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Recycling petroleum coke in blended cement mortar to produce lightweight material for Impact Noise Reduction

J. Olmeda *, M. Frías, M. Olaya, B. Frutos, M.I. Sánchez de Rojas

Eduardo Torroja Institute of Construction Sciences, CSIC, Madrid, Spain

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ABSTRACT

This work introduces a new way to use low-cost petroleum (pet) coke as lightweight aggregate in cement mortars to make sound barriers. The feasibility of adding pet coke in cement matrix was investigated: an in-depth characterization of as-received coke and the new lightweight mortar was made. The acoustic behaviour herein was assessed by constructing a large dimension mortar slab (made of cement and coke as aggregate) used as floor covering and measuring, according to the procedure described in international standards, the impact noise pressure level over the range of frequencies 100–5000 Hz. Impact Noise Reduction (INR) was also obtained and the results were compared to the ones experimentally obtained from a control mortar slab (made of cement and sand). Results showed that coke addition leads to a decrease in mechanical properties of resultant mortars, this is principally due to an increase of the porosity (∼60%). A gradual increase of impact noise insulation was observed in lightweight floor covering from middle to higher frequencies tested, reaching, within this range, a remarkable improvement of sound insulation compared to control slab (∼14 dB).

1. Introduction

In recent years much effort has been invested into finding the best way to reuse wastes from different sources in the production of new lightweight materials [1–3]. The two major advantages of such applications are the reduction in raw material costs and the avoidance of disposal costs with the reused waste material. Materials such as clay, expanded perlite or vermiculite are convenient starting materials for the production of lightweight aggregates [4–6]. A well-known lightweight aggregate with a very low apparent density and closed porosity is produced from glass by a foaming process [7].

Coke, also referred to as pet coke, is formed as final by-product of petroleum industry from desulfurisation processes during crude oil distillation. It is classified in the European Waste Catalogue with the code 050116 [8]. More than 90 Mt of coke are produced each year by the oil refining industry worldwide [9].

While certain technological reuse applications already exist for some sort of coke, for example as graphite precursors, electrodes in aluminium and steel plants, other quantities do not have such reuse and therefore their supply largely outstrips demand. This is the case of green coke, also named as fuel coke, which, following the first removal of the most valuable fractions of crude oil, accumulates all the most undesirable substances initially present in crude oil. Green coke is normally used as fuel in steam power stations and cement works. However, in such cases, green coke combustion significantly increases the levels of SO_x compounds present in exhaust gases and increases the costs and complexity of gas scrubbing systems required to comply with increasingly stringent emission legislation [10]. Therefore, any possible reuse application of these green coke by-products that does not entail their combustion is of enormous interest not only for the refineries themselves, but also for society in general, which would benefit from a reduction in greenhouse gas and sulfurous gas emissions.

The reuse of several types of materials for making sound barriers in both buildings and road asphalt surfaces has recently been the subject of extensive research. For instance Wolfe and Gjinolli [11] investigated the abilities of a cement-wood composite from construction waste as traffic sound barriers; and Yamaguchi et al. [12] studied the sound absorption mechanisms of a porous asphalt surface by comparing it with other porous materials. A substantial number of materials and compounds are currently available in the market to be used with constructive elements for acoustic protection (glass mineral wool, plastic foam, textile fibre felt, recycled rubber, expanded polyurethane, among others). However, some of these materials, to varying extents, could be expensive or show a reduction in their beneficial acoustic characteristics with time and exposure to the environment. In addition to the loss of performance, degradation of some of these materials results in the formation of micro fibres potentially harmful to human health.

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* Corresponding author. Tel.: +34 91 302 04 40; fax: +34 91 302 07 00.
E-mail address: javier.olmeda@ietcc.csic.es (J. Olmeda).

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Table 1
Granulometric distribution of as-received pet coke after sieving.

Ø > 5 mm	5 > Ø > 2 mm	2 > Ø > 0.5 mm	Ø < 0.5 mm
35.5%	20.4%	34.6%	9.5%

Green coke, herein referred to as coke, due to its low density, open porosity and granular format, has been of significant interest as a potential substitute for lightweight aggregate in cement based products. In this way Frías et al. [13] carried out a study to evaluate the changes in sound absorption of cement-based mortar blocks with incremental coke additions, identifying the optimal coke/cement ratio to maximise sound insulation performance in compliance with minimum associated mechanical strength loss. The work herein focuses on the feasibility of using recycled pet coke as aggregate to construct lightweight coke-based materials for sound barrier fabrication by carrying out an in-depth characterization of the raw material and the resultant cement-coke composite; and then assessing the acoustic behaviour of a large dimension slab (3 m^2) made of cement and pet coke for use as a floor covering in dwellings. Impact sound pressure levels will be determined, and the results will be compared to the control slab (made of cement and sand, and tested under the same conditions) to obtain the Impact Noise Reduction level (INR) according to International Standards.

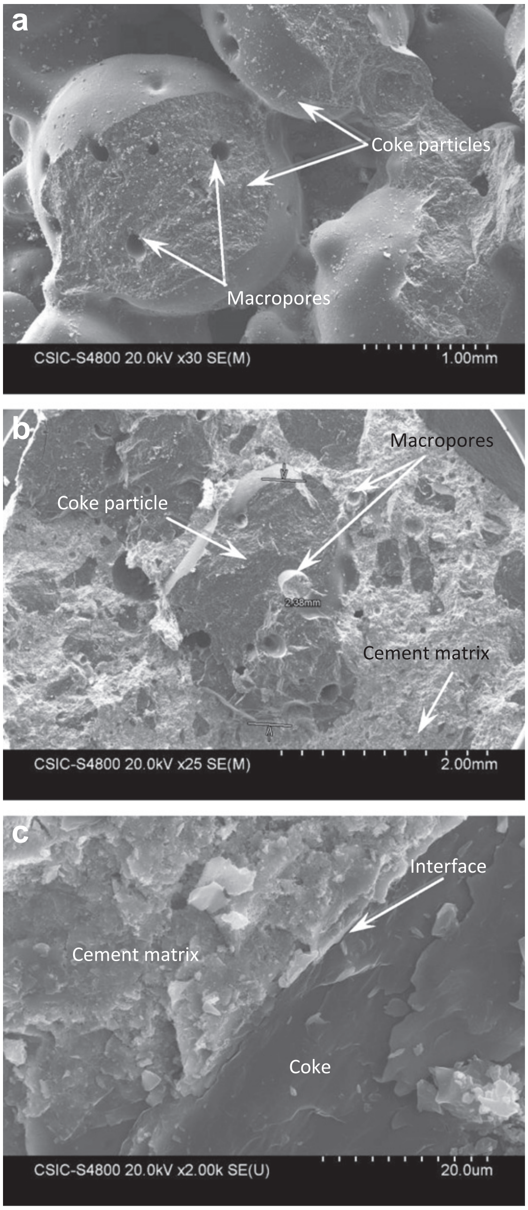

Fig. 1. SEM images of (a) coarse grained coke at 30×, (b) coke particles in cement matrix at 25×, and (c) cement-coke interface at 200×.

2. Materials

As-produced pet coke was obtained from the Repsol oil refinery situated near La Coruña, Galicia, Spain. Representative sub-samples of the as-received pet coke were dried at 85 °C for 24 h, thoroughly homogenised, and the particle size distribution analysed by sieving, as shown in Table 1.

The particles between 5 and 2 mm (coarse) have been used in subsequent experiments (Fig. 1a). Previous studies [13] set up this grain fraction to be used in sound insulation experiments for two reasons: (a) it is similar in diameter to sand particles; (b) grain fraction >5 mm were too irregular in its size distribution and grain fraction <2 mm decreases porosity that affects adversely to the aim of this study.

CEM II/B-M type 32.5 N Portland cement [14] was used. The composition, analysed by X-ray Fluorescence (model S8 Tiger, manufactured by Bruker) is summarised in Table 2. Standardised silica sand [15] with 98 wt.% of silica content and 2 mm maximum particle size was used to prepare control mortar mixes.

3. Experimental set-up

3.1. Sample preparation

Table 3 shows the quantity and composition of sample mixes prepared in this study. Control slab contained 25 % by dry mass CEM II/B-M and 75% sand. Lightweight slab also contained 25% cement and the rest 75% pet coke. The quantity of water used in both mixes was fixed in order to maintain a constant degree of workability. As can be observed in Table 3, keeping constant the cement/aggregate ratio, a decrease of cement quantity (∼36%) needed is achieved when sand is substituted by coke. On the other hand, coke-based fresh mixture required more water to achieve standard consistency compared to control (∼66%). This increase

Table 2
Chemical composition (%) by XRF of CEM II/B-M used.

SiO_2	Fe_2O_3	Al_2O_3	CaO	SO_3	MgO	Alkali	LOI
19.45	5.37	2.82	60.39	3.22	0.46	0.40	7.89

Table 3
Mixtures used for the two samples elaborated.

	Cement (kg)	Coke dry basis (kg)	Sand dry basis (kg)	Total water (kg)	Cem/agg. ratio (by wt.)	Water/cem ratio (by wt.)
Control floor covering (sand-based mortar slab)	140	–	422	57	0.33	0.41
Lightweight floor covering (coke-based mortar slab)	90	261	–	62	0.35	0.68

of water/cement ratio effectively agrees with water demand studies carried out to cementitious samples with increasing pet coke additions (Fig. 2). Samples were prepared following the procedures described in UNE EN 196–1 standards [15]. Vibration was employed during fresh mixtures placement to aid removal of air voids.

One 200 × 150 × 8 cm sample (hereinafter floor covering) was constructed for each mix. Cured at 14 ± 5 °C and 70 ± 10% relative humidity for 28 days. Fig. 3a and b shows the appearance after de-molded of the floor covering made with cement and coke.

Six 4 × 4 × 16 cm specimens were also prepared in order to test mechanical properties and volumetric density [15]. These samples were cured at 15 ± 2 °C and 100% relative humidity, and tested after 28 days. To determine volumetric density, samples were dried in oven at 40 °C to constant weight.

The quantity of cement and aggregate used, based on the material density, was varied for each mix in order to accomplish mould volume requirements. The density of cement, raw pet coke and sand was determined by helium pycnometry (Accupyc 1330 – Micromeritics) and summarised in Table 4.

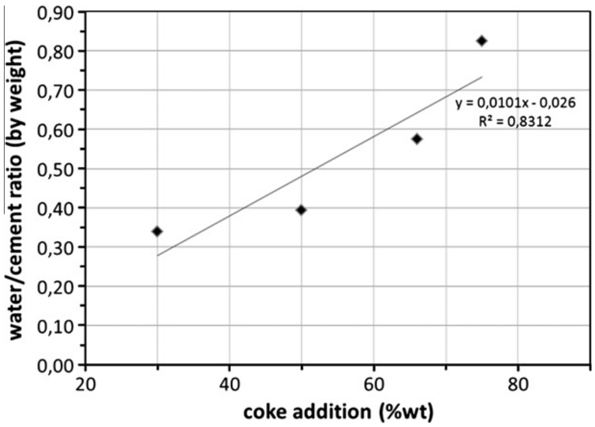

Fig. 2. The effect of cement substitution by pet coke on the water to cement ratio required in mortar samples.

3.2. Instrumental techniques of analysis

Ash content of raw pet coke was measured according to the standards [16]. Moisture content was determined by mass loss after heating the sample at 105 °C for 2 h.

Carbon, Hydrogen and Sulfur contents were calculated by FTIR (LECO – CHNS-932) from the sample combustion (1050 °C) gases. Nitrogen and Oxygen content were quantified with a Thermal Conductivity Detector and in a graphite oven (LEC – VTF-900), respectively. The other elements given in Table 5 were analysed by ICP-AES (Iris Adv. Duo – Thermo Fisher) after treating the ashes with $NaCO_3/Na_4B_4O_7\cdot 10H_2O$ and HCl to dissolve both metal and non-metal elements existing in the sample.

X-ray diffraction analysis was carried out using a D8 Advance, manufactured by Bruker.

The microstructure of carbon coated surfaces of raw material and mortar samples containing pet coke were observed using SEM-SEI microscopy (Hitachi, S-4800). The Energy Dispersive Spectroscopy (EDX) analysis was conducted using a Si/Li detector and DX4i analyzer. Carbon was not determined due to this technique is not able to detect lighter elements.

Table 5
Elemental composition, moisture and ash analysis of as-received pet coke.

Moisture and ash analysis (%wt.)							
Moisture							**Ash**
0.52							1.83
Elemental analysis (%wt. dry ash free basis)							
C		**H**		**N**		**S**	**O**
85.65		3.95		0.91		6.04	1.55
Ash analysis (ppm)							
V	**Fe**	**Ca**	**Si**	**Al**	**Ni**	**Na**	**Zn**
1300	570	520	390	380	280	240	21
Cr	**K**	**Mg**	**Mo**	**Mn**	**Pb**	**As**	**Hg**
3	<50.0	<50.0	<50.0	<20.0	<10.0	<0.1	<0.1

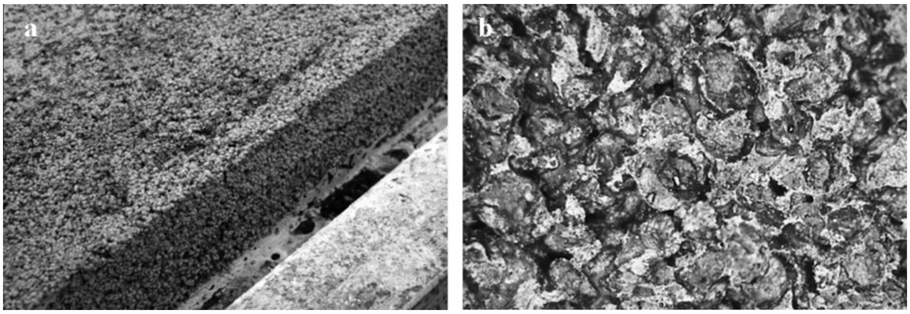

Fig. 3. (a) Appearance of lightweight floor covering after de-moulded and (b) Detail at ∼11× by optical microscope.

Table 4
Density and porosity of as-received pet coke and of the floor coverings studied.

	He pic density (kg/m3)	*Volumetric density (kg/m^3)	Porosity (%)			
			Total	Micro Ø < 0.01 μm	Meso 0.01 < Ø < 5 μm	Macro Ø > 5 μm
CEM II/B-M 32.5 N	2984	–	–	–	–	–
Standardised silica sand	2553	–	–	–	–	–
Pet coke (coarse grained fraction)	1337	–	50.03	4.63	20.72	74.65
Control floor covering (sand-based slab)	2511	2400	10.75	5.34	85.42	9.24
Lightweight floor covering (coke-based slab)	1549	1333	17.10	1.45	65.77	32.78

* Averaged data.

Accupyc 1330 and Autopore 9505, both manufactured by Micromeritics, were used to obtain He picnometry density and mercury intrusion porosity (MIP) data of raw pet coke and mortar samples.

3.3. Technique and method of impact sound insulation assessment

3.3.1. Acoustic laboratory

The test emplacement consisted in two vertically adjacent chambers (Fig. 4a): the emission chamber, where the specimens were tested, and the receiving chamber, placed below emission chamber and where the impact sound emission levels were recorded; this room has been constructed in order to accomplish isolating requirements of specific standards for reverberation time [17,18]. Both chambers (emission and receiving) are split by the standardized heavyweight floor (Fig. 4a), a solid concrete heavyweight tile of 150 mm thickness constructed according to the relevant standards [19].

3.3.2. Measure equipment

The equipment used in the present work (Brüel and Kjaer) complies with international standards [20,21] and consisted of:

- Modular precision sound-level metre in 1/3 of octave bands (B&K 2260).
- Microphone (B&K 4189).
- Multi-source (B&K 4296).
- Power amplifier (B&K 2716).
- Impact machine (or Tapping machine) of 5 standardized pistons (B&K 3207).

Sound-level metre, Microphone, Multi-source and Power Amplifier were placed in the receiving chamber (Fig. 4b) to measure and record sound waves emitted from the emission chamber. The way this measure equipment is placed inside the receiving chamber has to be at least 1 m far from the testing samples and 0.7 m far from the chamber walls [22,23].

The Tapping Machine, placed in the emission chamber, is the sound emission source when its pistons hit on the sample surface.

3.3.3. Measure sequence and theoretical basis

Impact sound pressure level values of the standardized heavyweight floor and the both floor coverings were tested following the impact sound measurement standards [19,23] and determined as shown in the following equation:

$$L = 10\log\left(\frac{1}{x}\sum_{j=1}^{m}10^{L_j/10}\right) \tag{1}$$

where L is the impact sound pressure level in dB from L_j to L_m in x positions of measurement within receiving chamber. The received sound level (dB) is given by the normalised impact sound pressure level (L_n) as follows:

$$L_n = L + 10\log\frac{A}{A_0} \tag{2}$$

where A_0 is the reference absorption area that corresponds to 10 m^2 and A is the equivalent absorption area of the receiving room in m^2 determined from Sabine equation:

$$A = 0,161\ \mathrm{V/T} \tag{3}$$

where V and T are, respectively, the volume (m^3) and the associated reverberation time (s) of the receiving chamber.

Prior to sample construction, the impact sound pressure level of the standardized heavyweight floor (L_{n0}) was determined. For this, the Tapping Machine worked for 65 s emitting a sound frequency range within 100–5000 Hz; meanwhile, in the receiving chamber, the Sound-level metre measures and records the sound pressure level transmitted by the heavyweight floor at every frequency emitted. The impact sound pressure level determined of the standardized heavyweight floor was an average of 8 measurements on different positions.

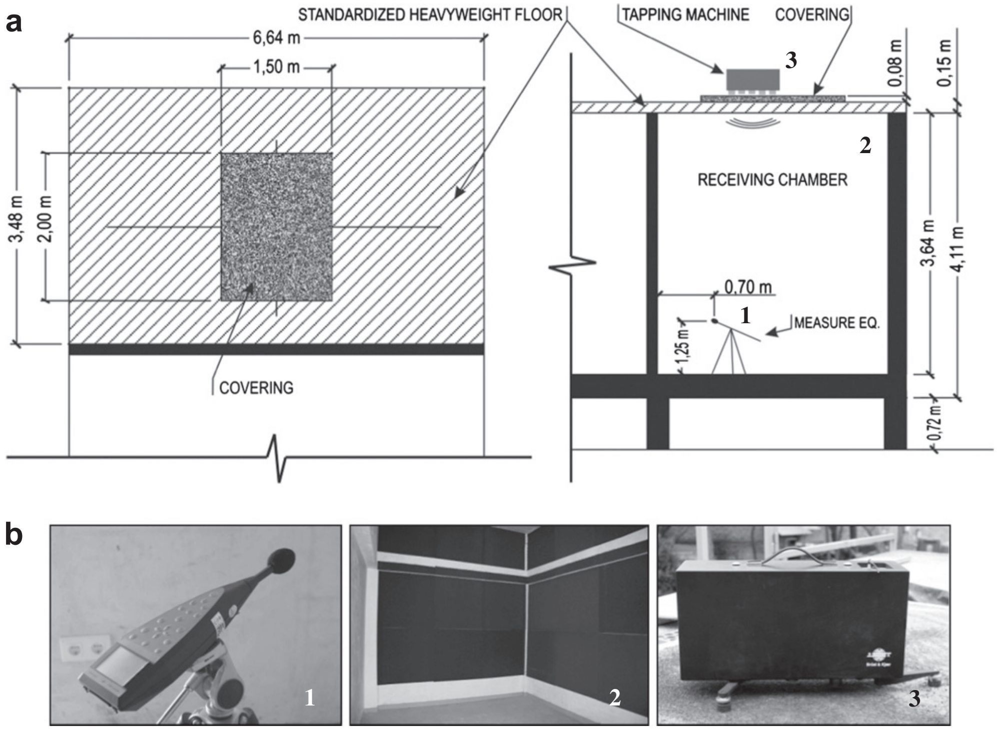

Fig. 4. (a) Floor plan and elevation view of the impact noise laboratory and (b) Sound-level metre, Receiving chamber and Tapping machine.

Once L_{n0} has been tested, the control (sand-based) floor covering was constructed and left to cure for 28 days, after this time sound pressure level of this floor covering in combination with the standardized heavyweight floor was tested, obtaining L_{n1}. Finally, the lightweight (coke-based) floor covering was constructed to determine, after 28 days of curing time, L_{n2} value corresponding to this composite.

The impact sound pressure levels of the elements tested (L_{n0}, L_{n1} and L_{n2}) have a reference line associated. From these reference lines, calculated according to UNE-EN ISO 717–2 for a 100–3150 Hz range, the weighted normalised impact sound pressure level (L_{n0w} and L_{nw}) of each material was obtained.

The Impact Noise Reduction level (ΔL_{nw}) that results from the each floor covering installation, according to standards [19,23] for a 1/3 of octave band, is defined as follows:

$$\Delta L_{nw} = L_{n0w} - L_{nw} \tag{4}$$

where L_{n0w} is the weighted normalised impact sound pressure level of the standardized heavyweight floor, and L_{nw} is the normalised impact sound pressure level of the floor coverings tested in combination with the standardized heavyweight floor.

The final assessment will be calculated by comparing the INR level of the two floor coverings (sand-based and coke-based) investigated in the present work [24].

4. Results and discussion

4.1. Analysis and characterization of raw pet coke

Analytical data, moisture and ash content for the pet coke is summarised in Table 5. Pet coke is predominantly Carbon (~86 wt.%), with a high C/H ratio and low Oxygen content (~1.6 wt.%). This waste material also contains significant levels of Sulfur (~6 wt.%) and other metals including V, Fe, Ca, Si, Al, Ni and Na.

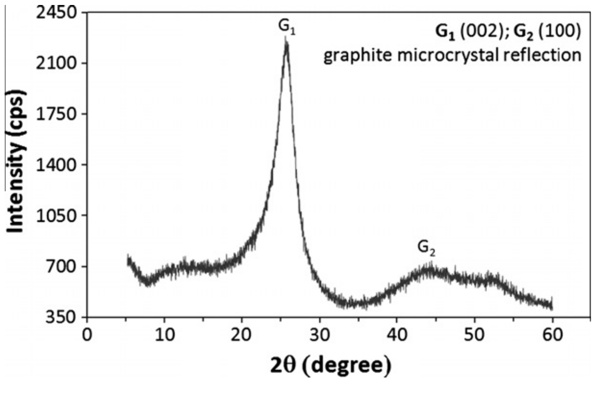

Fig. 5. X-ray diffraction spectra of as-received pet coke.

X-ray diffraction data of pet coke sample given in Fig. 5 shows an amorphous profile with two broad peaks located at approximately 26° and 44° 2Θ corresponding to (002) and (100) reflections of graphite micro-crystals.

The sharpness of peak at 26° 2Θ reveals the number similarly orientated graphite micro-crystals, and therefore the level of structural order in the material. The broad nature of the peak can be attributed to a low lattice order.

Fig. 1a shows the Scanning Electron Microscope (SEM) image at 30× of coarse grained coke presenting several big pores on the surface, which can reach values up to 100 mm in diameter. The analytical results of ten EDX analysis on different points all over the material surface is shown in Table 6. Sulfur is homogeneously present on pet coke surface with a high concentration. The rest of compounds are both in a low concentration and heterogeneously displaced.

He picnometry density and mercury intrusion porosity (MIP) data for raw pet coke are shown in Table 4. Coarse grained fraction has a noticeable high total porosity (~50%) which is mainly constituted by pores >5 μm (~75%). Some studies showed that non-flexible materials need to have high macropososity with interconnected pores in order to develop impact sound insulation properties in constructive elements [22].

4.2. Analysis and characterization of mortars made with cement and coke

4.2.1. Density and mercury intrusion porosimetry

Density and porosity are important factors influencing the thermal conductivity of a solid material. Samples with lower densities tend to have higher volume percentages of porosity and, consequently, develop better sound insulation properties.

Table 4 shows He picnometry and volumetric density data for mortar samples. It is clear that pet coke addition causes a significant decrease (>38%) in mortars density, as its inherent density (1337 kg/m^3) is much lower than that of the sand (~2550 kg/m^3) [25]. This density decrease in mortars with pet coke is proportional to the increase of total porosity. MIP data reveals a remarkable increase of total porosity (~60%) when pet coke is the aggregate. Such increase of total porosity is mainly provoked by an increase of macropores volume (~255%) in the material structure.

Mortars made with coke tend to be lighter than the ones made with sand, the reasons of this is clear: pet coke is a material that has high volume of porosity which is mainly constituted by macropores (~75%); coke-based mortar needs more water requirement, thus increasing the water content consequently increases the degree of sample porosity in the hydrated cement.

4.2.2. Micro-structural analysis

Fig. 1a and b shows representative SEM images of the microstructure of cement samples containing pet coke. The pet coke particles appear to be effectively bound into the cement matrix maintaining the original porosity. There is no evidence of second-

Table 6
Chemical EDX analysis of pet coke surface.

Oxides (%)	1	2	3	4	5	6	7	8	9	10	$\bar{x}$
Al_2O_3	2.26	–	0.54	–	0.04	–	0.95	–	–	5.15	1.79
MgO	1.39	1.27	1.54	0.31	–	–		–	–	1.53	1.21
SO_3	80.21	95.81	91.40	92.83	93.06	96.32	94.60	95.86	88.21	77.13	90.54
Fe_2O_3	1.23	1.26	1.55	0.03	1.36	–	0.35	–	1.78	3.05	1.33
CaO	0.13	–	–	0.21	–	–	–	–	1.23	–	0.52
Na_2O	11.67	–	1.15	–	–	–	2.56	–	2.73	3.35	4.29
K_2O	0.41	–	–	0.32	–	–	0.68	0.29	0.85	0.05	0.43
SiO_2	2.70	1.67	3.82	6.30	5.54	3.69	0.85	3.85	5.20	9.73	4.34

ary reaction or mineral phase formation at the pet coke-cement interface. It is clear that water increase in the mixture has provoked and eventually increase of macropores in the cement matrix.

4.2.3. Mechanical properties

The 28 day mechanical data is shown for control (sand-based) and lightweight (coke-based) samples in Fig. 6. This clearly shows a remarkable decrease in both flexural (∼82.6%) and compressive (∼88.0%) strength for samples made with pet coke as aggregate compared to control. Control 4 × 4 × 16 cm samples made with CEM II/B-M 32.5 N and 75% by dry mass of sand developed higher compressive strength than the ones made with the same type of cement and the same mass percentage of coke. However this kind of material complies with UNE-EN 998–2:2001 [26] and can be assigned to M5 class for masonry mortars (note that the use of a 42.5 R or 52.5 R cement would increase compressive strength of the resultant mortars).

4.3. Impact Noise Reduction level assessment

Fig. 7 shows the comparation of the normalised levels of acoustic pressure (L_n) of the heavyweight floor with no floor covering (HWF) and the combination of the floor coverings tested (sand-based and coke-based slab) plus the heavyweight floor (CON + HWF and LIG + HWF, for control and lightweight combination, respectively) and the corresponding displaced reference lines generated.

Three zones can be clearly distinguished in the figure and determined by different frequency ranges: The low frequency zone (<400 Hz), corresponding to bass sounds, both floor coverings groups (CON + HWF and LIG + HWF) present higher levels of acoustic pressure than the heavyweight floor with no floor covering (HWF). This could be due to *self-resonance-frequency* effect (f_0) [22,27]. This effect normally occurs at low frequencies, and is directly proportional to the superficial density of the solid material. Thus, the higher the superficial density of a specific material is the higher the level of acoustic pressure. Therefore, as the combination of the floor covering (CON or LIG) plus the heavyweight floor (HWF) has higher superficial density than the heavyweight floor with no floor covering (Table 7), a lower impact sound insulation in this frequency zone is expected.

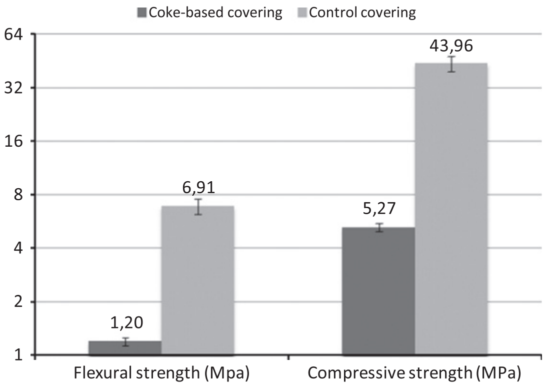

Fig. 6. Flexural and compressive strength of control and coke-based samples tested.

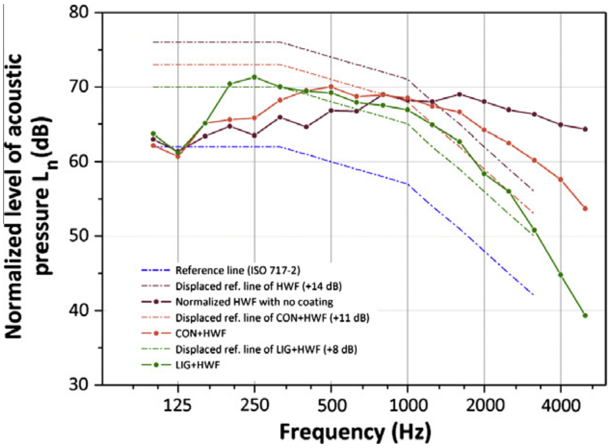

Fig. 7. Normalised levels of acoustic pressure of the heavyweight floor and the floor coverings investigated.

Within middle frequency interval, from 400 to 1600 Hz, the levels of acoustic pressure obtained from both combinations (CON + HWF and LIG + HWF) tend to decrease. From 650 Hz onwards coke-based floor covering is the one that exhibits the lowest L_n data.

In the zone of higher frequencies, from 1600 Hz, region predominant of treble sounds, a remarkable decrease take place in the normalised level of acoustic pressure of both CON + HWF and LIG + HWF. This means a noticeable increase of impact sound insulation in this frequency range.

The two floor coverings investigated in the present work show a L_n reduction from 400 Hz onwards. A comparative analysis between them reveals that LIG + HWF increases the impact sound reduction from ∼630 Hz. This improvement suffers a progressive increase up to 14 dB in comparison to CON + HWF at 5000 Hz.

Sound insulation improvement at high frequencies could be due to mass law theory [28–30] which states that the global acoustic insulation of a specific material increases 6 dB when either the material mass or the frequency of the incident sound wave is doubled. According to this, sand-based floor covering plus heavyweight floor (CON + HWF), based on its higher superficial density (Table 7), should have improved the insulation compared to LIG + HWF group at higher frequency range. However, at these frequencies (>500 Hz) a more pronounced decrease in L_n is observed in the case of the constructive group with pet coke (Fig. 7), where the line show more negative trend.

Therefore, density, porosity, tortuosity and structural morphology, among others factors, contribute to this impact sound insulation improvement at middle and high frequencies shown by floor covering made with cement and pet coke.

It is no easy to find in current literature some representative impact noise spectra which adequately represents the common impact sound source in dwellings, and in which a given sample can be rated under a specific conditions of optimal performance.

Some authors [31,32] shown that the most frequently impact sound sources are male and female walking, small falling objects, floor cleaning activities, moving of furniture and jumping children. Gerretsen [32] set up a graph of sound pressure levels of some household activities relative to the normalised tapping machine from own measurements.

Based on this study, it can be said that coke-based floor covering would insulate better with high frequency noise sources, this in-

Table 7
Superficial densities of the constructive elements studied.

Constructive element	Superficial density (kg/m^2)
Normalised heavyweight floor with no floor covering (HWF)	435
Control floor covering plus heavyweight floor (CON + HWF)	627
Lightweight floor covering plus heavyweight floor (LIG + HWF)	537

Table 8
Weighted normalised impact sound pressure level and the regarded INR obtained from the floor coverings investigated.

[*] *Heavyweight floor (HWF)*		
	L_{n0w} (dB)	74
[*] *Floor covering + Heavyweight floor*		
Control (sand-based) slab (CON + HWF)	L_{n1w} (dB)	71
Lightweight (coke-based) slab (LIG + HWF)	L_{n2w} (dB)	68
[*] *Floor covering*		
Control (sand-based) slab (CON)	ΔL_{n1w} (dB)	3
Lightweight (coke-based) slab (LIG)	ΔL_{n2w} (dB)	6

[*] Averaged data.

volves sounds generated by light mass source (that would induce less acoustic vibration in the building structure and so that less low frequency waves). Under this conditions the kind of impact sound sources that fit better would be small falling objects, floor cleaning activities and female walking.

In Table 8 appear the weighted normalised impact sound pressure level (calculated from their corresponding displaced lines shown in Fig. 7 of HWF (L_{n0w}), CON + HWF and LIG + HWF groups (L_{n1w} and L_{n2w}, respectively), as well as the Impact Noise Reduction level (ΔL_{n1w} and ΔL_{n2w}) performed by each floor covering itself (CON and LIG), with no standardized heavyweight floor (HWF), according to standards [19,23].

The INR level exerted by the floor covering made with cement and pet coke reaches 6 dB, and the one by sand-based floor covering is 3 dB. INR improvement that eventually comes from a pet coke substitution instead of sand is therefore 3 dB.

5. Conclusions

The following conclusions are drawn from the present study:

The characterization of raw pet coke and cement-coke composite comprehends different techniques to assess the feasibility of using pet coke as aggregate in cement to produce lightweight mortar. Results showed that coke is formed mainly by C and S with other elements content such as V and Fe as the most relevant metals. Its structure presents a low crystalline degree showing S homogeneously dispersed all over its irregular surface. Among the physical properties this waste material can offer are low density and high porosity (~50%), this latter is greatly formed by pores larger than 5 μm in diameter. SEM images reveal that total porosity is eventually maintained once pet coke has been added to cement matrix. Furthermore, this inherent porosity of pet coke contributes to obtain a lightweight mortar (<1500 kg/m^3), increasing ~60% of total porosity and >38% of density of the resultant composites compared to mortars made with sand.

On one hand, it is clear that pet coke acts like an inert material not interfering with cement hydration processes. There is no evidence of second-reaction in cement-coke interface. On the other hand, beside of reducing the required cement quantity when it substitutes sand, coke increases the water to cement ratio in mortars. Such increment is due to coke porosity and hydrophobic properties, which, therefore, enhance at the same time the volume percentage of total porosity of resultant lightweight mortar.

The porosity increase drastically affects to mechanical properties: samples made with coke showed ~83% and ~88% less flexural and compressive strength, respectively, than the ones made with sand.

The installation of coke-based mortar slab as floor covering entailed an impact sound insulation improvement, although this was lower than expected. Despite the great behaviour at middle and higher frequencies shown by the lightweight mortar slab, which reached 14 dB of insulation improvement at 5000 Hz, this is not sufficient for this material to be used as an effective floor covering in dwellings. The covering had a low capacity to reduce low frequency waves (<400 Hz). This spectral range contains the majority of impact noises.

However, given the range of properties found in cement-coke composites, there remains a potential for application of these materials as environmentally sensitive alternatives to current options for reducing impact and airborne noise.

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References

[1] González-Corrochano B, Alonso-Azcárate J, Rodas M, Luque FJ, Barrenechea JF. Microstructure and mineralogy of lightweight aggregates produced from washing aggregate sludge, fly ash and used motor oil. Cement Concrete Comp 2010;32(9):694–707.
[2] Wang HY, Tsai KC. Engineering properties of lightweight aggregate concrete made from dredged silt. Cement Concrete Comp 2006;28(5):481–5.
[3] Chao-Wei T, How-Ji C, Shun-Yuan W, Spaulding J. Production of synthetic lightweight aggregate using reservoir sediments for concrete and masonry. Cement Concrete Comp 2011;33(2):292–300.
[4] Chandra S, Berntsson L. Lightweight aggregate concrete. science, technology and applications. Norwich, New York: Noyes Publications, William Andrew Publishing; 2003.
[5] Shah SP, Ahmad SH. High performance concretes and applications. London: Edward Arnold; 1994.
[6] Lanzón Torres M, García-Ruiz PA. Lightweight pozzolanic materials used in mortars: evaluation of their influence on density, mechanical strength and water absorption. Cement Concrete Comp 2009;31(2):114–9.
[7] Köse S, Bayer G. Schaumbildung im system altglas-SiC und die eigenschaften derartiger schaumgläser. Glastech Ber 1982;55(7):151–60.
[8] European waste catalogue and hazardous waste list. Environmental Protection Agency; 2002.
[9] Santos AR, Silva RJ. Análisis del consumo de coque de petróleo en algunos sectores industriales. Inform Tecnol 2008;19(2).
[10] Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants. OJL 309; 2001. p. 1.
[11] Wolfe RW, Gjinolli A. Durability and strength of cement-bonded wood particle composites made from construction waste. J For Prod 1999;49(2):24–31.
[12] Yamaguchi M, Nakagawa H, Mizuno T. Sound absorption mechanisms of porous asphalt pavement. J Acoustic Soc Jpn 1999;E(20):75–84.
[13] Frías M, Jiménez-Mateos JM, Pfretzschner J, Olmeda J, Rodríguez RM, Sánchez de Rojas MI. Development of blended cement mortars with acoustic properties using petroleum coke. Constr Build Mater 2011;25:1086–92.
[14] European standard EN 197-1. Composition, specifications and conformity criterions for common cements; 2011.
[15] European standard UNE-EN 196-1. Methods of testing cements. Part 1: Determination of strength; 2005.
[16] Spanish standard UNE-EN 32-004. Solid mineral fuels. Determination of ashes; 1984.
[17] International standard UNE-EN ISO 140-1. Measurements of sound insulation in buildings and of buildings elements. Part 1: Requirements for laboratory test facilities with suppressed flanking transmission; 1998.
[18] European standard UNE-EN 20354. Acoustics. Measurement of sound absorption in a reverberation room; 1994.
[19] International standard UNE-EN ISO 140-8. Measurement of sound insulation in buildings and of buildings elements. Part 8: Laboratory measurements of the reduction of transmitted impact noise by floors floor coverings on a heavyweight standard floor; 1999.
[20] CEI 651. Sound-level-meters; 1979.
[21] CEI 942. Sound-calibrators; 1988.
[22] Rodríguez Francisco Javier, Crespo Javier de la Puente. Acoustic guide of construction. Cie Dossat 2007;235 (ISBN 84-96437-10-8-17).
[23] International standard UNE-EN ISO 140-6. Measurement of sound insulation in buildings and of buildings elements. Part 6: Laboratory measurements of impact sound insulation of floors; 1999.
[24] International standard UNE-EN ISO 717-2. Rating of sound insulation in buildings and of buildings elements. Part 2: Impact sound insulation; 1997.
[25] Code on structural concrete (Instrucción de hormigón estructural, EHE-08). Real Decreto 1247/2008. Ministerio de Fomento. Gobierno de España.
[26] European standard UNE-EN 998-2. Specifications for masonry mortars. Part 2: Mortar for masonry; 2002.

[27] Harris CM. Handbook of acoustical measurements and noise control. 3rd ed. Mc Graw Hill; 1995.

[28] Documento Básico HR de protección frente al ruido. Código Técnico de la Edificación (CTE). Secretaría de estado de vivienda y actuaciones urbanas. Ministerio de fomento. Gobierno de España; 2009.

[29] Machimbarrena M. Comparative study of acoustic insulation by pressure and intensity methods. Doctoral Thesis. 180 pp. Escuela Técnica Superior de Arquitectura Departamento de óptica y física aplicada. Universidad de Valladolid; 2002.

[30] Noguera Querol JM. Aislamiento acústico en la edificación: proyecto, cálculo, control técnico y administrativo. Ed. Silva. Col.legi d'Aparelladors i Arquitectes Tècnics de Tarragona; 2003.

[31] Fothergill LC, Carman T. Insulation-impact sound. A comparison of methods for rating the insulation of floors against impact sound. Batiment Int, Build Res Pract 1990;18(4):245–9.

[32] Gerretsen E. A new system for rating impact sound insulation. Appl Acoust 1976;9(4):247–63.