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Evaluation of green walls as a passive acoustic insulation system for buildings

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ABSTRACT

Greenery on buildings is being consolidated as an interesting way to improve the quality of life in urban environments. Among the benefits that are associated with greenery systems for buildings, such as energy savings, biodiversity support, and storm-water control, there is also noise attenuation. Despite the fact that green walls are one of the most promising building greenery systems, few studies of their sound insulation potential have been conducted. In addition, there are different types of green walls; therefore, available data for this purpose are not only sparse but also scattered. To gather knowledge about the contribution of vertical greenery systems to noise reduction, especially a modular-based green wall, two different standardised laboratory tests were conducted. The main results were a weighted sound reduction index (R_w) of 15 dB and a weighted sound absorption coefficient (α) of 0.40. It could be concluded that green walls have significant potential as a sound insulation tool for buildings but that some design adjustments should be performed, such as improving the efficiency of sealing the joints between the modular pieces.

1. Introduction

In the relatively recent past, in society's haste to pursue progress through relentless development, the many advantages that sustainable urbanisation can bring have been ignored. The results of such a short-sighted approach are present for all to see: noise, pollution, congestion and the serious erosion of the quality of city life. Sustainable development requires the consideration of (A) a whole host of interconnected elements, (B) the reduction of energy and water consumption, (C) the minimisation of waste and pollution, (D) the use of environmentally friendly materials, and (E) the availability of efficient public transportation [1].

Urban green space, including the greening of buildings involving both green roofs and green walls, is just one piece of the puzzle. Modern cities provide enormous areas of roof and wall space, in many cases stretching high above the street. Not all of this space is appropriate for growing plants, but much of it is, certainly much more than has been utilised in recent years [1]. Among the benefits that are associated with greenery systems for buildings, such as energy savings, biodiversity support, and storm-water control, there is also noise attenuation [2,3].

Previous studies concerning the sound interception provided by plants refer to the acoustic effect of the belts of trees/vegetation near roads [4]. From these studies, it is known that vegetation can reduce sound levels in three ways. First, sound can be reflected and scattered (diffracted) by plant elements, such as trunks, branches, twigs and leaves. A second mechanism is absorption by vegetation. This effect can be attributed to mechanical vibrations of plant elements caused by sound waves, leading to dissipation by converting sound energy to heat. There is also a contribution to attenuation by thermo-viscous boundary layer effects at vegetation surfaces. As a third mechanism, one might also mention that sound levels can be reduced by the destructive interference of sound waves. The presence of soil can lead to destructive interference between the direct contribution from the source to the receiver and a ground-reflected contribution. This effect is often referred to as the acoustical ground effect or ground dip. The presence of vegetation leads to an acoustically very soft (porous) soil, mainly due to the presence of a litter layer and plant rooting. This

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result is a more pronounced ground effect and produces a shift towards lower frequencies compared to sound propagation over grassland. As a result, this ground dip is more efficient in limiting the typical engine noise frequencies (approximately 0.100 kHz) of road traffic [4].

Generally, it can be considered that the sound insulation effect of vegetation in urban environments is small, with the reductions ranging from 5 to 10 dB. The factors that affect the function of vegetation in sound insulation are multiple, such as the species, the screen dimensions, and the shape and location with respect to the source of the noise. The vegetation itself can reduce noise levels by up to 8 dB and occasionally more [5].

Regarding the sound insulation effects of vegetation when incorporated in buildings, previous studies usually mostly consider the contribution of green roofs to acoustic insulation, while references to green walls are more scarce. In addition to the fact that few studies address the noise reduction that is provided by vertical greenery systems for buildings, we must keep in mind that these constructive systems are very different and, therefore, that their acoustic behaviour will be very different. According to the previously established classifications, the vertical greenery of buildings can be addressed by means of two different construction systems, green walls or green façades [6]. Regarding green walls, also called living walls, basically two main types can be differentiated. The first type uses geotextile felts to support plants without a substrate (Fig. 1), while in the second typology, the substrate and the plants are placed in modules (boxes), either plastic or metal, sometimes pre-cultivated, that are fixed to a vertical support structure or directly to the building façade wall (Fig. 2) [6].

This study focuses on the second type, i.e., module-based green wall. Despite the design differences between companies, module-based green walls are the most widespread system, whereas geotextile-based systems, due to their artistic orientation, have a more limited use.

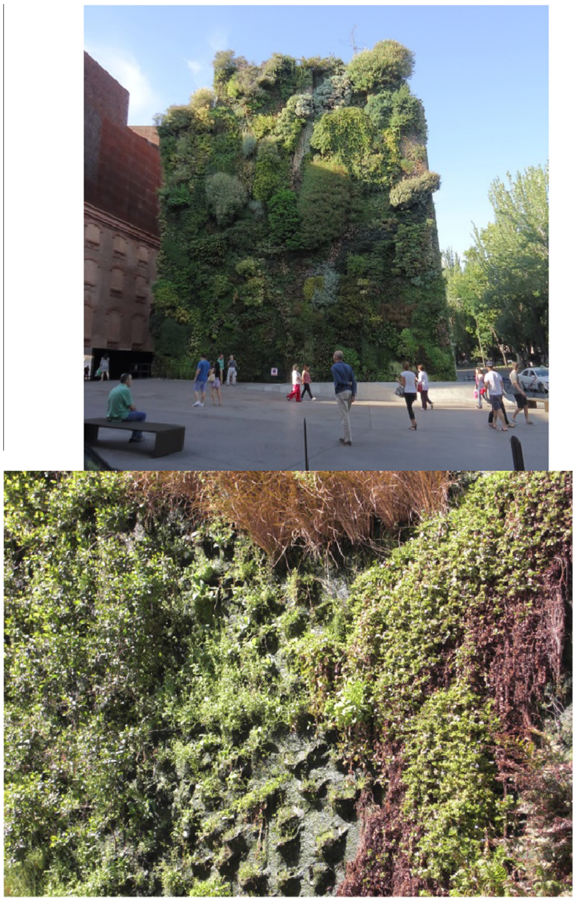

Fig. 1. Geotextile-based green wall.

In reference to the urban noise attenuation by vegetation, Dunnet and Kingsbury stated that the hard surfaces of urban areas tend to reflect sound rather than absorb it. The author highlights that green roofs can absorb sound, with both the substrate and plants contributing. The substrate tends to block lower sound frequencies, whereas plants block higher frequencies [3]. However, in the case of module-based green walls, the substrate is not exposed directly but rather is inserted into a lightweight structure (module or box) that is usually made of plastic or metal; consequently, the acoustic behaviour could change considerably from that offered by green roofs.

From the few studies investigating the acoustic insulation capacity of green walls, it can be deduced that these systems positively contribute to improving the building/city acoustics. However, these experiments are very different, and the results are so diverse that it is difficult to determine the real contribution of green walls, i.e., the acoustic insulation level that is provided by green walls.

Wong et al. conducted a study to evaluate the acoustic impacts of different vertical greenery systems on the insertion loss of building walls [7]. From the results of this study, it can be concluded that the insertion loss shows a stronger attenuation to middle frequencies due to the absorbing effect of the substrate, while a smaller attenuation is observed at high frequencies due to scattering from greenery. Although not every studied vertical greenery system exhibits a good noise reduction, low to middle frequency range reductions of approximately 5–10 dB were measured. For the high frequencies, the insertion loss reductions ranged from 2 to 3.9 dB, except for one, which reached the maximum value of 8.8 dB. However, a second objective of the Wong et al. study was the sound absorption coefficient determination of a green wall in a reverberation chamber. From this experiment, it can be concluded that the sound absorption coefficient of the studied greenery system has higher values than those of other building materials and furnishings. Moreover, it can be confirmed that the absorption coefficient increases with increasing frequencies and with larger greenery coverage.

Positive results were found by Fernández-Bregón et al. when studying the effects of vertical greenery on the thermal and sound mitigation for indoor walls [8]. For the effect on sound mitigation, the average decrease in dB was between 2% and 3%, using frequency weightings that were equivalent to the sound frequencies that the human ear perceives, without and with excluding extreme frequencies, respectively.

Van Renterghem et al. carried out a numerical study of road traffic noise, which is the most important and widespread environmental noise source in the urban environment and the potential of building envelope greening to achieve quietness [9]. Three types of theoretical measures were considered, green roofs, green walls and vegetated low-height noise barriers positioned near roof hedges. The conclusions of this study stated that the effects of wall vegetation strongly depend on the assumptions of the material parameters in the reference case. While acoustically softer bricks were assumed, i.e., the use of a reflection coefficient of 0.82, the effectiveness of green walls becomes rather modest: the maximum effect remains below 2 dB. Additionally, some inconsistencies at very low frequencies appear because the measured absorption coefficients of the wall vegetation could become smaller than those of bricks. However, calculations using a reflection coefficient of 0.95 could be considered as yielding the maximum possible effects: an insertion loss of 4.4 dB in the case of fully vegetative-source canyon façades. This study indicates that the substrates that are usually used for green walls have a high porosity and low

Fig. 2. Module-based green wall.

density and consequently show a complex acoustic behaviour. Therefore, high absorption values already at lower frequencies and strong variations in the absorption coefficient at frequencies above 0.500 kHz could be observed and are not well-captured by the used model. Moreover, the presence of water inside the substrate could strongly affect its absorption properties so that in extreme cases, when the porous medium is fully water-saturated, similar effects as for a rigid material could be expected.

Horoshenkov et al. conducted an experiment in an impedance tube to quantify the ability of four different plant species to absorb sound against an acoustically hard surface or on the top of porous soil [10]. From the results, it was concluded that the absorption coefficient of plants is controlled predominantly by the leaf area density and the angle leaf orientation, so that the larger the leaf area density and the larger the dominant angle of leaf orientation of a plant are, higher values of the acoustic absorption coefficient can be attained. Referring to the substrates, two different soils were analysed, a light-density soil substrate and a high-density, clay-based soil. The texture of the two soils determines the pore size distribution, which controls their acoustic properties. The presence of fibres, large particles of perlite and polymer gel in the substrate, gives rise to large pores and, therefore, significantly influences its acoustic absorption coefficient, whereas the texture of the high-density clay-based soil is finer with closely arranged particles that are less than 2 mm in diameter. The absorption coefficient of the low-permeability, high-density, clay-based soil is low.

According to Yang et al. ground media and vegetation play different roles in absorbing and scattering sound [11]. In this study, a series of measurements were carried out in a reverberation chamber to examine the random-incidence absorption and scattering coefficients of vegetation considering various factors, such as the soil depth, the soil moisture content and the level of vegetation coverage. The results for different soil depths (50, 100, 150, and 200 mm) showed that even a thin soil layer with a depth of 50 mm provided a significant absorption coefficient of approximately 0.9 at approximately 1.000 kHz and that there were only slight changes in the absorption coefficient of approximately 0.1 with increased soil depth. A significant decrease by approximately 0.6 in the absorption coefficient was observed with an increase in the soil moisture content. With increasing vegetation coverage, the absorption coefficient increased by approximately 0.2 at low and middle frequencies, whereas at frequencies greater than approximately 2.000 kHz, the absorption coefficient slightly decreased by approximately 0.1. A stronger effect on the sound absorption and scattering by aboveground vegetation components (excluding the roots and soil) was found at higher frequencies with increasing vegetation coverage. The maximum absorption and scattering coefficients of the studied aboveground vegetation were 0.49 at 5.000 kHz and 0.43 at 2.500 kHz, respectively. In addition, a green wall with a highly porous substrate maintained a relatively high absorption coefficient of approximately 0.6 even though it was nearly saturated.

As can be observed, the number of studies concerning the potential of green walls as an acoustic insulation tool is poor, and the methodologies that were used were very different; consequently, no consistent conclusions can be obtained when comparing these methodologies. It must be considered that the final purpose of architectural acoustics is to control the noise that people endure while inside buildings. Although it may be more logical to control the acoustic parameters in existing buildings by testing in situ, it is better to prevent problems rather than to detect them when it is too late to act. Therefore, it is desirable to predict the acoustic behaviour of a designed construction system before being used in a building. As a result, from these test results, the contribution of different sound sources and acoustic effects cannot be isolated. To solve this problem, acoustic laboratory tests must be conducted in which, in a very controlled manner, the particular acoustic properties of a building material or element can be measured or calculated. According to this idea, the main objective of this study is to measure the acoustic characteristics under laboratory conditions of a module-based green wall. These data must enhance the knowledge of the contribution of vertical greenery systems to noise reduction both at an urban and building scale.

2. Materials and methods

2.1. Green wall description

For this evaluation of green walls as passive acoustic insulation system for buildings, an existing precultivated modular-based system was used [12]. The system is based on recycled polyethylene modules that are resistant to UV radiation and are 600 mm wide by 400 mm high and 80 mm thick (Fig. 3). Each modular cultivation unit is a closed box filled with a recyclable and environmentally friendly substrate: coconut fibre. The thickness of the recycled plastic (3 mm), in helping to solve an environmental problem with the recycling of plastics, also provides resistance and prevents the evaporation of water from the rhizosphere of plants, thus contributing to the increased efficiency of water use. Less evaporation of this unit is one of its main advantages over geotextile-based systems. Each unit has recycled polyethylene hooks that hold them to the supporting structure. The support structure consists of stainless steel tubes where the modules are adjusted hanging on the hooks so that they cannot be drawn perpendicular to the wall, preventing theft. The irrigation system responds to fertigation techniques in which the nutrient solution is distributed through self-compensating drippers, so that by adjusting the nutrient solution, plant growth can be controlled, reducing the irrigation requirements. This system comprises two independent

Fig. 3. Recycled polyethylene modules with *Helichrysum thianschanicum.*

pipe networks: a pressurised (2–5 bar) fertigation injection system and an evacuation system that uses gravity to collect the drainage in a reserve tank from which it is later pumped. Prior to recirculation, the nutrient solution in the reserve tank is rebalanced and disinfected with a peracetic acid solution. The essential characteristic of the fertigation system is that the nutrient solution that enters each modular cultivation unit does not contact the drainage of any other modular cultivation unit. Consequently, there is no risk of infection being transmitted from one modular cultivation unit to another. This lack of risk is the main advantage of this system compared to other systems, such as vertical gardens based on geotextile-based designs. This green wall was designed to use any small shrub, although normally native plants that are well adapted to the climate are used. In this study, *Helichrysum thianschanicum* specie was used. It is widely used in gardening in Mediterranean climate and in particular in plant façades due to its high resistance to drought and high temperatures. Each module has 24 pre-vegetated plants with an average height of 0.4 m.

2.2. Acoustic insulation evaluation

2.2.1. Measurement of airborne sound insulation

The measurement and calculation of the sound insulation properties of building elements is regulated by UNE-EN ISO 10140-2 standards. The separation elements can be between two different rooms, such as doors or partitions, or between the indoors and outdoors, such as walls, windows, etc. These tests are carried out in transmission rooms (side by side), vertically or horizontally, depending on the type of element to be analysed. During the test, a sound signal is generated in the source room, and the sound levels in both of the rooms (in the third octave bands) are measured. From the differences in these levels, the sound isolation curve for the tested partition is obtained and is technically named the sound reduction index (R) of the analysed building element, which depends on the frequency. These results can also be translated to the Weighted Sound Insulation Index (R_w), which is a value that is expressed as a single number (UNE-EN ISO 717-1). This index communicates less information than does the curve (R values depending on the frequency), but it is easier to manage and may be used to compare the building elements. This standard also includes a method to obtain the correction terms both for traffic noise (Ctr) and for pink noise (C). The normalised traffic noise spectrum gives more weight to low frequencies, allowing the gathering of more realistic noise indices against urban traffic, railway traffic at low speeds, disco music or certain industrial noises (R_w + Ctr). The index of insulation from pink noise is more realistic against traffic noise at high speeds, both road and rail, living activities (talking, music, radio, and TV), or noise that is generated within dwellings ($R_w + C$).

With the aim of measuring the green wall acoustic capacity, the airborne sound insulation standard UNE-EN ISO 10140-2 was performed. The sample that was used consisted of 10 modular cultivation units, representing an area of 1.205 mm wide and 2.005 mm high. The sample was inserted in a wall, each module was hung from two horizontal steel bar of 0.02 m diameter and the perimeter was sealed with sealing mastic Perennator TX 2001 S to fulfil the test requirements according to the standard (Fig. 4).

The test was conducted in horizontal transmission chambers consisting of a source room and a receiving room, fulfilling the standard specifications (Fig. 5).

In Table 1, the instrumentation that was used to conduct the airborne sound insulation test is summarised.

The sound reduction index (R) for each one-third octave has been calculated according to UNE-EN ISO 10140-2. The expression for R is as follows:

$$R = L_1 - L_2 + 10 \cdot \lg \frac{S}{A} \tag{1}$$

where L_1 is average sound pressure level in the source room, L_2 is the average sound pressure level in the receiving room, S is the area of the sample, and A is the equivalent sound absorption area in the receiving room. The average sound pressure levels L_1 and L_2 was measured by emitting an equalised white noise (between 0.100 kHz and 5 kHz) by means of a movable omnidirectional source.

The sonorous field in the source and the receiving rooms has been sampled by means of microphone by rotating with a radius of one meter at a 16 s/cycle speed for 32 s/cycle of measurement. The equivalent sound absorption area was evaluated as the reverberation time (T) measured in the receiving room using Sabine's formula:

$$B = 0.16 \cdot \frac{V}{T} \tag{2}$$

where B is the equivalent sound absorption area in the receiving room, T is the reverberation time of the receiving room, and V is the receiving room volume. The reverberation time of the receiving room was determined using two source positions and three fixed microphone positions for each source position, each offset by 120° during the microphone haul. At the frequency of 5 kHz, the measured reverberation time was $0.97 < 1$ due to the presence of the sample. Finally, the background noise of the receiving room was measured for each third octave from 0.1 kHz to 5 kHz according to the same procedure as for the sonorous field in the receiving room.

Fig. 4. Sample front and back views.

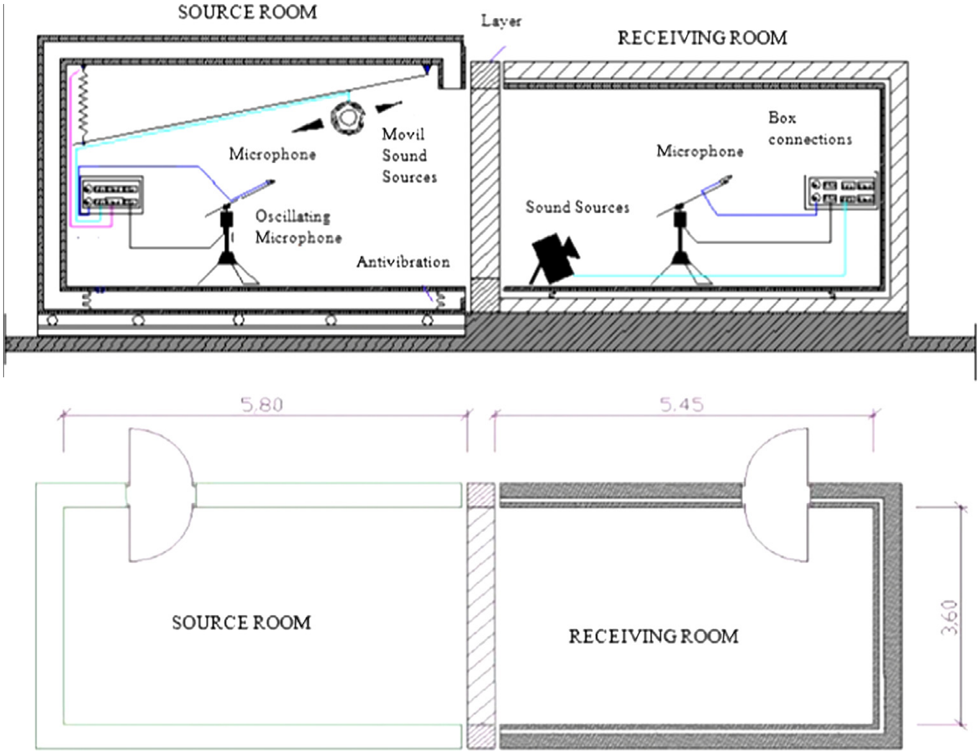

Fig. 5. Horizontal transmission chamber scheme.

Table 1
Instrumentation for the airborne sound insulation measurements.

	Source room	Receiving room
Microphones	Brüel & Kjaer 4943	Brüel & Kjaer 4943
Preamplifiers	Brüel & Kjaer 2669	Brüel & Kjaer 2669
Sound sources	Brüel & Kjaer 4296	CERWIN VEGA
Oscillating microphone	Brüel & Kjaer 3923	Brüel & Kjaer 3923
	Control room	
Analyser	Brüel & Kjaer 2144	
Amplifier	LAB Gruppen; LAB 300	
Equaliser	Sony, SRP-E100	
Calibrator	Brüel & Kjaer 4231	
Atmospheric conditions measurer	Ahlborn Almemo 2590-3S	

2.2.2. Measurement of the sound absorption in a reverberation room

The sound absorption coefficient α of a material or a construction element is defined as the proportion of sound energy that is absorbed by the material from an incident sound. Because this absorption capacity depends on the sound frequency, the sound absorption coefficient α is usually shown by means a curve

Table 2
Sound absorption coefficients of common building materials [13].

Material	Frequency (kHz)					
	0.125	0.250	0.500	1.000	2.000	4.000
Concrete block – coarse	0.36	0.44	0.31	0.29	0.39	0.25
Brick: unglazed	0.03	0.03	0.03	0.04	0.05	0.04
Glass: window	0.35	0.25	0.18	0.12	0.07	0.04
Wood: plywood panel (10 mm thick)	0.28	0.22	0.17	0.09	0.1	0.11
Fibreglass board (25 mm thick)	0.06	0.2	0.65	0.9	0.95	0.98

depending on the sound frequencies, although it also can be expressed as a single global index. In laboratory tests, α is usually measured in third octave bands. Table 2 shows the typical values for the sound absorption coefficient of some common building materials in octave bands [13]. Generally, it could be stated that low frequencies are more difficult to absorb than are high frequencies.

The sound absorption test was carried out according to UNE-EN ISO 354 standards. The sample consists of a prototype that is composed of 42 modular cultivation units (3.6 m × 2.8 m = 10.08 m^2). The prototype was built inside the reverberation room in a horizontal position, leaving an air chamber 120 mm under the modules, with four wooden shims each reproducing the same conditions in which the wall would be installed on a façade building wall. The horizontal position does not affect the final results. Around the sample, a wooden perimeter frame was placed, and the hole was sealed with tape (Fig. 6).

The test was performed in a reverberant chamber of 7 m × 6 m × 5 m and a total area of their surfaces (walls, floor and ceiling) of 211.8 m^2. The diffusivity of the sonorous field in the reverberation chamber was achieved by means of twenty diffusers (between 0.8 and 1 m^2) that were suspended from the chamber ceiling and eight corner diffusers (Fig. 7). The reverberant chamber satisfied the specifications of the standard.

Table 3 summarises the instrumentation that was used to measure the sound absorption in the reverberation room.

The sound absorption coefficient (α) for each third octave band between 0.100 kHz and 5 kHz was determined according to the standard using the following formula:

$$\alpha = \frac{C_T}{S} \tag{3}$$

where C_T is the equivalent absorption area of the sample (m^2), and S is the area of the test sample (m^2).

The equivalent absorption area of the sample was calculated using the following formula:

$$C_T = 55.3 \cdot V \cdot \left(\frac{1}{c_2 \cdot T_2} - \frac{1}{c_1 \cdot T_1}\right) - 4 \cdot V(m_2 - m_1) \tag{4}$$

where V is the volume of the empty reverberation chamber (m^3), c_1 is the sound propagation speed in air in the empty reverberation chamber (m/s), c_2 is the sound propagation speed in air in the reverberation chamber with the sample (m/s), T_1 is the reverberation time of the empty reverberation chamber (s), T_2 is the reverberation time of the reverberation chamber with the installed sample (s), and m_1 and m_2 are the sound attenuation coefficients that were calculated according to ISO 9613-1 using the climatic conditions in the reverberation chamber.

The reverberation times were measured by mean of the emission of equalised pink noise through two omnidirectional sound sources using six fixed microphone positions. For each microphone and source position, the reverberation time was taken as the average of five decay curves in each third octave band from 0.100 kHz to 5 kHz. The reverberation times of the reverberation chamber, both empty and with the sample inside, were measured consecutively.

Fig. 6. Prototype in the reverberation room.

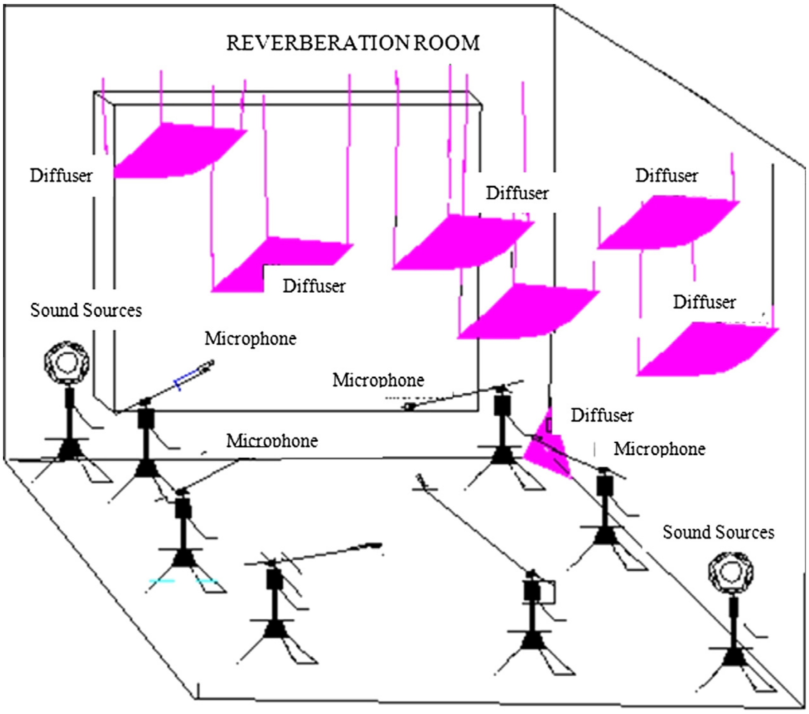

Fig. 7. Reverberant chamber scheme.

Table 3
Instrumentation for the airborne sound absorption measurements.

	Reverberation chamber	
Microphone	Brüel & Kjaer 4192	
Preamplifiers	Brüel & Kjaer 2669	
Sound sources	Brüel & Kjaer 4292	Brüel & Kjaer 4296
	Control room	
Analyser	Brüel & Kjaer 2144	
Amplifier	LAB Gruppen; LAB 300	
Equaliser	Sony, SRP-E100	
Calibrator	Brüel & Kjaer 4231	
Atmospheric conditions measurer	Ahlborn Almemo 2590-3S	

3. Results and discussion

3.1. Measurement of the airborne sound insulation

The sound reduction index (R) characterises the sound-insulating properties of a material or construction element in a stated frequency band-laboratory measurement. R is calculated according to UNE-EN ISO 10140-2 standards. The tests were carried out at the acoustic area of the Laboratory for Quality Control of Buildings – of the Basque Government managed by TECNALIA [14].

The conditions under which the test was carried out were as follows: the volume of the receiving room was 55 m^3, the volume of the source room was 65 m^3, the specimen area was 2.42 m^2, the estimated surface mass was 57 kg/m^2, the room temperature was 11.4 °C, the room relative humidity was 56% and the room pressure was 968 mbar.

The sound reduction index (R) values from the lab measurements are summarised in Table 4 and Fig. 8.

The weighted sound reduction index (R_w) is a single-number quantity that characterises the airborne sound insulation of a material or constructive element over a range of frequencies. The R_w is calculated from R values according to UNE-EN ISO 717-1 standards. The calculated weighted sound reduction index was $R_w = 15$ dB, and the correction terms were $Ctr = -1$ dB for the noise traffic and $C = -1$ dB for the pink noise. In case the modules were used as a sound barrier they would be ranked as B1.

In Fig. 9, a comparison between the results for green wall sound reduction index (R) in reference to the R values for different

Table 4
Measured sound reduction index (R) values.

f (kHz)	R (dB)
0.100	12.9
0.125	13.3
0.160	9.7
0.200	12.9
0.250	14.6
0.315	15.4
0.400	15.8
0.500	16.4
0.630	17.1
0.800	16.3
1.000	14.7
1.250	12.5
1.600	13.0
2.000	13.5
2.500	15.1
3.150	15.1
4.000	14.8
5.000	17.1

materials and constructive solutions [15] is shown. The materials and constructive solutions for this comparison are described as follows:

A. Thermal double glazing (6-12-6), timber frame ($R_w = 30$).
B. Brick, 100 mm thick, no finish ($R_w = 44$).
C. Lightweight aggregate block 215 mm thick with plaster finish both sides ($R_w = 51$).
D. Two leaves of 12.5 mm + 19 mm plasterboard on metal studs, separated by 250 mm cavity with 100 mm mineral wool ($R_w = 70$).

As can be observed in Fig. 9, the capacity of the green wall to reduce airborne noise, which is expressed by the R coefficient, was lower than the other constructive solutions. It must be considered that the basic principles of sound insulation are the mass, sealing and structural insulation. Therefore, this value can be conditioned by the lower mass of the green wall, which is approximately 50 kg/m^2, compared to the brick mass of 200 kg/m^2 or 280 kg/m^2 of the lightweight aggregate block. However, in reference to impermeability, the fact that the green wall is made of modular pieces indicates the existence of joints, which may interrupt the continuity between the modules and consequently the sealing, unlike other solutions, such as thermal double glazing or two leaves of plasterboard with mineral wool. In case the joints between modules were sealed the calculated Weighted Sound Reduction Index was $R_w = 18$ and the correction terms were Ctr = −1 dB for the noise traffic and $C = -1$ dB for the pink noise. In case the modules were use as a sound barrier they would be ranked as B2.

Finally, structural insulation refers to avoiding contact between the spaces to insulate, which should be considered when installing the green wall on the building façade, because the amount of soundproofing that is provided by the green wall (R value) could be reduced due to the contact and the vibration effect through the anchors to the building wall.

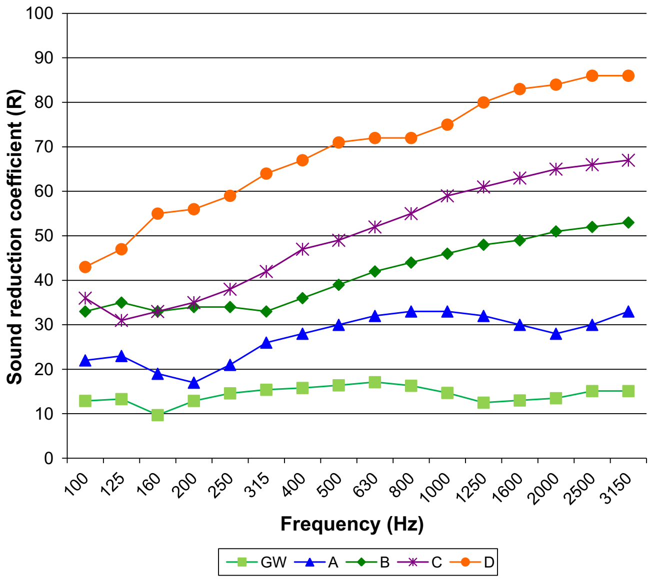

Fig. 9. Sound reduction coefficient (R) comparison between the green wall (GW) and common constructive solutions: A. Thermal double glazing (6-12-6), timber frame, B. Brick, 100 mm thick, no finish. C. Lightweight aggregate blockwork 215 mm thick with plaster finish both sides. D. Two leaves of 12.5 mm + 19 mm plasterboard on metal studs, separated by 250 mm cavity with 100 mm mineral wool.

3.2. Measurement of the sound absorption in a reverberation room

The sound absorption test was carried out according to UNE-EN ISO 354 standards. The tests were carried out at acoustic area of the Laboratory for Quality Control of Buildings – of the Basque Government managed by TECNALIA [14]. The conditions under which façade the test was carried out were as follows: the volume of the reverberation room was 209.6 m^3, the reverberation room surface was 211.8 m^2, the specimen area was 8.10 m^2, the estimated surface mass was 51 kg/m^2, the empty room temperature was 15.5 °C, the empty room relative humidity was 50%, the empty room pressure was 971 mbar, the temperature of the room with the sample inside was 15.5 °C, the relative humidity of the room with the sample inside was 73% and the pressure of the room with the sample inside was 971 mbar.

Table 5 summarises the results of the test in which the reverberation time of the empty room (T_1) and the reverberation time after locate the sample inside the room (T_2), as well as the difference between these two values ($T_1 - T_2$), can be observed. Table 5 also shows the obtained values for the sound absorption coefficient α in third octave bands between 0.100 and 5.000 kHz. The calculated value of the weighted sound absorption coefficient was $\alpha = 0.40$.

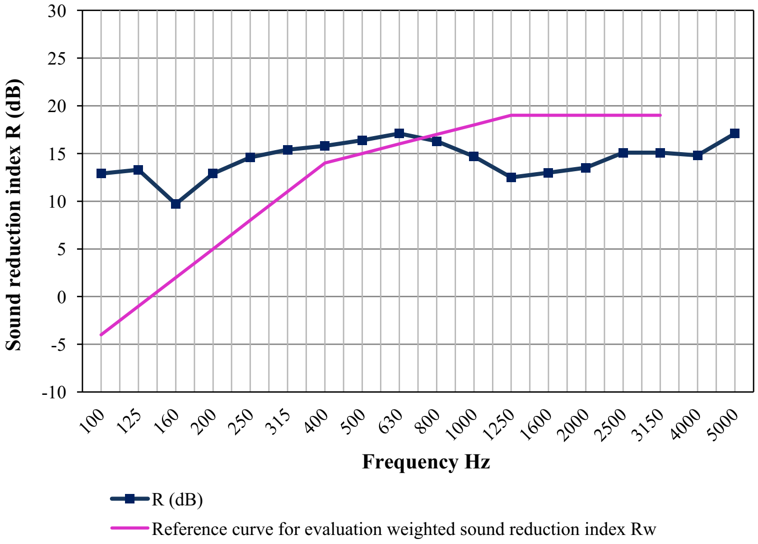

Fig. 8. Measured sound reduction index (R) values.

Table 5
Measured reverberation times and sound absorption coefficient.

f (kHz)	T_1	T_2	$T_1 - T_2$	α
0.100	7.87	3.90	4.0	0.44
0.125	7.85	3.60	4.3	0.51
0.160	9.05	4.16	4.9	0.44
0.200	10.34	4.40	5.9	0.44
0.250	10.38	4.52	5.9	0.42
0.315	8.54	4.31	4.2	0.39
0.400	8.61	4.40	4.2	0.37
0.500	9.43	4.70	4.7	0.36
0.630	9.33	4.63	4.7	0.36
0.800	8.78	4.60	4.2	0.35
1.000	8.18	4.29	3.9	0.37
1.250	7.26	3.79	3.5	0.43
1.600	6.32	3.53	2.8	0.44
2.000	5.33	3.27	2.1	0.44
2.500	4.28	2.87	1.4	0.46
3.150	3.36	2.50	0.9	0.46
4.000	2.52	2.03	0.5	0.52
5.000	1.91	1.71	0.2	0.51

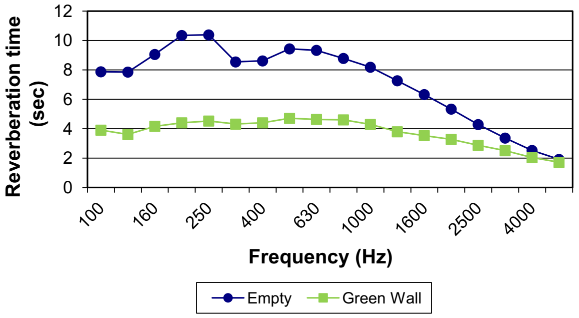

Fig. 10. Measured reverberation times.

In Fig. 10, the reverberation times for the empty room and for the room with the specimen inside are drawn. After introducing the green wall in the reverberation chamber, there was a considerable decrease in the reverberation time. These findings correspond to those that were obtained by Wong et al. [7], in which considerable reductions in the reverberation time were measured, especially in the frequency range between 0.200 kHz and 1 kHz. In this study, the differences in the reverberation time before and after placing the specimen inside the reverberation room range from 4.2 to 5.9 in the frequency band between 0.125 kHz and 1 kHz. Likewise, this difference between the reverberation times decreases with increasing frequency and is virtually eliminated at 5 kHz.

Fig. 11 compares between the results that were obtained in the reverberation room for the sound absorption coefficient by Wong et al. [7] and the results that were obtained for the green wall that was studied in this paper. The specimen that was used in the Wong et al. test consists of two wooden frames with different racks slanting inwards where several pots of plants were placed to simulate a green wall. Depending on the number of pots located on each shelf, the coverage could vary so that it was possible to achieve 43%, 71% or 100%. According to this author, the substrate performs well at low frequencies by absorbing the acoustic energy, whereas plants perform better at high frequencies, although their mechanism is to scatter the sound noise. However, this fact was not reflected in the sound absorption coefficient curves (Fig. 11), because the values were below 0.3 from the frequency range 0.100 to 0.400 kHz.

Regarding the green wall that was tested in the present study, the sound absorption coefficient remains more constant between 0.35 and 0.51, reflecting a good performance of the green wall not only at low frequencies but at high frequencies as well. It should also be considered that, in this study, the specimen was built with an air chamber 12 cm thick so that the test simulated the real conditions of placement on a building façade.

Moreover, the sound absorption coefficient obtained using the green wall differ significantly from those that were obtained by Yang et al. [11] with a different typology of the green wall and without vegetation.

In the Yang et al. results, the sound absorption coefficient, for a considerable level of water content in the substrate, ranged between 0.4 and 0.8, showing a decrease at low frequencies from 0.6 (0.100 kHz) to 0.4 (0.160 kHz) and increasing again to 0.7 (0.400 kHz) and staying constant at this level from 0.400 to 4 kHz. Finally, from 4 kHz the frequency increased to 0.8. The wall that was tested by Yang et al. was very different from that tested in the present study, because it consisted of a modular system made up of galvanised steel frames designed to clad a building. Geotextile linings within the steel mesh held the substrate (coconut fibres with some perlite and water-retaining polymer). The wall had a depth of 200 mm.

From these results it can be deduced that the green walls provide good sound absorption capacities, but the magnitude of their contribution depends on the design and materials that are used in each system.

With the data that were obtained in this study and comparing them with those of previous studies, the potential of green walls

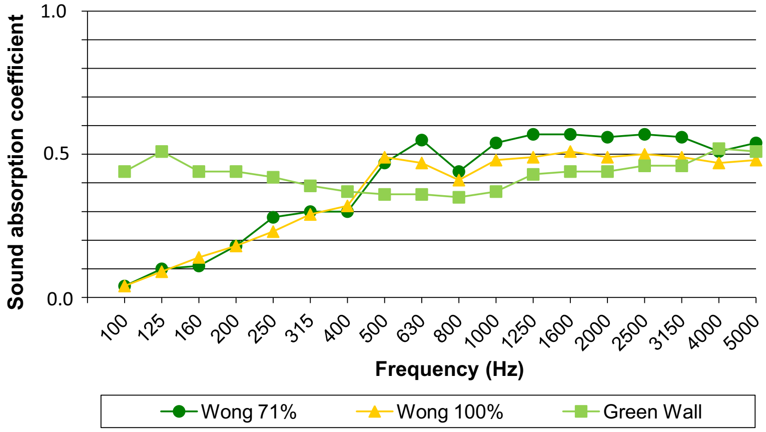

Fig. 11. Sound absorption coefficient value comparison between the green wall and the results reported by Wong et al. [7].

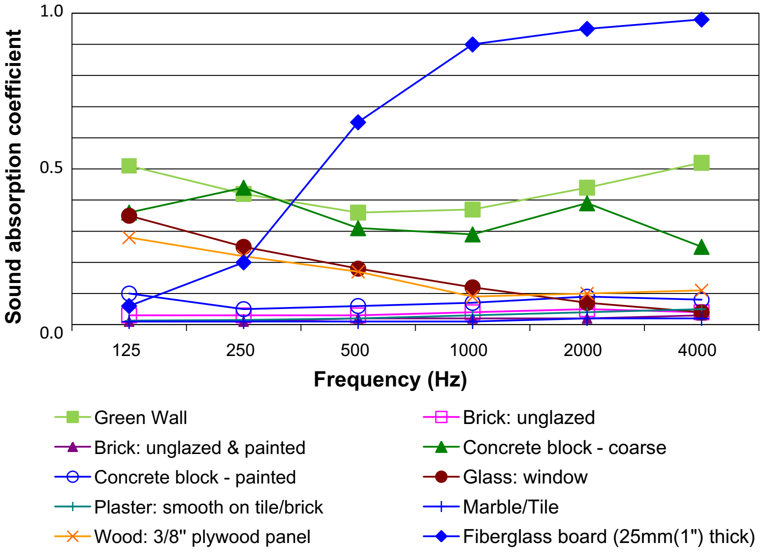

Fig. 12. Sound absorption coefficient value comparison between the green wall and common building materials.

as tools for sound insulation for buildings can be confirmed. However, the low number of previously conducted studies and the differences in the construction systems that were used in these studies do not allow for obtaining accurate values of the real contribution of green walls to noise attenuation on buildings.

Fig. 12 compares the obtained values for the green wall sound absorption coefficient and different common building materials [13]. The green wall provides the same or better sound absorption characteristics than many of these materials at low frequencies. Moreover, although the green wall cannot compete with materials such as fibreglass board, it also performs well at high frequencies.

4. Conclusions

In this study, the use of the green wall as a passive acoustic insulation system for buildings was evaluated. In reviewing previous studies concerning the acoustic insulation contribution of green walls to buildings, it was found that the number of studies to date was very small. Moreover, because the experimental methodologies that were used in these studies were very different, and the construction systems that were analysed also differed greatly from each other, no strong conclusions could be drawn.

Because green walls are very new construction systems, it is necessary to obtain data about their acoustic properties in the lab in a controlled manner following international standards so that the results can be compared with studies of similar systems. This approach avoids the problem of in situ measurements once the construction element is installed in the buildings, which are conditioned by the characteristics of the building environment, such as anchoring systems and their possible sound transmission or outside noises.

The tests were performed to measure the airborne sound insulation according to UNE-EN ISO 10140-2 standards. The obtained results and conclusions were as follows:

- The sound reduction index (R) values from the lab measurements are summarised in Table 4 and Fig. 8.
- The calculated weighted sound reduction index was $R_w = 15$ dB, and the correction terms were Ctr = −1 dB for traffic noise and $C = -1$ dB for pink noise. In case the modules were use as a sound barrier it would be ranked as B1.
- These values, although lower than those for other common constructive solutions, are promising and could be enhanced with some simple improvements to both increase the mass of this constructive system and efficiently seal the joints between the modular pieces. in that case the calculated weighted sound reduction index was $R_w = 18$ and the correction terms were Ctr = −1 dB for the noise traffic and $C = -1$ dB for the pink noise In case the modules were use as a sound barrier it would be ranked as B2.

Moreover, from the measurement of the sound absorption in the reverberation room according to UNE-EN ISO 354 standards, the main findings and conclusions were as follows:

- The reverberation times, both of the empty room (T_1) and after placing the sample inside the room (T_2), as well as the values for the sound absorption coefficient α, are summarised in Table 5.
- The calculated value of the weighted sound absorption coefficient was $\alpha = 0.40$.

Comparing these results with those of previous studies, it can be concluded that the introduction of the green wall specimen into the reverberation room implies a reduction in the reverberation time (from 4.2 to 5.9 in this study), highlighting and quantifying the sound absorption capacity of this construction system.

Regarding the sound absorption coefficient, some differences with previous studies were found, most likely due to the differences in the tested constructive system in each case. However, despite these differences, the potential of the green wall sound insulation tool for buildings can be confirmed.

The green wall showed a similar or better acoustic absorption coefficient than other common building materials, and its effects on low frequencies were of particular interest because its observed properties were better than those of some current sound-absorbent materials at low frequencies.

Taking into consideration that the voice frequency was around 60 dB, this correspond to the frequency at witch this modular green façade is more efficient absorbing sound, so it could be used very effectively in public places for instance restaurants, hotels, and halfway up the street to the passage of people.

In this study, only the direct transmission of sound through the green wall was considered. Because sound can also be transmitted by indirect pathways, future studies should consider a more realistic situation with the green wall placed on a building façade wall.

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References

[1] Johnston J, Newton J, Greater London Authority. Building green: a guide to using plants on roofs, walls and pavements. London: Greater London Authority; 2004.
[2] Newton J. Construction Industry Research and Information Association; Ecology Consultancy Ltd.; Livingroofs.org; Great Britain, Department of the Environment, Transport and the Regions, Environmental Protection Group. Building greener: guidance on the use of green roofs, green walls and complementary features on buildings. London: CIRIA; 2007.
[3] Dunnet N, Kingsbury N. Planting green roofs and living walls. Portland: Timber Press; 2008.
[4] Van Renterghem T, Botteldooren D, Verheyen K. Road traffic noise shielding by vegetation belts of limited depth. J Sound Vib 2012;331:2404–25.
[5] Cook D, Van Haverbeke DF. Suburban noise control with plant materials and solid barriers. Lincoln, NE: University of Nebraska, College of Agriculture, Agricultural Experiment Station; 1977.
[6] Pérez G, Rincón L, González JM, Cabeza LF. Green vertical systems for buildings as passive systems for energy savings. Appl Energy 2011;88:4854–9.
[7] Wong NH, Tan AYK, Tan PY, Chiang K, Wong NC. Acoustics evaluation of vertical greenery systems for building walls. Build Environ 2010;45:411–20.
[8] Fernández-Bregón N, Urrestarazu M, Valera DL. Effects of a vertical greenery system on selected thermal and sound mitigation parameters for indoor building walls. J Food Agric Environ 2012;10:1025–7.
[9] Van Renterghem T, Hornikx M, Forssen J, Botteldooren D. The potential of building envelope greening to achieve quietness. Build Environ 2013;61:34–44.
[10] Horoshenkov KV, Khan A, Benkreira H. Acoustic properties of low growing plants. J Acoust Soc Am 2013;133:2554–65.
[11] Yang HS, Kang J, Cheal C. Random-incidence absorption and scattering coefficients of vegetation. Acta Acust United Acust 2013;99:379–88.
[12] Urrestarazu M, Burés S. Sustainable green walls in architecture. J Food Agric Environ 2012;10:792–4.
[13] SAE Institute. School of Audio Engineering. SAE Technology College; 2014. <http://es.sae.edu/es/home/>. [accessed 16.05.14].
[14] Laboratory for the Quality Control in Buildings (LCCE) of the Basque Government. <http://www.garraioak.ejgv.euskadi.net/r41-19385/es/contenidos/informacion/2575/es_2151/es_11804.html> [accessed 14.05.14].
[15] The National Physical Laboratory. Kaye & Laby tables of physical & chemical constants. <http://www.kayelaby.npl.co.uk/> [accessed 14.05.14].