More than just a Green Facade
The sound absorption properties of a vertical garden with and without plants

Davis, Michael; Tenpierik, Martin; Ramirez, Francisco; Perez, Maria Elena

DOI
10.1016/j.buildenv.2017.01.010

Publication date
2017

Document Version
Accepted author manuscript

Published in
Building and Environment

Link to formal publication Building and Environment (Elsevier): http://dx.doi.org/10.1016/j.buildenv.2017.01.010

More than just a Green Facade: the sound absorption properties of a vertical garden with and without plants

M. J. M. DAVIS[1, 2], M. J. TENPIERIK[3], F. R. RAMÍREZ[1] and M. E. PÉREZ[4]

[1]*Faculty of Architecture, Design and Arts, Pontificia Universidad Católica of Ecuador, Quito, Ecuador*
[2]*Evolution Engineering, Design and Energy Systems Ltd., Exeter, UK*
[3] *Faculty of Architecture and the Built Environment, TU Delft, Delft, the Netherlands*
[4] *Independent Researcher and Vertical Garden Designer, Quito, Ecuador*

Abstract

Up to 44% of EU residents are exposed to noise levels that are detrimental to health. In this context, vertical gardens could play an important role in architectural acoustics, where the main absorber material is the substrate soil. Plants have a beneficial effect for higher frequencies when planted in a large density. In this paper a vertical garden design developed at the Pontificia Universidad Católica of Ecuador (PUCE) was tested for interior acoustic design. The modules solely with substrate and planted with ferns were tested. The objective was to ascertain and explain the random incidence sound absorption coefficient of vertical garden modules. 50 modules making up a total floor area of 10.125 m^2 were used for the measurements. Six different configurations were measured: connected versus dispersed and directly on the floor versus with an air cavity of 5 and 10 cm. Furthermore, each configuration was tested with modules solely filled with substrate and with substrate filled modules with densely planted ferns. The weighted random incidence sound absorption coefficient of the modules densely planted with ferns equals 1.00. This applied to all different configurations tested. The sound absorption coefficient in the lower frequencies (100-315 Hz), mid frequencies (400-1250 Hz) and high frequencies (1600-5000 Hz) was 0.59-0.80, 1.00 and 1.00 respectively. This makes this type of building technology highly suitable for applications where sound needs to be attenuated, paving the way for applying vertical garden systems as a design tool for improving the acoustics of indoor spaces or urban squares.

1. Intro

The aim of this research is to show how vertical gardens can be a useful tool for mitigating noise pollution in urban environments.

The Paris Accord recognizes the need to restore natural habitats and prevent deforestation: “Parties are encouraged to take action to implement and support…enhancement of forest carbon stocks” [1]. Urbanisation in the world is also on the increase, where Latin America in particular almost doubled its percentage of urbanization from 41.4% to 75.3% between 1950 and 2000 [2]. Coupled with this, the growth of cities tends to go hand in hand with a decrease in vegetation, which then in turn leads to temperature increases related to the urban heat island effect [3].

Many spaces inside buildings, or urban environments like public squares, are noisy or reverberant. In order to maintain stable and comfortable indoor air temperatures, generally thermal mass is used. In order to be effective, this thermal mass needs to be exposed to the air. As a result, concrete or masonry walls and floors with - in warm countries - tiles on top are often used. These so-called acoustically hard materials lack sound absorption and as a result lead to noisy and reverberant indoor spaces. Also urban environments are often made up of stone, brick, concrete and asphalt, which leads to an increased urban heat island effect and to a lack of sound attenuation. According to Renterghem and Botteldooren [4] in 2000 up to 44% of residents of the European Union were subject to noise levels above the recommended limits for health. Noise pollution in urban areas typically stems from traffic outdoors [4] [5], as well as indoor sources such as HVAC systems [6]. Furthermore, the need for noise control systems is recognised as important in sustainable building design, in addition to the more widely accepted parameters of air quality and temperature control [6] [7].

The application of green roofs and vertical gardens offer multiple benefits in urban environments, including surface water runoff retention, reductions in the urban heat island effect and an increase in urban biodiversity [8]. Furthermore, building incorporated vertical gardens play an important role in reducing the heat transfer between a building and the surrounding environment, as well as providing protection from solar irradiation [9]. An example of a review paper discussing the effects of greenery on thermal comfort inside and energy use of buildings is offered by Raji et al.[10]. Moreover, contact with plants is highly beneficial. First, the microbial activity in the root systems filters Volatile Organic Compounds from the air [11]. Second, particulate matter is captured and retained on the leaves [12]. Third, a person's productivity and wellbeing increases when in contact with plants, coupled with a decrease in stress levels [12] [13] [14]. More recently, Davis and Hirmer [15] put forward a mathematical model based on the FAO-56 Penman Monteith equation, that set out to build on experimental work by Davis & Ramirez [16] in the use of vertical gardens activated as evaporative air conditioning units. A vertical garden design was then developed for this to be studied in greater depth by Davis, Ramirez and Pérez [17]. The garden was modular, using a lightweight substrate mix of coco chips, sphagnum and soil. This research uses the same design for the vertical garden modules, but where there sound absorption qualities are looked into. The aim is to have vertical gardens as active elements in mitigating noise pollution in urban environments.

It has been known since the 80's that single leaves have little effect on sound attenuation, but that the cumulative effect of all sum of the leaves on say, a tree, could contribute [18]. On the other hand, Wong et al [5] argue that vegetation plays an important in combatting acoustic contamination in cities. Connelly and Hodgson [19] reinforce this by showing that green roofs could be designed for sound absorption in relation to their mass, density and the moisture content. This was further substantiated by case studies by the City of Sydney [8]. Such initiatives are particularly useful when noise pollution comes from above due to airports and flight routes [19]. In Posada et al.'s research [20], vertical gardens had a beneficial effect in mitigating noise from traffic. Furthermore, Restrepo and González [21] found vertical gardens led to sound levels being reduced by up to three times. Costa and James [22] state that plants are useful in mitigating "annoying high pitch noises" (pg. 17) [22], as they have a greater effect in mitigating noise pollution at higher frequencies. Additionally, Asdrubali et al. [23] researched the absorption coefficient of tropical plants in a hydroponic porous substrate. An impedance tube was used in accordance with ISO 10534-2 [24] to determine the normal incidence absorption coefficient. Second, a reverberation chamber was used to determine the diffuse field absorption coefficient. From the five plant species selected for the study, ferns (Nephroepis Exaltata) were found to work best, although leaves of the plants only slightly increased the sound absorption coefficient in the higher frequencies [23]. Unfortunately, the chamber dimensions were lower than those required by ISO 10534-2 [23]. Nevertheless, the work demonstrated the main absorber material to be the substrate soil, where plants had a beneficial effect only when planted in a large density [23]. Testing in a full size reverberation chamber was carried out specifically for vertical gardens by Azkorra et al. [25], where a calculated value of the weighted sound absorption coefficient of α=0.40 was found. The same study cited work from Van Renterghem et al. [26], Horoshenkov et al. [27] and Yang et al. [28], stating the importance the substrate thickness, density and moisture content has in the sound absorption qualities of vertical greenery. A saturated substrate can be said to behave similar to a rigid material [26], and where an increase in moisture content corresponds to a decrease in the sound absorption coefficient [28]. Additionally, an increase in the thickness of the substrate over and above 50mm showed only minor changes in the absorption coefficient [28].

This paper seeks to build on Asdrubali et al.'s [23] and Azkorra et al.'s [25] work, where a vertical garden design developed at the Pontificia Universidad Católica of Ecuador (PUCE) was tested for interior acoustic design. The modules solely with substrate and planted with ferns were under scrutiny. The objective was to ascertain and explain the random incidence sound absorption coefficient of vertical garden modules.

2. Methodology

The main research question of this study was:

> Which values does the random incidence sound absorption coefficient of the vertical garden modules developed at the Pontificia Universidad Católica del Ecuador filled only with substrate (case 1) and densely planted with ferns (case 2) have over the frequency range from 100 to 5000 Hz?

Difference configurations are possible for the vertical garden modules: connected as one continuous garden, or dispersed as segments of smaller gardens. Additionally, the modules can either be directly connected to a (load-bearing) wall, or can be on a supporting structure placed in front of a wall. As such, the following three sub-research questions were formulated:

1. To what extent will the random incidence sound absorption coefficient of the garden modules be different between connected and dispersed configuration?

2. To what extent will the random incidence sound absorption coefficient of the garden modules be different when the modules are directly connected to a wall, placed in front of a wall with a 5 cm air cavity or placed in front of a wall with a 10 cm air cavity?

3. To what extent will the dense planting of the modules with ferns have an effect on the random incidence sound absorption coefficient of the garden modules?

In order to answer these questions, measurements were conducted in the reverberation chamber at the Delft University of Technology. The size of the chamber was 200 m^3, and as such complied with the ISO 354: 2003 [29]. The research followed both the procedure of the interrupted noise measurement with white noise as sound and the integrated impulse response method using a logarithmic sweep as sound. Both methods comply with the requirements of the ISO 354: 2003 [29].

Six positions were set out in the reverberation chamber (Figure 3), which were used for positioning the microphone. The microphone was approximately 1.3 m above the floor. The sound source was located at positions 5 and 6, denoted B and A. The sound source was located 1.5 m above the floor. As such, 10 source-microphone combinations were used in total for the experimental work. Furthermore, in case of the interrupted noise method, each measurement was repeated at least three times. This meant a total amount of at least 30 measurements were carried out for each tested configuration. In case of the integrated impulse response method, 4 sweeps were used for each combination of source and receiver leading to a total of 40 sweeps per configuration. From these 30 measurements or 40 sweeps average values for the reverberation time per 1/3rd octave band were calculated per configuration in order to obtain the sound absorption and sound absorption coefficient of the modules.

Measurements were performed in 1/3rd octave bands with center frequencies starting from 100 Hz up till 5000 Hz. The total exposed surface area of the modules was considered to calculate the random incidence sound absorption coefficient of the modules, including the top and side surface area. The random incidence sound absorption of the modules was determined by first calculating the total sound absorption in the room with modules corrected for air absorption (Sabine's equation with air absorption; see ISO 354: 2003), then subtracting the total sound absorption in the empty reverberation room corrected for air absorption and then taking the difference between these two figures. Next, the absorption coefficient was determined in two different ways: 1.) by dividing the absorption of the modules through the total exposed surface area of the modules (the top and side surface area); and 2.) by dividing through only the top surface area. The first method is the correct one which is generally used throughout this paper; the second method is only used in section 4.2 to highlight the difference between the connected and dispersed configuration. The areas are provided below. ISO 9613-1: 1993 [30] was used as a methodology to determine effects of sound absorption by the air in the reverberation chamber.

Met opmaak: Links

The equipment used for the measurements was:

- Norsonic Nor140 class 1 calibrated sound analyser.
- Norsonic Nor276 dodecahedron omni-directional loudspeaker.
- Norsonic Nor280 power amplifier, connected to the Nor276.
- Behringer UCA222 USB-interface to connect the Nor140 and Nor280 to a laptop.
- Laptop with a custom written script in Matlab to generate sweep signals and to analyse the data.
- Voltcraft DT8820 environmental variables meter.

The vertical garden modules were 10 cm thick, with dimensions of 0.45x0.45 m^2. They were made from of a steel mesh with 5 cm apertures on the outside, with a fine plastic mesh sock inside that was filled with a substrate mixture of potting soil, coco chips and sphagnum moss. The modules were saturated at the time of the experiment, having been thoroughly watered earlier in the day. The modules differed from the vertical garden used Azkorra et al. [25], in that the substrate mix mitigated the need for the plants to be sustained by hydroponics. Additionally, for Azkorra et al. [25] the modules consisted of recycled plastic containers filled with a substrate of coconut fibre. As such the substrate itself was lightweight, low density and "not exposed directly" to noise (pg. 47) [25]. The modules designed at the Pontificia Universidad Católica del Ecuador were of a denser substrate mix, where the soil was saturated and where more substrate surface was exposed. 16 medium sized boston ferns (Nephrolepsis) per module were planted, in accordance to the density used by Asdrubali et al. [23]. A total of 50 modules were used, which correlated to a total surface area of 10.125 m^2. The modules were organized in two basic configurations on the floor of the reverberation room: connected and dispersed.

Figure 1: Modules in connected configuration without (a) and with (b) ferns.

Figure 2: Modules in dispersed configuration without (a) and with (b) ferns.

Connected: The modules were connected forming a grid of 7 x 7 modules, plus one module attached to one of the sides (Figure 1). The total area of the sides in this configuration was 30 x 0.45 x 0.1 = 1.35 m^2.

Dispersed: The configuration formed five groups of 2 x 5 modules (Figure 2). These five groups of modules were distributed over the floor of the reverberation room. The total area of the sides in this configuration was 70 x 0.45 x 0.1 = 3.15 m^2.

Furthermore, these two configurations were tested with a 5 cm and 10 cm air cavity between the floor and the modules. 5cm thick Styrofoam blocks in one and two layers were used to create the cavities. The sides of the modules were exposed, meaning that the air cavities and the sides of the panel were accessible for the sound. This was done as it represented the way the modules are used in practice for vertical gardens.

Measurements of the random incidence sound absorption coefficient in a reverberation chamber according to ISO 354: 2003 sometimes lead to sound absorption coefficients higher than 1. This also happened for the measurements shown in this paper. One cause is that the sides of the modules also absorb sound. For calculating the absorption coefficient in this paper, these sides are therefore explicitly taken into account. However, in case of the raised modules also a very small part of the underside of the modules may have participated in the sound absorption behaviour as such slight raising the absorption coefficient as compared to the on the floor configuration. The second general reason for higher than 1 absorption coefficients is bending of the sound waves along the edges of the modules, so-called edge-scattering. Although this phenomenon physically is not the same as sound absorption, its effect is that a small increase of the absorption coefficient is measured. Generally, absorption coefficients higher than 1 are rounded to 1.00. An important additional factor is that when the modules were planted, the sides of the modules are increased with the height of the plants and the plants add more volume on top of the modules. Because of its irregularity, this extra surface or volume was not taken into account when calculating the absorption coefficients. Also this has some effect on the calculated values.

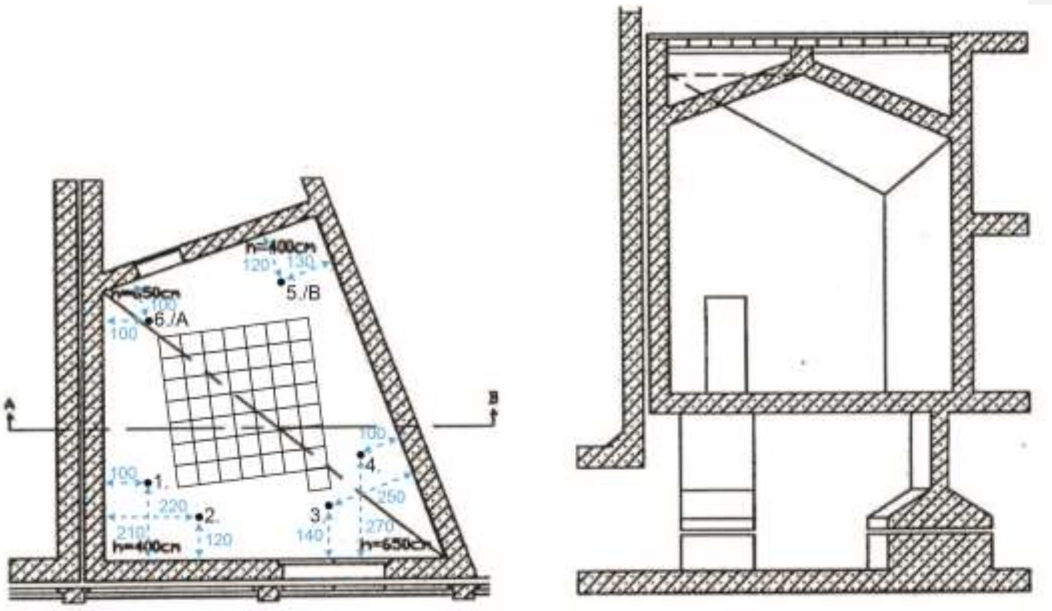

Figure 3: Location of the measurement points inside the reverberation chamber (sizes in cm).

3. Results

3.1 Modules solely filled with substrate

Table 1 and Figures 4a and 4b present the results of the measurements for all of the configurations. The black lines represent the connected configurations, whereas the grey lines represent the dispersed configurations. Furthermore, the continuous lines represent the 'directly on the floor' configurations, the broken lines the 'with 5 cm air gap' configurations and the dotted lines the 'with 10 cm air gap' configurations. Additionally, the error bars shown in the figure represent the imprecision or uncertainty of the measurements based on the recommendations of ISO 354: 2003 [29]. In the figure, some values of the absorption coefficient are higher than 1, which results from edge scattering. The temperature during the measurements varied between 23.7 °C and 23.9 °C while the relative humidity varied between 71% and 77%. These variations were accounted for in the air absorption.

Table 1: weighted (α_w), low frequency (α_L; average of 100 – 315 Hz), mid frequency (α_M; average of 400 – 1250 Hz) and high frequency (α_H; average of 1600 – 5000 Hz) random incidence sound absorption coefficient of the measured configurations solely with substrate. Values > 1 are rounded to 1.00.

Configuration	α_w	α_L	α_M	α_H
Connected - on floor	1.00	0.76	1.00	0.94
Connected - 5 cm air gap	1.00	0.82	1.00	0.98
Connected - 10 cm air gap	1.00	0.80	1.00	0.99
Dispersed - on floor	1.00	0.73	1.00	0.93
Dispersed - 5 cm air gap	1.00	0.74	1.00	0.95
Dispersed - 10 cm air gap	1.00	0.73	1.00	0.93

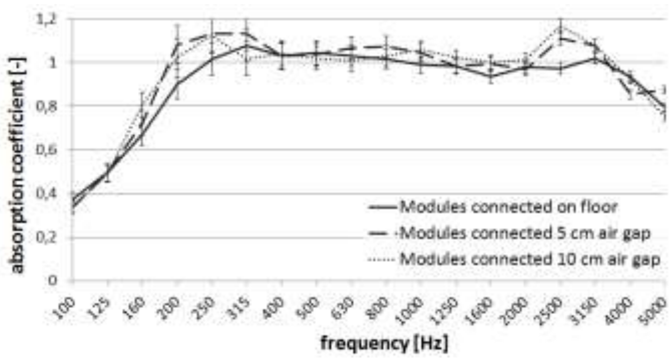

Figure 4a: Random incidence sound absorption coefficient, α_s, of the connected configurations.

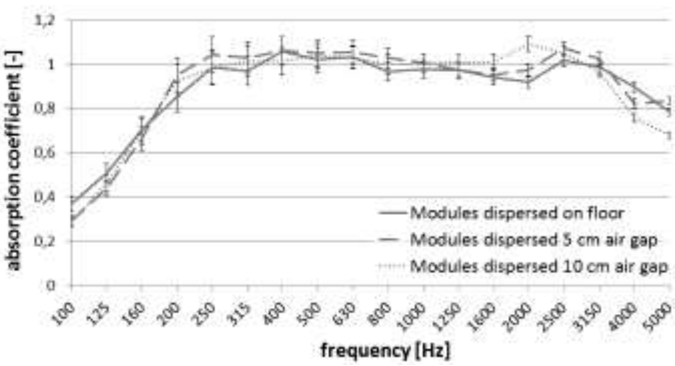

Figure 4b: Random incidence sound absorption coefficient, α_s, of the dispersed configurations.

3.2 Modules filled with substrate and densely planted with ferns

Table 2 and Figures 5a and 5b show the measurement results for all of the configurations of the modules densely planted with ferns. The black lines represent the connected configurations, whereas the grey lines represent the dispersed configurations. Furthermore, the continuous lines represent the 'directly on the floor' configurations and the dotted lines the 'with 10 cm air gap' configurations. Additionally, the error bars shown in the figure represent the imprecision or uncertainty of the measurements based on the recommendations of ISO 354: 2003 [29]. As previously, some values of the absorption coefficient are higher than 1, which results from edge scattering. The temperature during these measurements varied between 23.1 °C and 24.0 °C while the relative humidity varied between 71% and 79%. These variations were accounted for in the air absorption.

Table 2: weighted (α_w), low frequency (α_L; average of 100 – 315 Hz), mid frequency (α_M; average of 400 – 1250 Hz) and high frequency (α_H; average of 1600 – 5000 Hz) random incidence sound absorption coefficient of the measured configurations densely planted with ferns. Values > 1 are rounded to 1.00.

Configuration	α_w	α_L	α_M	α_H
Connected - on floor	1.00	0.64	1.00	1.00
Connected - 10 cm air gap	1.00	0.80	1.00	1.00
Dispersed - on floor	1.00	0.59	1.00	1.00
Dispersed - 10 cm air gap	1.00	0.69	1.00	1.00

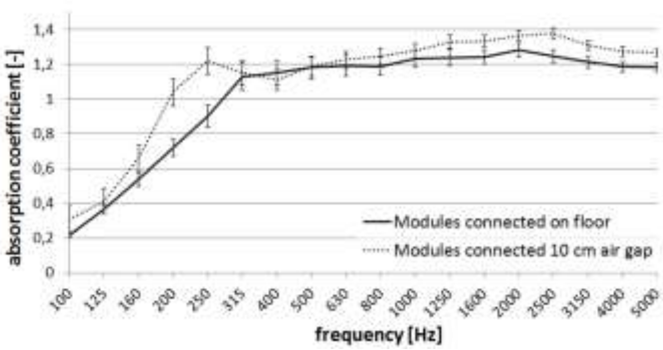

Figure 5a: Random incidence sound absorption coefficient, α_s, of the connected configurations.

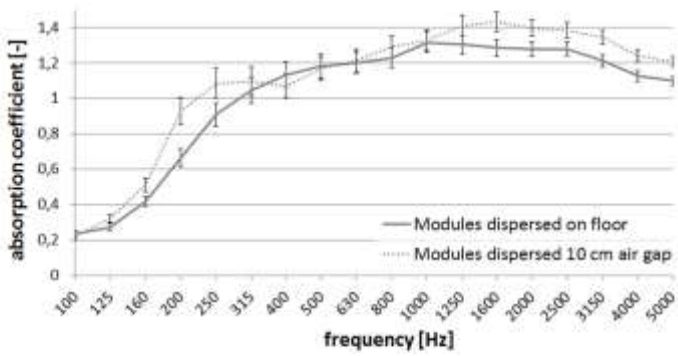

Figure 5b: Random incidence sound absorption coefficient, α_s, of the dispersed configurations.

4. Discussion of results

4.1 On floor versus raised

As can be seen from Figures 4 and 5, the substrate behaves as a porous absorber, with low sound absorption in the lower frequencies and high sound absorption in the higher frequencies. Between 250 Hz and 3150 Hz, the sound absorption coefficient is around 1 (a value that slightly larger than 1 value can be seen due to the effect of edge scattering). A slight reduction in the sound absorption is visible for values above 3150 Hz. However, this is generally due to inconsistencies in the measuring equipment, more than the material under investigation.

Furthermore, there is only a small difference between the modules directly on top of the floor and the raised modules with a 5 or 10 cm air gap. In general, one could say that the raised modules show a very small shift of the absorption graph to the left, i.e. to the lower frequencies. This can be explained by the fact that due to the raised configuration the distance between the floor and the top of the absorption material has increased. As a result, the top of the absorption material is closer to the place where the highest vibration velocities of air molecules occur for slightly lower frequencies; or in other words the absorption material has become slightly more effective for lower frequencies. This effect is particularly visible for the modules that were densely planted with ferns (Figure 5).

The raised configurations with substrate only also show slightly higher peaks around 2500 Hz, in any case for the connected modules. The dispersed configurations do not show such peak deviations. The peak around 2500 Hz may be due to the onset of standing waves inside the modules. Such standing waves arise when the thickness of the material under investigation corresponds to half a wavelength of the sound or n times half a wavelength. Assuming that it is the sound in the pores that is in standing wave mode, the first frequency where this happens is 343/2/0.1=1715 Hz. If it is assumed that due to variations in the module homogeneity and that it was possible that in a number of places the substrate was less than 10 am thick, then it would be reasonable to deduce the frequency could be raised and that this value was therefore fairly close to 2500 Hz.

In general, also the modules densely planted with ferns and raised 10 cm from the floor show slightly higher absorption coefficients in the higher frequencies than the modules densely planted with ferns but placed directly on the floor.

4.2 Connected versus dispersed

Figure 6a shows the random incidence sound absorption coefficient of the modules placed directly on the ground with substrate only, both in connected and in dispersed configuration. The sound absorption coefficients are based on the assumption that all exposed surface areas are taken into account. As can be seen from the figure, there is no significant difference between the connected and dispersed configuration.

Figure 6a shows the results for the total exposed surface area. The difference between the connected and dispersed configuration can be found when only the top surface area is considered (Figure 6b), and where the total sound absorption is normalised on the top surface area only. The absorbing surface area exposed of the dispersed configuration is bigger due to the sides adding to the area. As such, the total sound absorption and subsequent sound absorption coefficient is higher. However, for characterising the substrate as a material, it is important to consider the total area that is exposed to sound, thus including the side areas (as presented in Figure 6a). These same observations also apply for the modules that were densely planted with ferns.

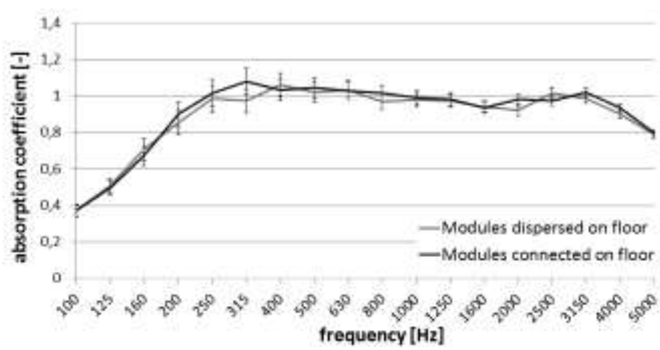

Figure 6a: Random incidence sound absorption coefficient, α_s, of the 'on the floor' configurations in case the total exposed surface area (top and side area) is used for calculating the absorption coefficient.

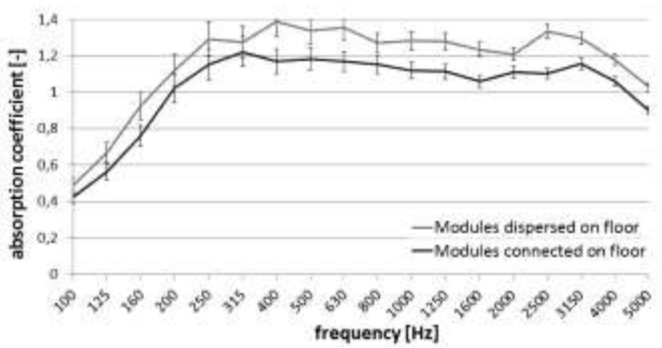

Figure 6b: Random incidence sound absorption coefficient, α_s, of the 'on the floor' configurations in case only the top area is used for calculating the absorption coefficient.

4.3 Comparison to theory: substrate

It is interesting to see how well the measured results correspond to the theory of porous absorbers. In order to make the comparison, the model of Delany-Bazley was choosen [31]. Figure 7 shows the results of the theoretical predictions according to this model for five different layer thicknesses: 5, 8, 10, 12 and 15 cm substrate for random incidence of sound, and compares these to the measured results of the 'connected / on the floor' configuration for the modules with substrate only (data points with uncertainty bars). It can be clearly seen that the general trend of the absorption coefficient of the substrate (measured) is similar to the theoretical predictions.

However, the measured results - with a substrate thickness of around 10 cm – slightly deviate from the theoretical results for the 10 cm thick substrate in the lower frequencies. There is a small difference for the frequencies below 315 Hz.

First, one uncertainty in the theoretical predictions results from the chosen value of the flow resistivity, σ. In 1985, Martens at al. investigated several different types of soil. For acoustically soft materials (which would describe the substrate under investigation) they found flow resistivity values below 100 kPa·s·m^{-2}[18]. The average flow resistivity for this group of materials was found to be 64.9 kPa·s·m^{-2}. Although the exact value of the flow resistivity of the substrate under investigation was not measured and therefore not known. The value of 64.9 kPa·s·m^{-2} was taken for the theoretical predictions.

Second, the Delany-Bazley model was derived for fibrous absorbents and is generally considered to be inaccurate when $\rho_0 f/\sigma$ is smaller than 0.01 or larger than 1 [31]. In this equation ρ_0 is the density of air (kg·m^{-3}), f is the frequency (Hz) and σ is the flow resistivity (Pa·s·m^{-2}). For this particular case, the model becomes inaccurate below a frequency of 500 Hz.

Third, although the substrate was designed to be 10 cm thick, in reality the thickness had a tendency to vary. As a result, the measured results should lie somewhere between the theoretical curves of the 8 and 10 cm substrates, which indeed is the case.

In general, therefore, the sound absorption coefficient of the used substrate follows the impedance model of Delany-Bazley quite well.

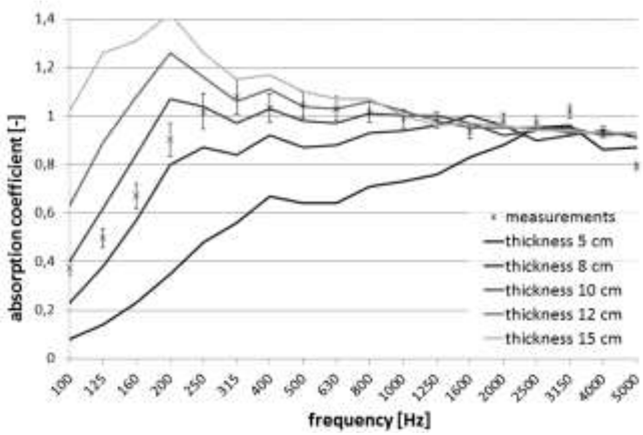

Figure 7: Random incidence sound absorption coefficient, α_s, of the 'connected - on floor configuration' compared to theoretical curves according to the Delany-Bazley model (assumed flow resistivity of substrate 64.9 kPa·s·m^{-2}).

4.4 *Effect of vegetation*

Figures 8a and 8b show a comparison of the results for the modules with substrate only and the modules densely planted with ferns. The experimental results confirm that most of the sound absorption is related to the soil, and not so much to the plants. As can be seen from Figures 8a and 8b, the most important influence the ferns have on the random incidence sound absorption coefficient is in the higher frequencies, or more precisely above around 400 Hz. The ferns increase the sound absorption coefficient of the modules in these higher frequencies by around 0.2 to 0.3. Ding et al. [32] showed, with numerical simulations for normal incidence of sound, that viscous damping is responsible for the sound absorption by the leafs of the plants. They also showed however, that for normal incidence of sound leafs on top of a low-density substrate tend to decrease the sound absorption coefficient for frequencies higher than around 2000 Hz. Such a decrease was not found in the experimental work for this paper, which was based on diffused field measurements and used a high density substrate. Furthermore, the results presented in this research are in line with the findings of Asdrubali et al. [23], who found an increase of the sound absorption coefficient of the same order for modules with soil and 90 ferns in a 1.06 x 1.06 m^2 module from about 630 Hz onwards. The ferns were planted with a similar density for this research, with 16 ferns per 0.45 x 0.45 m^2 module. As long as the sound reaches the substrate underneath the plants, the plants add thermo-viscous damping increasing the total amount of friction and thus sound absorption of the system.

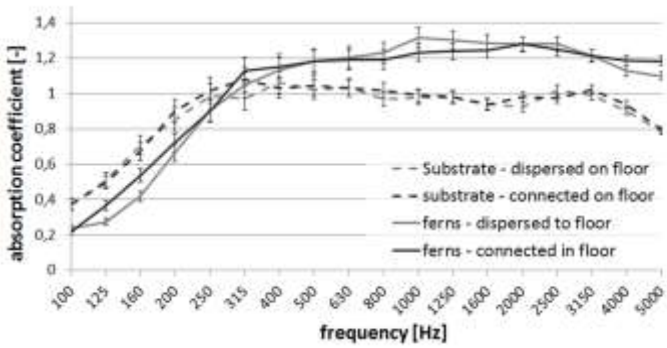

Figure 8a: Random incidence sound absorption coefficient, α_s, of the 'on the floor' configurations (total absorbing surface is used for calculating the absorption coefficient) comparing the modules with only substrate and the modules densely planted with ferns.

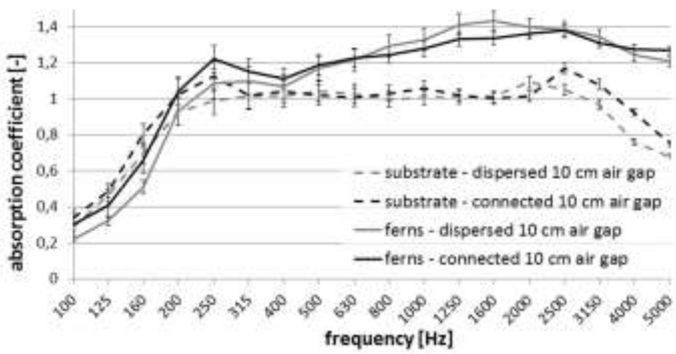

Figure 8b: Random incidence sound absorption coefficient, α_s, of the '10 cm air cavity' configurations (total absorbing surface is used for calculating the absorption coefficient) comparing the modules with only substrate and the modules densely planted with ferns.

5. Conclusions

In this research the random incidence sound absorption coefficient of the vertical garden modules (solely with substrate and densely planted with ferns) developed at the Pontificia Universidad Católica del Ecuador (PUCE) were measured in the reverberation room at the Delft University of Technology. A total floor area of 10.125 m^2 made up from 50 garden modules was used for the measurements. Six different configurations were measured: connected versus dispersed and directly on the floor versus with an air cavity of 5 or 10 cm. Furthermore, each configuration was tested with modules solely filled with substrate and with substrate filled modules with densely planted ferns.

In general, no large differences were found between the six different configurations tested: neither air gaps, nor dispersing the modules had a large effect on the sound absorption coefficient. Raising the modules from the floor, thus creating an air cavity underneath, did slightly shift the sound absorption curve towards lower frequencies, in particular for the modules planted with ferns. The most notable effect found was the increase in sound absorption caused by the ferns for frequencies higher than around 400 Hz. Densely planting the modules with ferns raised the random incidence sound absorption coefficient by 0.2 to 0.3. In general however, the substrate was responsible for most of the sound absorption. The sound absorption of the substrate used follows the pattern of porous absorbers: low absorption in the lower frequencies, high absorption in the higher frequencies.

A comparison to the theoretical model by Delany-Bazley shows that the thicker the substrate gets, the higher the sound absorption coefficient in the lower frequencies is. This knowledge enables designers of vertical gardens to tune the thickness of the substrate to specific acoustic requirements. If lower frequencies are not so important, a thinner substrate can be used; if lower frequencies are important, a thicker substrate can be chosen. However, 8 to 10 cm seemed to be a minimum thickness that results in a good sound absorption spectrum overall.

The weighted random incidence sound absorption coefficient of the modules densely planted with ferns, α_w, equals 1.00. This applies to all the different configurations tested. The sound absorption coefficient in the lower frequencies (100-315 Hz), mid frequencies (400-1250 Hz) and high frequencies (1600-5000 Hz) was 0.59-0.80, 1.00 and 1.00 respectively. This makes this type of substrate highly suitable for applications were sound needs to be attenuated, paving the way for applying vertical garden systems for improving the acoustics of indoor spaces or public areas such as urban squares.

Acknowledgments

Special thanks needs to be given to Reni Nobel, whose work and dedication was invaluable in obtaining the plants for this research. In addition, sincere thanks are due to Antonia Maks, Arq. Tatiana Armijos Moya MSc., Arq. Pamela Zhindon Andrade MSc. and to Foteini Setaki MSc, who were of great help during the work at TU Delft.

References

[1] Framework Convention on Climate Change, Conference of the Parties; 2015 30 November to 11 December; Paris, United Nations, 2015, pp. 23-24.

[2] Lattes AE. Población urbana y urbanización en América Latina. La ciudad construida. 2001:49.

[3] Grimmond S, Secretariat WM. Towards integrated urban weather, environment and climate services. WMO Bulletin. 2014;63(1):10-4.

[4] Renterghem, T. van and Botteldooren, D., Reducing the acoustical facade load from road traffic with green roofs, *Building and Environment*, Elsevier, 44(2009), 1081-1087, Jul, 2008.

[5] Wong, N.H. *et al.*, Acoustics evaluation of vertical greenery systems for building walls [Singapore]. *Building and Environment*, Elsevier, 45(2), 411-420, Feb, 2010.

[6] Khaleghi, A., Bartlett, K. and Hodgson, M., Relationship between Ventilation, Air Quality and Acoustics in "Green" and "Brown" Buildings, *Journal of the Canadian Acoustical Association*, Canadian Acousticas, 36(3), 76-77, 2008.

[7] Field, C., Acoustic Design in Green Buildings. *ASHRAE Journal*, 60-70, Sep, 2008.

[8] City of Sydney, 2012. Green Roofs and Walls Strategy, June 2012. Policy. Retrieved from http://www.cityofsydney.nsw.gov.au/__data/assets/pdf_file/0007/109384/Green-roofs-and-walls-strategy.pdf on October 02, 2015.

[9] Pérez G, Rincón L, Vila A, González JM, Cabeza LF. Green vertical systems for buildings as passive systems for energy savings. Applied energy. 2011 Dec 31;88(12):4854-9.

[10] Raji B, Tenpierik MJ, van den Dobbelsteen A. The impact of greening systems on building energy performance: A literature review. Renewable and Sustainable Energy Reviews. 2015 May 31;45:610-23.

[11] Wolverton BC, Douglas WL, Bounds K. A study of interior landscape plants for indoor air pollution abatement, 1989.

[12] Fjeld T, Veiersted B, Sandvik L, Riise G, Levy F. The effect of indoor foliage plants on health and discomfort symptoms among office workers. Indoor and Built Environment. 1998 Sep 25;7(4):204-9.

[13] Ulrich RS, Simons RF, Losito BD, Fiorito E, Miles MA, Zelson M. Stress recovery during exposure to natural and urban environments. Journal of environmental psychology. 1991 Sep 30;11(3):201-30.

[14] Lohr VI, Pearson-Mims CH, Goodwin GK. Interior plants may improve worker productivity and reduce stress in a windowless environment. Journal of Environmental Horticulture. 1996 Jun;14:97-100.

[15] Davis MM, Hirmer S. The potential for vertical gardens as evaporative coolers: An adaptation of the 'Penman Monteith Equation'. Building and Environment. 2015 Oct 31;92:135-41.

[16] Davis M, Ramirez F. Muro orgánico urbano silvestre sostenible (MOUSS). InInstituto Nacional de Eficiencia Energética y Energías Renovables, Primer Congreso Internacional y Expo Cientifica. Investigación Sostenible Energías Renovables y Eficiencia Energética. Quito, Republic of Ecuador 2013 Nov (Vol. 28).

[17] Davis MJ, Ramirez F, Pérez ME. More than just a Green Façade: Vertical Gardens as Active Air Conditioning Units. Procedia Engineering. 2016 Dec 31;145:1250-7.

[18] Martens, M.J.M, Heijden, L.A.M. van der, Walthaus, H.H.J. and Rens, W.J.J.M. van (1985), ”Classification of soils based on acoustic impedance, air flow resistivity, and other physical soil parameters”, *J. Acoust. Soc. Am.* 78 (3): 970 – 980.

[19] Connelly, M. and Hodgson, M., Thermal and Acoustical Performance of Green Roofs. Sound transmission Loss of Green Roofs. *Sixth Annual Greening Rooftops for Sustainable Communities*. *Conference, Awards & Trade Show*, 1-11, Baltimore, USA, 2008.

[20] Posada, M.I., Arroyave, M.d.P., and Fernández, C., Influencia de la Vegetación en los Niveles de Ruido Urbano, *Revista EIA*, 12, 79-89, Dec, 2009.

[21] Restrepo, A.C. and González, A., Jardines Verticales para Absorción Acústica de Ruido Urbano. *V Encontro Nacional e III Encontro Latino-Americano sobre Edificações e Comunidades Suntentáveis,* ELECS, Recife, Brazil, 2009.

[22] Costa P, James RW. Constructive use of vegetation in office buildings. In Proceedings the plants for people symposium 1995 Nov (Vol. 23, pp. 1-23).

[23] Asdrubali, F., D'Alessandro, F., and Mencarelli, N., Sound absorption properties of tropical plants for indoor applications in *Proceedings of the 21st international congress on sound and vibration ICSV 21*, Horoshenkov, K.(Ed.), 1-8, Beijing, China , 2014.

[24] ISO 10534-2: 1998, Acoustics – Determination of sound absorption coefficient and impedance in tubes – Part 2: Transfer-function method.

[25] Azkorra Z, Pérez G, Coma J, Cabeza LF, Bures S, Álvaro JE, Erkoreka A, Urrestarazu M. Evaluation of green walls as a passive acoustic insulation system for buildings. Applied Acoustics. 2015 Mar 31;89:46-56.

[26] Van Renterghem T, Botteldooren D, Verheyen K. Road traffic noise shielding by vegetation belts of limited depth. Journal of Sound and Vibration. 2012 May 7;331(10):2404-25.

[27] Horoshenkov KV, Khan A, Benkreira H. Acoustic properties of low growing plants. The Journal of the Acoustical Society of America. 2013 May 1;133(5):2554-65.

[28] Yang HS, Kang J, Cheal C. Random-incidence absorption and scattering coefficients of vegetation. Acta Acustica united with Acustica. 2013 May 1;99(3):379-88.

[29] ISO 354: 2003, Acoustics – Measurement of sound absorption in a reverberation room, International Standardization Organization.

[30] ISO 9613-1: 1993, Acoustics - Attenuation of sound during propagation outdoors - Part 1: Calculation of the absorption of sound by the atmosphere, International Standardization Organization.

[31] Delany, M.E. and Bazley, E.N. (1970), "Acoustical properties of fibrous absorbent materials", *Applied Acoustics* 3: 105–106.

[32] Ding, L., Renterghem, T. van, Botteldooren, D., Horoshenkov, K. and Khan, A. (2013), "Sound absorption of porous substrates covered by foliage: experimental results and numerical predictions", *Journal of the Acoustical Society of America* 134 (6): 4599-4609.