22) for non-acoustic properties. EN 14388 (23) shows the different requirements for these tests. The results were also compared to the properties of other construction materials commonly used in the same applications.

The sound absorption coefficient complied with EN ISO 354 (24) in the reverberation room. The test was performed in the INERCO-ACÚSTICA laboratory at 14 ºC, in a room with a volume of 150 m^3, with a relative humidity of 32% and a static pressure of 1 atm. The standard requires a minimum surface area of 10 m^2. This requirement was adjusted to 3.08 m^2 due to the limitations of the research methodology. Small samples and/or reverberation chambers are not new at all and there is great interest in them, despite the fact that they are not standardized (25, 26). Nevertheless, the room volume provides a diffuse sound field. Additionally, a previous study (25) showed a coefficient of determination of essays with limitations similar to those of our study versus standardized size, showing a coefficient of determination very close to 1 at frequencies higher than 400 Hz. Consequently, it was determined that the results could be used for comparison purposes.

The acoustic absorption assessment index (DL_α) was determined according to EN 1793-1 (19) from the sound absorption coefficient.

The transmission loss index (*R*) was calculated using the airborne sound insulation test, as defined in EN 10140-2 (27) by the INASEL authorized laboratory. The data were the following: air temperature 17ºC, static pressure 1 atm, relative humidity 36%, barrier surface 3.08 m^2, receiver room volume 66.2 m^3 and transmitter room volume 57.4 m^3. The transmission loss assessment index (DL_R) was determined according to EN 1793-2 (28).

The mechanical characteristics were determined experimentally. Compressive tests were carried out according to (29) using 50 × 50 × 50 mm-sized cubes. All the cubes were made of the same matrix to avoid any differences in the properties of the material. The load was progressively increased at a rate of approximately 0.5 MPa/s until the specimen was completely ruptured. Flexural tests were carried out according to (30) using 40 x 40 x 160 mm samples. Impact strength tests were carried out according to (31) and superficial hardness tests were carried out according to (32), both on panels of 160 x 160 x 40 mm.

The open void ratio (VR) was determined since it is strongly related to the acoustic behavior of materials. A vacuum water saturation method was followed (33). Samples were previously dried at 105 ºC in a furnace. Next, they were weighed (S1) and submerged in water in a vacuum vessel until saturation. Subsequently, they were lifted out of the water and weighed (S2). The open void ratio was determined as VR (%) = WV/SV·100, where WV is the water volume and SV is the total volume of the sample. Water volume can be calculated as WV=(S2-S1)/ρ_w, wherein ρ_w is the water density. The density was determined by weight (S1) and volume (dimensions) of the samples. The pH was measured as defined in EN 12859 (32). Five grams of barrier were extracted and left in contact with water in a mass ratio of 10/1 (water/solid). The pH was measured after 5 minutes. The moisture content (MC) was determined according to EN 12859 (32). The mass of the barrier at ambient temperature (C1) and after heating at 40 ºC until reaching a constant mass (C2) were determined. The MC value is MC=100·(C2-C1)/C1.

Four different samples were tested for physical and mechanical characterization.

According to the environmental and general safety regulations defined in EN 1794-2 (22), the resistance of a noise reducing device must be measured in the case of a fire in the brushwood nearby. Hence, a fire test was carried out according to EN 1363-1 (34). For the fire test, small panels (270 × 320 mm and 20 and 40 mm thick) were prepared. These two thicknesses were chosen (40 mm was the maximum) because the size of the furnace for the fire test did not make it possible to test panels of 120 mm in thickness.

As regards environmental safety, Table 2 shows that fly ash can be classified as non-hazardous waste and therefore that its use in acoustic barriers is not harmful to people or the environment Nevertheless, the final material was subjected to the NEN 7345 tank leaching test (35). This is a monolithic leaching test that makes it possible to assess the leaching of heavy metals from the final material and not only from the raw materials separately. This is

Figure 2. Sample of the FA barrier.

important when wastes are mixed with other solid materials like cement, because a solidification/stabilization process occurs. The main leaching factor in construction materials is rain, which mainly affects the outer surface of the construction material. One of the advantages of this test is that it simulates rain conditions.

3. RESULTS

All the acoustic and non-acoustic parameters required by the various standards for road traffic noise reducing devices using this material were assessed. Specifically, physical and mechanical properties, fire resistance and environmental impact; only wind resistance was not evaluated. It should be noted that some of the tests had limitations, which are mentioned in the text.

3.1. Physical properties

Physical properties are shown in Table 3. As observed, open porosity was high, although porous concretes, used as sound absorbing materials (composed only of cement and coarse aggregates) can reach 40% (36).

As observed in Figure 2, the porosity of the FA barrier presented a flaky structure due to the effect of the vermiculite and its pore size between 1 and 3 mm, while porous concretes show values between 3 and 10 mm of pore size according to a previous study that used X-ray computed tomography (37). Open porosity is strongly dependent on particle size and increases when a larger aggregate is used. Typical porous concrete (with coarse aggregates between 5-10 mm) has predominant pore sizes above 7 mm with a total porosity of 46%, while FA barriers (with vermiculite particle size lower than 1.14 mm) have pore sizes ranging mainly between 2 and 4 mm and a total porosity of 40%.

According to EN 12859, the barrier was classified as medium density (between 800 and 1100 kg/m^3). The density of the FA barrier was lower than that of a porous concrete commonly used to build road traffic noise reducing devices (900-1100 kg/m^3) (36). Despite this, the specific density of the fly ash and vermiculite was lower than that of cement and coarse aggregates (2.7 g/cm^3), resulting in a material with lower density. According to EN 12859, the barrier was classified as having normal pH (in the range between 6.5 and 10.5), which was lower than that of other barriers composed mainly of wastes (36). Moisture (M) was higher than in gypsum barriers (18) or other porous concretes (36). This was due to the fact that the water was located in the flaky structure of the FA barrier, while the larger pores of porous concrete cannot store much water.

3.2. Mechanical properties

Table 3 presents the mechanical properties of the barrier. Compressive and flexural strengths were low because of the porous and flaky nature of the barrier, which reduced the cohesion between the fly ash, cement and vermiculite. Other porous concretes with wastes have a compressive strength between 5 and 10 MPa (37). Flexural strength was higher than 0.6 MPa, the minimum level established for gypsum barriers (32), and higher than that of other porous concretes containing wastes (5, 36). The addition of fibers increased flexural strength due to its bridge effect, but this did not have a significant influence on compressive strength (18).

Table 3. Physical and mechanical properties of the barrier.

OVR (% wt)	32.0	**Compressive strength**	2.5 MPa
Density (kg/m^3)	886.9	**Flexural strength**	1.3 MPa
pH	9.7	**Impact resistance**	18 mm
M (% wt)	7.2	**Superficial hardness**	42 Shore C

EN 1794-2 (21) sets the requirement of the strength of noise reducing devices to withstand the impact if stones thrown from the road. It establishes that barriers must resist the impact of stones. The impact resistance of the FA barrier was higher than that of other recycled porous barriers, in which the diameter of the ball mark was around 20 mm (36).

Superficial hardness was low compared to the values of other barriers made with similar dosages of wastes (>60 Shore C) and was below the limits established for other types of barriers (non-acoustic applications: >55 Shore C for densities between 800 and 1000 kg/m^3) (37). The low superficial hardness was due to the effect of the expanded vermiculite, which is a highly elastic material and therefore reduces superficial hardness (38).

3.3. Acoustic properties

Figure 3 shows the sound absorption coefficient from the reverberation room test. The absorption coefficient was low for frequency bands below 200 Hz and reached 0.7 at 4000 Hz. This trend is comparable to the results shown by other researchers in noise reducing devices made from other wastes and with similar physical properties (24, 37).

The regulation establishes that DL_α must be calculated according to (19), according to which the barrier was classified in Category A (see Table 4). DL_α was 4.1 dB, leading to the classification of the material as A2. Porous concretes have a slightly higher DL_α, but they are classified in the same category (39, 40). Sound absorption is generally linked to the energy losses produced by the friction of sound waves in the wall holes. Thus, materials with a low open void ratio usually have a low sound absorption coefficient at different frequencies. However, the flaky structure of the FA barrier enables it to retain small air particles that absorb noise and reduce the reverberation time in a wide range of frequencies, increasing total absorption despite its low open porosity (41).

In addition, R was determined by adapting EN 1793-2 (28). Figure 3 presents the transmission loss of the FA barrier at different frequencies. From the transmission loss index, DL_R can be obtained in accordance with the standard established in (28); this led to the classification of the product in Category B (see Table 4). The DL_R of the fly ash-based product was 29 dB, so the product was classified in Category B3. Commercial concrete barriers usually consist of a combination of two layers: one made of porous concrete (50-100 mm of thickness), which absorbs the noise, and a hard-backing layer of non-porous concrete (50-150 mm of thickness), which increases the transmission loss index. In this case, the FA barrier is composed of a single layer, which makes its manufacture easier. Nonetheless, the FA barrier belongs to the same category as porous concrete noise barriers (40, 41).

3.4. Fire resistance

Figure 4 shows the change of temperature versus time on the non-exposed surface of the barrier when

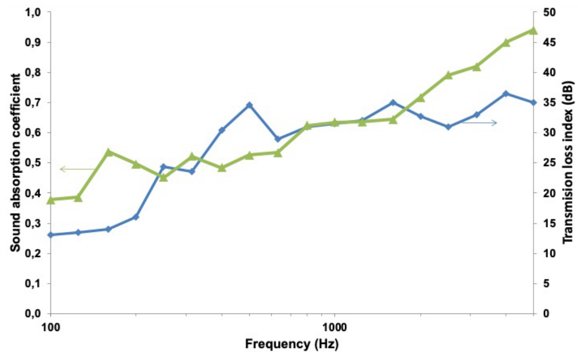

FIGURE 3. Sound absorption coefficient and transmission loss index at different frequencies.

the reverse is bearing the fire. Fire resistance can be defined as the time necessary to reach 180 ºC on the surface that is not exposed to the fire. This value was 22.4 and 34.2 min for barriers 20 and 40 mm thick, respectively. The duration of the evaporation plateau is the main factor that determines fire resistance. It is the time during which the temperature of the surface not exposed to fire remains constant at a temperature slightly below 100 °C. This is because porous construction materials have a high water retention capacity (7, 42). Fire resistance was lower than in other barriers using gypsum as binder, due to the high chemically bound water included in the gypsum (43), but such barriers cannot be used in outdoor environments because they have durability problems. However, it was higher than in other typical porous concretes used in sound absorbing barriers (34), because the flaky structure contains more water than the coarse aggregates of traditional porous concretes. An increase of the thickness led to a higher fire resistance. Hence, a barrier 120 mm thick would have about 110 min of fire resistance (44). In addition, no smoke was emitted from the barrier at any time during the fire test.

After the fire test, we analyzed some physical and mechanical properties of the FA barrier (Table 5). The mechanical properties after the fire test decreased as a result of mass loss during the fire. This loss is related to the free (humidity) and chemically bound water of the mix, which increases porosity and reduces mechanical strength. The decrease of superficial hardness was lower on the non-exposed surface, because the temperatures were lower than those on the exposed surface.

TABLE 4. Different categories according to DL_α (19) and DL_R (28).

Categories for sound absorption	A0	A1	A2	A3	A4	A5
DL_α	Not determined	<4	4-7	8-11	12-15	>15
Categories for sound insulation	B0	B1	B2	B3	B4	
DL_R	Not determined	< 15	15-24	25-34	>34	

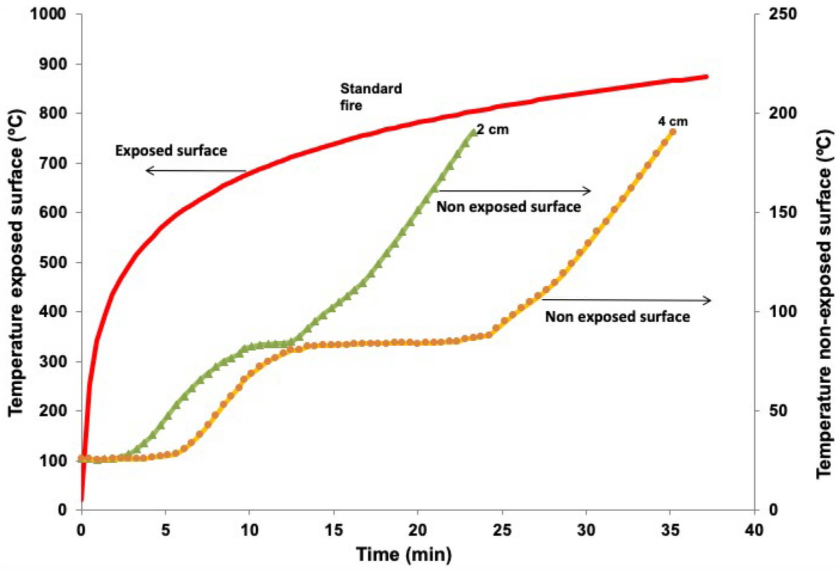

Figure 4. Fire resistance of the barrier.

3.5. Leaching properties

The introduction section of the EN 1794-2 (21) reads as follows: "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". It also states: "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".

For fly ash, the major environmental concern should be the emission of heavy metals (particularly Mo) through leaching into the groundwater, according to the results presented in Table 1. Despite this, neither leaching tests nor maximum values to limit their use can be found in the specific literature on road traffic noise reducing devices.

The Dutch Decree of Soil Quality (DSQ) (45) is considered the leaching standard reference. The DSQ contains test methods and limits for any waste in any construction material in order to prevent the pollution of the surface water and soil. NEN 7345 is the test established by DSQ for monolithic construction materials that contain wastes. The results of the leaching test of the fly-ash barrier compared to the DSQ limits are shown on Table 6. The use of a product composed essentially of fly ash does not pose any leaching problem according to the DSQ. The Mo concentration was slightly below the DSQ limit due to the stabilization of Mo produced by the cement in the matrix of the barrier.

Table 5. Physical and mechanical properties before and after the fire test.

	Density (kg/m^3)	Superficial hardness (Shore-C)		Flexural strength (MPa)
Before	886.9	42.0		1.3
After	798.2	Exposed surface	37.6	0.9
		Non-exposed surface	32.4	

Table 6. NEN 7345 results compared to the DSQ limits.

Elements	**Hg**	**Se**	**Pb**	**Sn**	**Cd**	**Ba**	**Co**	**Sb**	**F^-**
FA Barrier	<0.2	<0.4	<0.2	<0.3	<0.2	9.7	<0.2	<0.4	<32.4
Limits (mg/m^2)	0.43	1.4	120	26	1.1	600	29	3.7	1300
Elements	**V**	**Cr**	**Mo**	**As**	**Zn**	**Ni**	**Cu**	**Cl^-**	**$SO_4^=$**
FA Barrier	11.2	6.8	11.5	<0.2	<0.2	<0.7	<0.2	663.1	1605.6
Limits (mg/m^2)	230	140	14	41	200	50	51	18000	27000

4. CONCLUSIONS

We analyzed a noise reducing barrier composed of 60 wt.% of fly ash, 25 wt.% of cement, 14.5 wt.% of vermiculite and 0.5 wt.% of fibers from an acoustic, physical, mechanical and environmental perspective, encompassing all the requirements for noise reduction devices according to the European standards.

Regarding its acoustic performance, the barrier was categorized as a typical concrete barrier. DL_α led to its classification as A2 and DL_R led to its classification as B3.

Regarding the non-acoustic performance of the barrier, it was classified as having medium density. Compressive strength was lower than that of porous acoustic barriers. The addition of fibers increased its flexural strength above 0.6 MPa. Superficial hardness was lower due to the elastic effect of the vermiculite. The barrier had an adequate impact resistance, only showing small surface layer degradation (<20 mm). A barrier of 120 mm thickness had a fire resistance greater than 110 min, and preserved its integrity after the fire test. Despite the high fly ash content, the barrier did not present any environmental and human risks due to the leaching of heavy metals according to the Dutch standard to conduct the monolithic leaching test of construction materials that contain wastes.

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