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► **To cite this version:**

Emmanuel Attal, Nicolas Côté, Takafumi Shimizu, Bertrand Dubus. Sound absorption by green walls at normal incidence: physical analysis and optimization. *Acta Acustica united with Acustica*, 2019, 105 (2), pp.301-312. 10.3813/AAA.919313 . hal-02356531

HAL Id: hal-02356531

<https://hal.science/hal-02356531>

Submitted on 30 Jul 2021

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Sound absorption by green walls at normal incidence: physical analysis and optimization

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1 Summary

Sound absorption by different green wall systems at normal incidence is investigated between 100 and 1000 Hz. Measurements are conducted in an impedance tube in order to estimate the effective acoustic properties of plants and soils. Using these properties, the transfer matrix method is employed to simulate absorption coefficient and surface impedance of multi-layer green wall geometries. Results show that an adequate choice of layer geometries may result in an efficient sound absorption in a broad frequency range due to two main mechanisms: thickness resonances of the wall structure and quarter wave transformer effect of plant layer between air and soil media. To optimize the absorption bandwidth of green facade, continuous living wall system or modular living wall system, effect of plant, soil or air layer thicknesses on simulated absorption coefficient are also provided. **With a 16 cm thick optimized system, average absorption coefficients typically reach 0.2 between 300 and 1000 Hz for a green facade, 0.2 between 200 and 1000 Hz for a continuous living wall system and 0.9 between 300 and 1000 Hz for a modular living wall system.**

1 Introduction

Green walls are installed in urban areas to introduce more vegetation without occupying any space at street level. When applied in a significant urban scale, they may contribute to urban biodiversity [1], air quality [2], temperature reduction and mitigation of the heat island effect [3] and acoustic protection [4]. **Buildings and roads are made of acoustically rigid materials (asphalt, brick, concrete, glazing, ...) which reflect sound emitted from road traffic and therefore strongly amplify environmental noise. In that context, building envelope greening was found to be an efficient solution for different noise issues in cities: use of green roofs to attenuate sound propagating**

above buildings from streets toward courtyards [5]; significant traffic noise reduction with vegetated low-height noise barriers placed close to the driving lanes [6]; Abatement of noise reflection by facade in narrow urban streets in the presence of green wall systems [5].

Green walls can be subdivided in two main systems: green facades **are ground based systems** made of plants climbing along a wall ; living walls **are non-ground based systems involving a frame and a support and** allowing the use of a wider variety of plants [7]. The former falls into two categories: continuous living wall systems and modular living wall systems. In continuous living wall systems, the frame is fixed to the wall. An air gap is kept between the frame and the building wall to bring natural ventilation and protect against humidity. The frame is usually covered with layers of permeable and root proof screens forming pockets for the introduction of plants without substrate. Modular living wall systems are composed of several connected elements made of polymeric material containing both plants and a substrate made of organic or/and inorganic compounds where the roots can proliferate. They often have a flat backing surface which is directly fixed on the building surface. A schematic representation of these green wall systems is displayed in Figure 1. Green façade geometry is composed of a single layer of plants fixed on a building wall (idealized by a rigid backing condition). In continuous living wall system, the plant layer fixed on a support is separated from the building wall by an air gap. Type I modular living wall system is made of a plant layer atop a substrate layer directly mounted on a building wall. Finally, in type II modular living wall system, plant and soil layers are separated from building wall surface by an air gap.

Acoustic characterizations of green walls have been conducted both in situ [4, 8] and in reverberant rooms [4, 8, 9]. Insertion loss measurements performed in situ by Wong et al on types I and II modular living wall systems [4] displayed a strong dependence upon thickness of plants and substrate constituents in the audible frequency range. Sound absorption coefficient

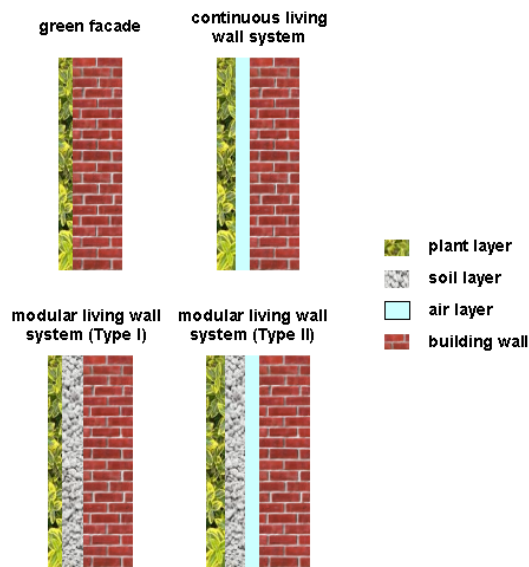


Figure 1: Schematic representation of different green wall systems

83 averaged for all incident angles was also measured
 84 in reverberant room using the ISO standard method
 85 [10]. **For living wall system thicknesses vary-**
 86 **ing between 9 and 48 cm, they reported aver-**
 87 **age sound absorption coefficients between 0.3**
 88 **and 0.5 for frequencies ranging from 300 Hz**
 89 **to 5 kHz. Such values were found higher**
 90 **than those measured for commonly used build-**
 91 **ing materials such as brick, concrete or glass.**
 92 Smaller values, between 0.05 and 0.3, were measured
 93 below 300 Hz. Shimizu et al demonstrated that in-
 94 sulation performance of a steel noise barrier may be
 95 improved by 0.5 to 5.5 dB when installing a type II
 96 living wall system [8]. They reported average absorp-
 97 tion coefficient higher than 0.75 between 100 Hz and
 98 1.6 kHz for this system. Sound reduction index mea-
 99 surement performed by Azkorra et al [9] showed that
 100 reduction of airborne noise with Type II living wall
 101 system is lower than those of **common construc-**
 102 **tive solutions such as brick or thermal double**
 103 **glazing.** Average absorption coefficient of their sys-
 104 tem was found similar to Wong's results [4] above 300
 105 Hz and much higher, between 0.4 and 0.5, below 300
 106 Hz.

107 Laboratory measurements have been realized sepa-
 108 rately on plants and soils to improve the understand-
 109 ing of sound absorption by green wall systems. As
 110 stated before, all incidence average absorption coef-
 111 ficient is measured in a reverberant room [10], while
 112 normal incidence absorption coefficient is character-
 113 ized in an impedance tube [11]. Yang et al provided
 114 average absorption coefficients for different configu-
 115 rations: soil, plants and soil covered by plants **with**
 116 **thicknesses varying between 9 and 30 cm for**

117 **plants and between 5 and 20 cm for soils** [12].
 118 They showed that sound absorption by plants is neg-
 119 ligible below 400 Hz. Conversely, average absorption
 120 coefficient of soil is moderate (between 0.25 and 0.5)
 121 below 200 Hz and high (between 0.5 and 0.9) above
 122 200 Hz and decreases with moisture content. A maxi-
 123 mum value of 0.9 was obtained at 1 kHz. The effect of
 124 plant coverage over a soil was found to be frequency
 125 dependent [13, 14, 15, 16, 17]: average absorption
 126 coefficient increases below 2 kHz and decreases above
 127 2 kHz. Normal-incidence absorption coefficient was
 128 studied by Horoshenkov et al [13] and Benkreira et
 129 al [14] for similar configurations including five types
 130 of plants and two different soils. As in reference [12],
 131 they observed that a foliage layer placed above a soil
 132 may lead to a significant increase of acoustic absorp-
 133 tion coefficient in a broad frequency range for normal
 134 incidence [13]. This result was correlated to leaf area
 135 density and orientation but the underlying physical
 136 phenomenon remained unclear. Ding et al [15] re-
 137 ported measurements and Finite Difference Time Do-
 138 main simulations of sound absorption by porous sub-
 139 strates covered by a single leaf. As in [12], they found
 140 that leaf coverage increases sound absorption below 2
 141 kHz and decreases it beyond 2 kHz. Attal et al [17]
 142 characterized the effective speed of sound and charac-
 143 teristic impedance of plant and soil samples separately
 144 and used the transfer matrix method in order to calcu-
 145 late normal incidence absorption coefficient of plant,
 146 soil and plant-soil samples of different **thicknesses.**
 147 **They found that quarter wavelength resonance**
 148 **of the sample influences greatly sound absorp-**
 149 **tion spectrum for rigid backing condition.**

150 In order to improve the physical understanding of
 151 sound absorption by green wall systems, this work
 152 provides measurements carried out in an impedance
 153 tube on plants and soil samples separately in order
 154 to determine their effective speed of sound and char-
 155 acteristic impedance. These experimental results are
 156 then used to calculate the normal incidence absorp-
 157 tion coefficient of composite samples made of plants,
 158 soil and air layers **using the Transfer Matrix**
 159 **Method. The experimental setup is described**
 160 **in section 2. Measurement of intrinsic proper-**
 161 **ties of plants and soils are reported in sections**
 162 **3 and 4 respectively.** Finally, sound absorption at
 163 normal incidence is studied in section 5 for the differ-
 164 ent green wall systems displayed in Figure 1. **Sim-**
 165 **ulation method is validated by comparing calcu-**
 166 **lated and measured absorption coefficients.**
 167 **Variation of sound absorption with plants, soil**
 168 **and/or air gap thicknesses is provided for each**
 169 **green wall system.**

2 Experimental setup and measurement method

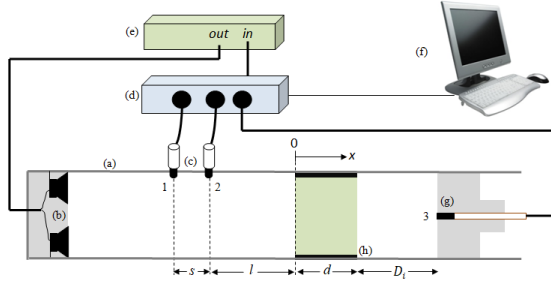


Figure 2: Schematic view of the experimental setup: (a) stainless steel tube; (b) cylindrical PVC disk integrating 4 loudspeakers; (c) microphones; (d) sound card; (e) amplifier; (f) computer; (g) flush mounted microphone on movable piston; (h) sample holder containing the sample.

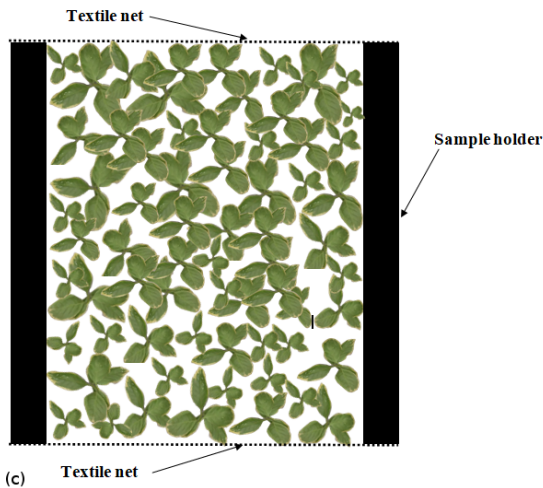
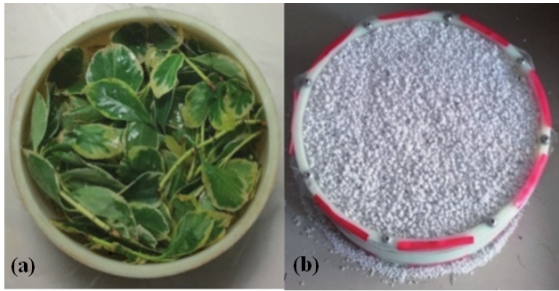


Figure 3: (a) Japanese spindle sample. (b) Perlite sample. (c) Schematic view of plant in sample holder.

Acoustic characterization of samples is performed in an impedance tube using the three-microphone two-load method [18, 19, 20]. The impedance tube of circular cross section (length 1.9 m, inner diameter 192 mm, wall thickness 15 mm) is made of stainless steel. Thus, a diameter significantly larger than sample heterogeneities (leaves, stones...) is used [17]. Four broadband loudspeakers (type Visaton FRS) are mounted in the PVC front disk located at the front end of the tube. A movable Teflon piston (axial thickness 61 mm) is positioned at the other end. **It is assumed to be acoustically rigid.** A plastic sample holder (axial thickness 16 cm) contains plants or soil maintained by two pieces of textile net. Acoustic pressure measurements are performed with three microphones (Sennheiser MKE 2P with 3.8 mm diameter). Two microphones are located in front of the sample respectively at 80 and 90 cm from the front end of the tube (Fig. 2). **According to [11], the lowest frequency of measurement corresponds to an acoustic wavelength in air equal to one hundredth of microphone separation distance i.e. 34 Hz for the considered geometry.** The third microphone is located at the center of the movable piston behind the sample. The sound card (RME-Fireface 802) control inputs and outputs of the system. The excitation signal is a step by step sine.

Measurement method is based on plane wave assumption in the tube which is **theoretically** verified up to 1037 Hz in air. This upper frequency bound decreases when speed of sound in sample material is lower than speed of sound in air. **As indicated in ISO 10534-2 standard [11], the minimal distance between sample surface and the closest microphone is larger than tube diameter in all experiments to retrieve a plane wave front at the microphone positions.** After calibrating each microphone using [21], the sample under test (thickness d) is inserted at a **fixed** position inside the tube. Then, transfer functions $H_{mn}(D_i)$ between microphones m and n ($1 \leq m \leq 3, 1 \leq n \leq 3, m \neq n$) are measured for backing cavity lengths D_i ($1 \leq i \leq 2$). Assuming $e^{+j\omega t}$ time dependency where ω is the circular frequency and t the time, acoustic pressure $P_i(x)$ and velocity $V_i(x)$ on sample front ($x = 0$) and back ($x = d$) surfaces are written for backing cavity i

$$P_i(0) = -2je^{jk_0l} \frac{H_{12}(D_i) \sin(k_0(l+s)) - \sin(k_0l)}{H_{12}(D_i)e^{jk_0s} - 1}, \quad (1)$$

$$V_i(0) = \frac{2je^{jk_0l}}{Z_0} \frac{H_{12}(D_i) \cos(k_0(l+s)) - \cos(k_0l)}{H_{12}(D_i)e^{jk_0s} - 1}, \quad (2)$$

$$P_i(d) = -2je^{jk_0l} \frac{H_{13}(D_i) \sin(k_0s) \cos(k_0D_i)}{H_{12}(D_i)e^{jk_0s} - 1}, \quad (3)$$

$$V_i(d) = \frac{2je^{jk_0l} H_{13} \sin(k_0s) \sin(k_0D_i)}{Z_0 H_{12}(D_i) e^{jk_0s} - 1}, \quad (4)$$

where ρ_0 , c_0 and $Z_0 = \rho_0 c_0$ are air density, speed of sound and characteristic impedance respectively and $k_0 = \omega/c_0$ is the acoustic wave number. Sample transfer matrix $\mathbf{T}(\omega)$ is written as

$$\begin{bmatrix} P_i(0) \\ V_i(0) \end{bmatrix} = \begin{bmatrix} T_{11}(\omega) & T_{12}(\omega) \\ T_{21}(\omega) & T_{22}(\omega) \end{bmatrix} \begin{bmatrix} P_i(d) \\ V_i(d) \end{bmatrix}. \quad (5)$$

Expressions of Eq. (5) for backing cavity $i=1$ and $i=2$ are combined in a 4x4 matrix

$$\begin{bmatrix} P_1(0) \\ V_1(0) \\ P_2(0) \\ V_2(0) \end{bmatrix} = \begin{bmatrix} T_{11}(\omega) & T_{12}(\omega) & 0 & 0 \\ T_{21}(\omega) & T_{22}(\omega) & 0 & 0 \\ 0 & 0 & T_{11}(\omega) & T_{12}(\omega) \\ 0 & 0 & T_{21}(\omega) & T_{22}(\omega) \end{bmatrix} \begin{bmatrix} P_1(d) \\ V_1(d) \\ P_2(d) \\ V_2(d) \end{bmatrix}. \quad (6)$$

From Eq. (6), elements of $\mathbf{T}(\omega)$

$$T_{11}(\omega) = \frac{P_1(0)V_2(d) - P_2(0)V_1(d)}{P_1(d)V_2(d) - P_2(d)V_1(d)}, \quad (7)$$

$$T_{12}(\omega) = \frac{P_1(d)P_2(0) - P_1(0)P_2(d)}{P_1(d)V_2(d) - P_2(d)V_1(d)}, \quad (8)$$

$$T_{21}(\omega) = \frac{V_1(0)V_2(0) - V_1(d)V_2(d)}{P_1(d)V_2(d) - P_2(d)V_1(d)}, \quad (9)$$

$$T_{22}(\omega) = \frac{P_1(d)P_2(0) - P_1(0)P_2(d)}{P_1(d)V_2(0) - P_2(d)V_1(0)}, \quad (10)$$

are determined using the transfer functions measured between the microphones.

Assuming that the sample may be described as an effective ideal fluid medium, $\mathbf{T}(\omega)$ is written as

$$\begin{bmatrix} T_{11}(\omega) & T_{12}(\omega) \\ T_{21}(\omega) & T_{22}(\omega) \end{bmatrix} = \begin{bmatrix} \cos(k_c d) & jZ_c \sin(k_c d) \\ \frac{j \sin(k_c d)}{Z_c} & \cos(k_c d) \end{bmatrix}, \quad (11)$$

where $k_c = \omega/c$ and Z_c are respectively the characteristic wave number and the characteristic impedance of the material constituting the sample. c is the effective speed of sound in the sample. k_c , Z_c and c are deduced from the transfer measured matrix using

$$k_c(\omega) = \frac{\arccos(T_{11}(\omega))}{d}, \quad (12)$$

$$c(\omega) = \frac{\omega}{k_c(\omega)}, \quad (13)$$

$$Z_c(\omega) = \sqrt{\frac{T_{12}(\omega)}{T_{21}(\omega)}}. \quad (14)$$

Finally, the absorption coefficient $\alpha(\omega)$ and the surface impedance $Z_s(\omega)$ of the sample in rigid backing condition are obtained using

$$\alpha(\omega) = 1 - \left| \frac{T_{11}(\omega) - Z_0 T_{21}(\omega)}{T_{11}(\omega) + Z_0 T_{21}(\omega)} \right|^2, \quad (15)$$

$$Z_s(\omega) = \frac{T_{11}(\omega)}{T_{21}(\omega)}. \quad (16)$$

3 Measurement of plant samples

Japanese spindle is an evergreen small shrub with oval leaves which are about 5 cm long and 3 cm wide (Fig. 3 a). **The sample is constituted by a set of small branches introduced in the sample holder (Fig 3.c). The foliage is disposed in the whole volume of the sample holder to obtain the most homogeneous distribution possible.** A sheet of tulle with fine mesh is added on the top and bottom of the sample holder to keep the air/plants interface perpendicular to tube axis. **The tulle net on the top side is assumed to be the front surface of the sample. Japanese spindle is chosen for several reasons: its is largely available; its leaves are small compared to tube diameter; its foliage is not altered when separated from the trunk during three days; its foliage is compact and thick allowing for samples of lower porosity and larger thickness.** The experimental results are reported for 8 and 16 cm thick samples made of Japanese spindle plants with a porosity of 95%. **Porosity is evaluated by dividing the total volume of the branches (obtained by submerging the branches in a water tank and measuring the water level variation) by the internal volume of the sample holder. Measurements made in winter on japanese shrubs indicate an average foliage thickness of 20 cm and an average porosity of 97%. Foliage porosity is inhomogeneous and increases when moving away from the source of light.** Acoustic measurements are performed for four different geometrical arrangements of the same branches.

Figure 4 displays the real part of the effective speed of sound, the imaginary part of the acoustic wave number (attenuation) and the real part of the characteristic impedance versus frequency. Above 250 Hz, spindle plants behaves as a nondispersive medium having an almost constant speed of sound of 250 m/s, a slowing down of approximately 25% with respect to air speed of sound. Attenuation increases monotonically but remains weak with a maximum value of 1 Np/m at 1000 Hz. The mean value of the real part of the characteristic impedance is about 620 Rayl in the 300-1000 Hz frequency range, a value corresponding to a 50% increase with respect to air characteristic impedance. **Similar measured values are obtained** with 8 and 16 cm thick samples. Some discrepancies are observed when the standard deviation between measurements becomes high: below 200 Hz for 8 and 16 cm thick samples and between 680 and 880 Hz for 16 cm thick samples. As attenuation is weak in plant sample, some elements of $\mathbf{T}(\omega)$ get close to zero when $kd \approx n\pi/2$. At these frequencies, inversion procedure becomes sensitive to small changes in

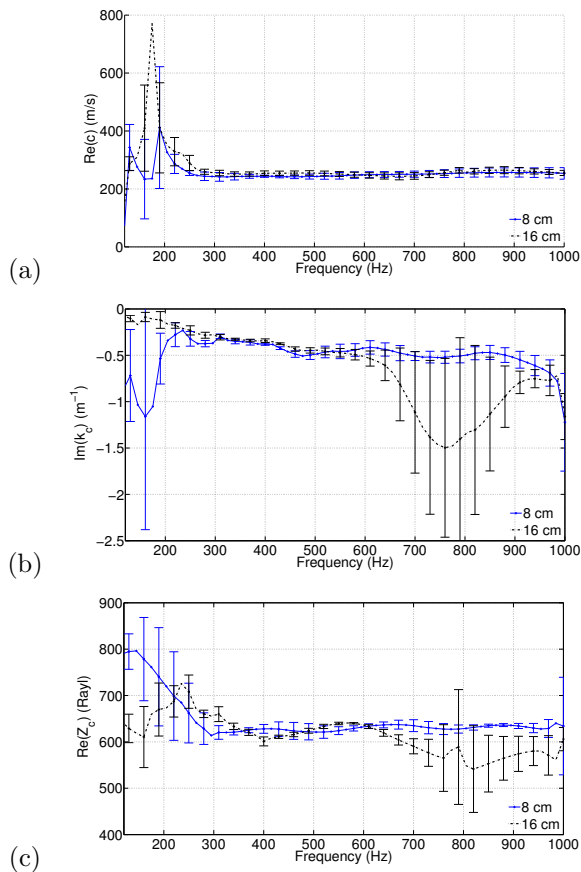


Figure 4: 8 and 16 cm thick Japanese spindle samples with 95% porosity: (a) real parts of effective speed of sound; (b) imaginary part of acoustic wavenumber; (c) real part of **non-normalized** characteristic impedance. **Quantities measured in an impedance tube.** Full line: average value; error bars: standard deviation.

274 sample geometry or small errors on phase measure-
275 ments.

276 Frequency spectra of the absorption coefficient and
277 the surface impedance modulus of Japanese spindle
278 samples in rigid backing condition are given in Figure
279 5. Variation of the surface impedance modulus versus
280 frequency displays minima associated to the quarter-
281 wavelength resonance of the sample at 781 Hz for $d =$
282 8 cm and 391 Hz for $d = 16$ cm for a speed of sound of
283 250 m/s. Maximum of the surface impedance mod-
284 ulus (antiresonance) at 781 Hz coincides with half-
285 wavelength resonance of 16 cm thick sample. Due to
286 weak attenuation (Fig. 4b), acoustic absorption re-
287 mains relatively low (< 0.35) in the whole frequency
288 range. **These values are close to previously pub-**
289 **lished measurements of plant samples having**
290 **similar porosity and thickness [13].** Highest ab-
291 sorption coefficients are obtained near sample **quar-**
292 **ter wave** resonance where a better matching is ob-
293 tained between the surface impedance of the sample
294 and air characteristic impedance.

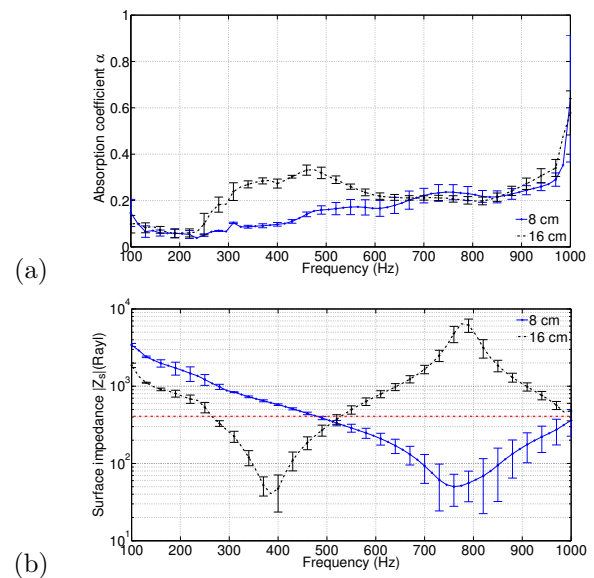


Figure 5: 8 and 16 cm thick Japanese spindle samples with 95% porosity in rigid backing condition: (a) absorption coefficient; (b) surface impedance modulus. **Quantities measured in an impedance tube.** Full line: average value; error bars: standard deviation; red dotted line: air characteristic impedance.

4 Measurement of soil samples

295 Perlite is an amorphous volcanous glass which ex-
296 pands greatly and becomes porous when heated above
297 850°C. Superheated perlite is used as a soil amend-
298 ment or alone as a medium for hydroponics, starting
299 cuttings and green walls. Experimental results are re-
300 ported for 8 and 16 cm thick samples of perlite (Fig.
301 3b). A sheet of tulle is used to keep the air/perlite
302 interface perpendicular to the axis of the tube. Acous-
303 tic measurements are performed for four different ge-
304 ometrical arrangements of the same pebbles.
305

306 Figure 6 displays the real part of the effective speed
307 of sound, the imaginary part of the acoustic wave
308 number (attenuation) and the real part of the char-
309 acteristic impedance of perlite sample versus frequency.
310 The real part of the effective speed of sound increases
311 monotonically from approximately 90 to 150 m/s in
312 the 100-1000 Hz frequency range (Fig. 6a). In that fre-
313 quency range, perlite behaves as a dispersive medium
314 with a speed of sound 2 to 4 times smaller than speed
315 of sound in air. Attenuation is much larger than
316 in plant sample and increases monotonically from 5
317 Np/m at 100 Hz to 15 Np/m at 1000 Hz (Fig. 6b).
318 Characteristic impedance spectra of 8 and 16 cm thick
319 samples differs strongly. From Fig. 6a, upper bound
320 frequency for plane wave propagation in perlite sam-
321 ple is approximately equal to 300 Hz. Therefore,
322 although incident and reflected waves are plane in
323 sample above 300 Hz in particular if air/perlite inter-
324

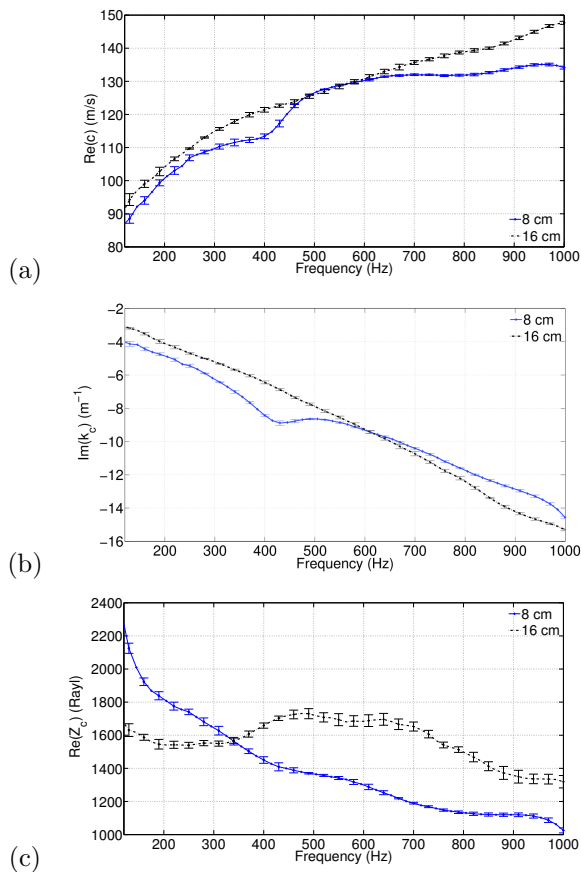


Figure 6: 8 and 16 cm thick perlite samples: (a) real parts of effective speed of sound; (b) imaginary part of acoustic wavenumber; (c) real part of **non-normalized** characteristic impedance (b) versus frequency. **Quantities measured in an impedance tube**. Full line: average value; error bars: standard deviation.

325 face is not perfectly perpendicular to the axis of the
 326 tube. **In addition, this type of substrate may**
 327 **exhibit graded properties (density, porosity...)**
 328 **requiring more sophisticated model and inver-**
 329 **sion method which are beyond the scope of**
 330 **this paper. Several authors have reported that**
 331 **acoustic absorption was significantly modified**
 332 **by the gradient of properties in functionally**
 333 **graded polyurethane foams [22, 23].**

334 Frequency spectra of the absorption coefficient and
 335 the surface impedance modulus of perlite samples
 336 in rigid backing condition are displayed in Figure
 337 7. **Absorption coefficient exhibits a resonance-**
 338 **like behaviour with frequency similar to the**
 339 **one previously reported for light substratum**
 340 **including perlite [13, 14]. Absorption coeffi-**
 341 **cient increases gradually from 0.2 at low fre-**
 342 **quency up to 0.8-0.9 at absorption peak and**
 343 **decreases slightly to a value close to 0.6-0.7 at**
 344 **higher frequencies. As for plant samples, quarter-**
 345 **wavelength resonances of perlite samples are associ-**

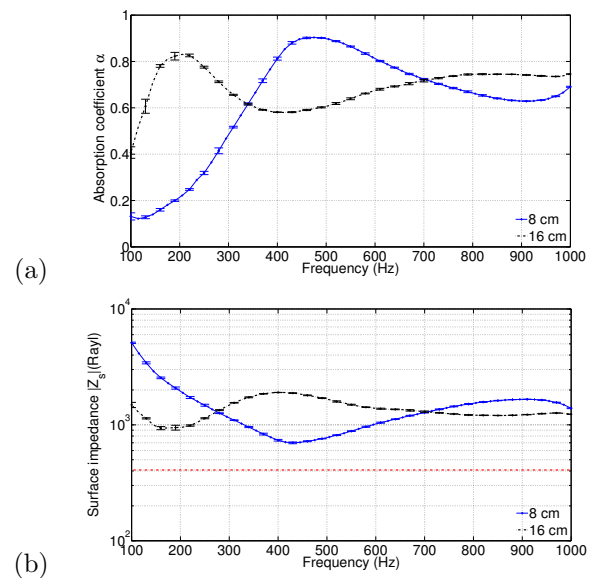


Figure 7: 8 and 16 cm thick perlite samples in rigid backing condition: (a) absorption coefficient; (b) surface impedance modulus. **Quantities measured in an impedance tube**. Full line: average value; error bars: standard deviation; red dotted line: air characteristic impedance.

346 ated to surface impedance minima at 433 Hz for $d =$
 347 8 cm and 166 Hz for $d = 16$ cm. Due to the high
 348 attenuation of perlite (Fig. 6b), no other resonance
 349 or antiresonance appears at higher frequencies. **Real**
 350 **and imaginary parts of surface impedance are**
 351 **of the same order of magnitude near quarter**
 352 **wave resonance and surface impedance modu-**
 353 **lus always remains larger than the character-**
 354 **istic impedance of air. Although impedance**
 355 **matching condition is not fulfilled in that case,**
 356 **it may be observed that the maxima of the**
 357 **acoustic absorption coefficient and the minima**
 358 **of the surface impedance modulus take place**
 359 **at nearby frequencies for both samples. An effi-**
 360 **cient absorption of incident acoustic energy by the**
 361 **perlite sample may be seen a two-step process which**
 362 **requires on one hand a limited impedance mis-**
 363 **match between the characteristic impedance of air**
 364 **and the surface impedance of the sample and,**
 365 **on the other hand, a high attenuation of the acoustic wave**
 366 **in the sample.**

367 5 Optimization of sound ab- 368

369 5.1 Calculation method 370

371 Acoustic absorption of samples composed of spindle,
 372 perlite and air layers may be calculated using matrix
 373 manipulation. **This model relies upon the reduc-**
 374 **tion of a real green wall system into the su-**

374 perposition of homogeneous layers represent-
 375 ing plants, substrate or air separated by plane
 376 interfaces. Such simplified model may not sim-
 377 ulate the whole complex interaction between
 378 air, plants and substrate or the natural gradi-
 379 ent of porosity of plants related to illumina-
 380 tion. However, it may be useful to identify the
 381 basic acoustic phenomena taking place when
 382 sound is absorbed by an air/plant/substrate
 383 multi-layered system. As spindle behaves as a
 384 homogeneous nondispersive medium, its transfer ma-
 385 trix $\mathbf{T}_{plant}(\omega, d_{pl})$ for a layer of thickness equal to
 386 d_{pl} , is calculated using measured effective speed of
 387 sound and characteristic impedance (deduced from
 388 the transfer matrix of 8 cm thick spindle samples)
 389 together with Eq. (11). For perlite layers, matrix
 390 $\mathbf{T}_{soil}(\omega, d_{so})$ measured for $d_{so} = 8\text{ cm}$ or $d_{so} = 16\text{ cm}$
 391 is employed as it is. Transfer matrix of a slab of air
 392 $\mathbf{T}_{air}(\omega, d_{ai})$ is calculated using Eq. (11) with $k = k_0$
 393 and $Z_c = Z_0$. Transfer matrices of composite sam-
 394 ples $\mathbf{T}_{comp}(\omega)$ used to determine absorption coeffi-
 395 cient and surface impedance with Eq. (15) and (16)
 396 are expressed as follow:

$$\mathbf{T}_{comp}(\omega) = \mathbf{T}_{plant}(\omega, d_{pl}) \quad (17)$$

for green facade,

$$\mathbf{T}_{comp}(\omega) = \mathbf{T}_{plant}(\omega, d_{pl})\mathbf{T}_{air}(\omega, d_{ai}) \quad (18)$$

for continuous living wall system,

$$\mathbf{T}_{comp}(\omega) = \mathbf{T}_{plant}(\omega, d_{pl})\mathbf{T}_{soil}(\omega, d_{so}) \quad (19)$$

for type I modular living wall system and

$$\mathbf{T}_{comp}(\omega) = \mathbf{T}_{plant}(\omega, d_{pl})\mathbf{T}_{soil}(\omega, d_{so})\mathbf{T}_{air}(\omega, d_{ai}) \quad (20)$$

for type II modular living wall system.

397 To validate the calculation method, calculated ab-
 398 sorption coefficient and surface impedance modulus
 399 are compared to measured ones in the 100-1000 Hz
 400 frequency range for **three** cases. The first test case
 401 is a 16 cm thick spindle layer with rigid backing con-
 402 dition. Calculated results are obtained by using the
 403 effective properties deduced from 8 cm thick spindle
 404 layer. They are compared to measurements in Fig. 8.
 405 A good agreement is found above 250 Hz. At lower
 406 frequencies, noticeable differences observed for both
 407 absorption coefficient and surface impedance modulus
 408 are the consequence of effective properties discrep-
 409 ancies between measurements on 8 and 16 cm spindle
 410 samples (Fig. 4).

412 The second test case is a sample composed of a 8
 413 cm thick spindle layer placed atop a 8 cm thick per-
 414 lite layer. A very good agreement is obtained in the
 415 whole frequency range for both absorption coefficient
 416 and surface impedance modulus (Fig. 9). A high ab-
 417 sorption coefficient is obtained in a broad frequency
 418 range when covering the soil with plants as previ-
 419 ously reported in [14]. The broad absorption peak

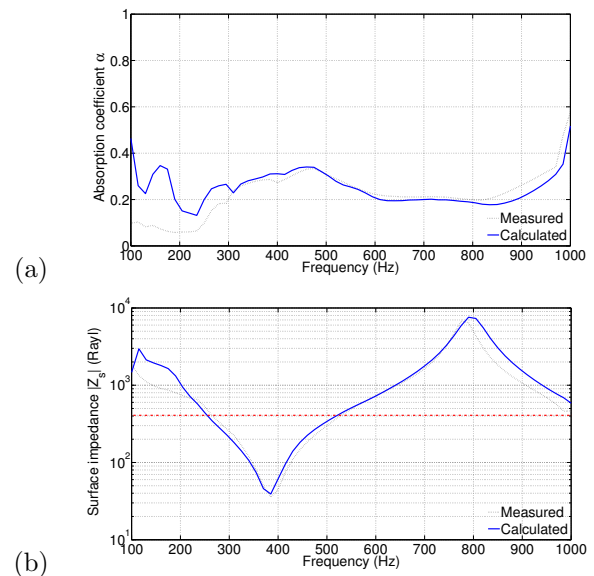


Figure 8: 16 cm thick spindle layer in rigid back-
 ing condition: (a) absorption coefficient; (b) surface
 impedance modulus. Red dotted line: air character-
 istic impedance.

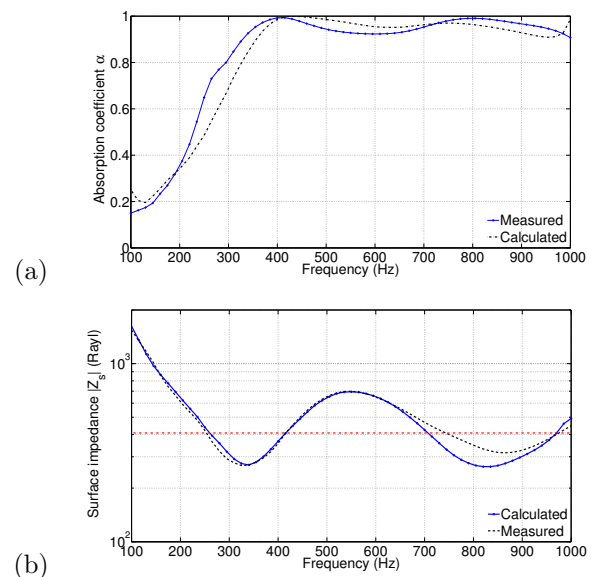


Figure 9: 8 cm thick spindle layer atop 8 cm thick
 perlite layer in rigid backing condition: (a) absorp-
 tion coefficient; (b) surface impedance modulus. Red
 dotted line: air characteristic impedance.

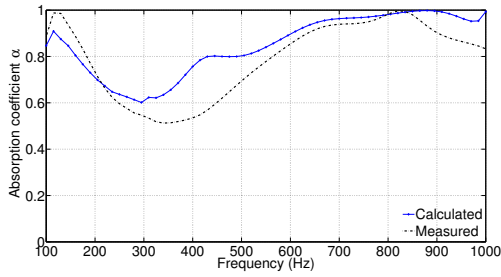


Figure 10: Absorption coefficient of a 8 cm thick spindle layer atop 8 cm thick perlite layer with a 16 cm thick air backing cavity.

420 between 400 and 1000 Hz is related to a good matching
 421 between the surface impedance of the sample and
 422 characteristic impedance of air ($Z_0 \approx 410$ Rayl) in
 423 this frequency range. The presence of two minima of
 424 the surface impedance modulus located near 350 and
 425 850 Hz **suggests** that at least two different physical
 426 phenomena contributes to this broadband impedance
 427 matching. This question is discussed in more details
 428 in section 5.4. When comparing both test cases, it ap-
 429 pears that discrepancies appearing at low frequency in
 430 effective properties of plants affect significantly simu-
 431 lation results only if the overall absorption coefficient
 432 is low.

433 **The last test case is constituted by the previ-**
 434 **ous sample in front of a 16 cm thick air back-**
 435 **ing cavity. Despite some differences between**
 436 **simulated and measured absorption coefficient**
 437 **spectra (Fig. 10), the main variations with re-**
 438 **spect to the second test case (Fig. 9a) are cor-**
 439 **rectly predicted by the transfer matrix model:**
 440 **first absorption peak shifts down from 400 Hz**
 441 **to approximately 130 Hz; second absorption**
 442 **stays around 850 Hz; absorption coefficient be-**
 443 **tween absorption peaks decreases from 0.95 to**
 444 **0.5-0.6.**

445 5.2 Sound absorption by green facade

446 Green facade geometry may be schematically repre-
 447 sented by a plant sample with rigid backing condi-
 448 tion studied in section 3. Normal incidence absorp-
 449 tion coefficient by green facade with $d_{pl} = 8$ cm and
 450 $d_{pl} = 16$ cm is displayed in Fig. 5a. Although thick-
 451 ness resonances occur in the 200-1000 Hz frequency
 452 range for this geometry, sound absorption remains
 453 limited by the weak acoustic attenuation in spindle.
 454 The effect of spindle layer thickness d_{pl} on the absorp-
 455 tion coefficient is displayed in Fig. 11 for d_{pl} vary-
 456 ing between 0 and 20 cm. Simulations are not per-
 457 formed below 200 Hz to avoid aforementioned discrep-
 458 ancies. When $d_{pl} \leq 12$ cm, absorption coefficient is
 459 low (< 0.3) in the whole frequency range. For thicker
 460 plant layers, the absorption coefficient increases near
 461 thickness resonance frequencies to reach a maximum

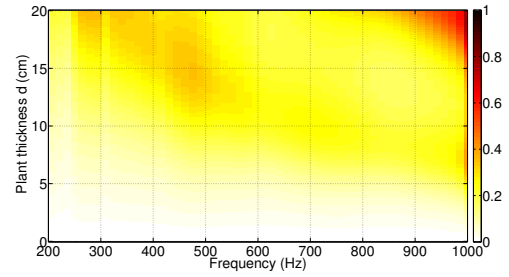


Figure 11: Green facade: variation of simulated absorption coefficient at normal incidence versus plant layer thickness.

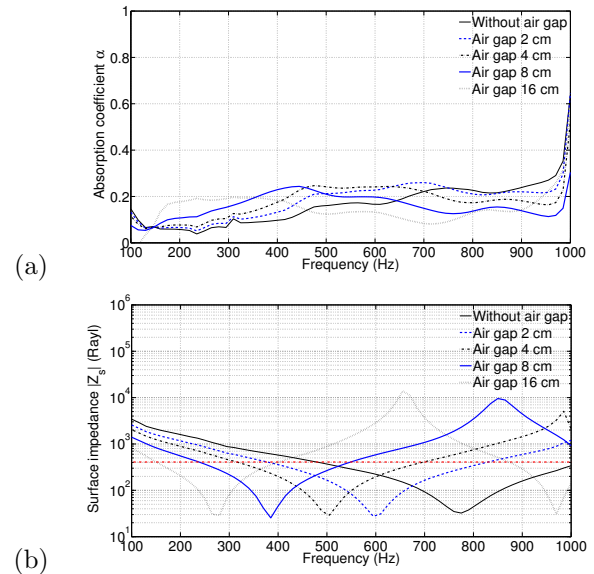


Figure 12: 8 cm thick spindle layer atop an air backing cavity of variable thickness: (a) absorption coefficient; (b) surface impedance modulus. Red dotted line: air characteristic impedance.

of 0.35 in the 300-500 Hz frequency range (quarter of
 wavelength resonance) and 0.6 above 900 Hz (three
 quarter of wavelength resonance).

455 5.3 Sound absorption by continuous 456 living wall system

457 From an acoustical perspective, the main difference
 458 between continuous living wall system and green facade
 459 is the presence of an air gap separating plants
 460 from building wall. The effect of air gap of thick-
 461 ness d_{ai} on the absorption coefficient and the surface
 462 impedance is illustrated in Figures 12 and 13 for d_{pl}
 463 equal to 8 and 16 cm respectively. In the consid-
 464 ered frequency range, both quarter of wavelength and
 465 three quarter of wavelength resonances shift down in
 466 frequency with increasing air gap thickness. Absorp-
 467 tion coefficient is always less than 0.3 for $d_{pl} = 8$ cm.
 468 It reaches 0.5 above 800 Hz for $d_{pl} = 16$ cm even when
 469

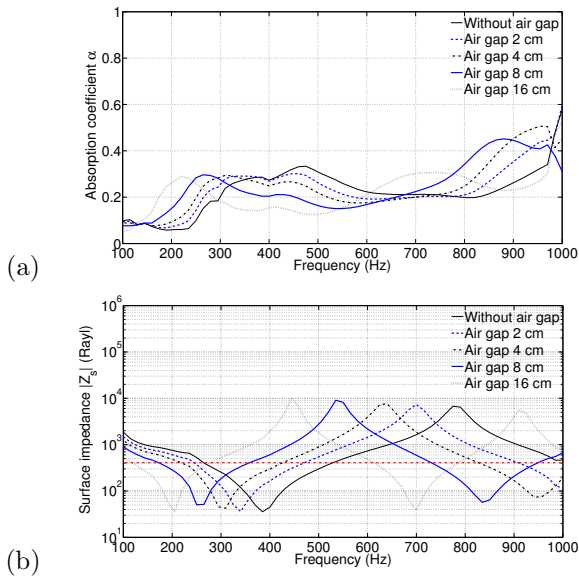


Figure 13: 16 cm thick spindle layer atop an air backing cavity of variable thickness: (a) absorption coefficient; (b) surface impedance modulus. Red dotted line: air characteristic impedance.

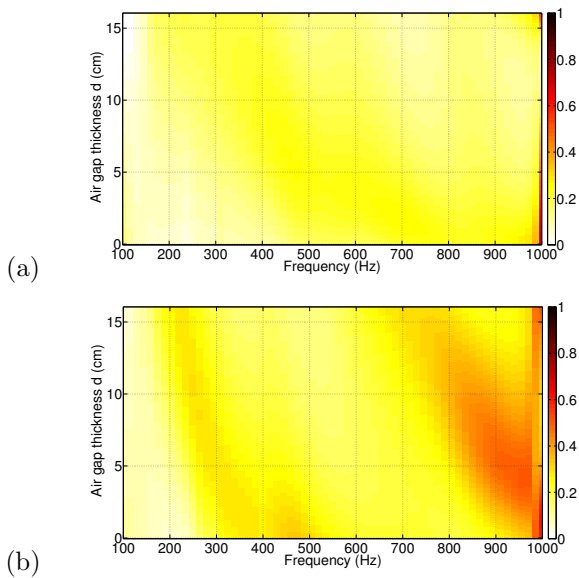


Figure 14: Continuous living wall system: variation of simulated absorption coefficient at normal incidence versus air gap thickness: (a) 8 cm thick spindle layer (b) 16 cm thick spindle layer.

air gap thickness is small. More generally, the variation of absorption coefficient with air gap thickness d_{pl} is displayed in Figure 14 for d_{ai} varying between 0 and 16 cm.

When comparing to green facade (Fig. 11), an increase of absorption coefficient is observed in the continuous living wall system with $d_{pl} = 16$ cm due to quarter of wavelength resonance between 200 and 500 Hz and to three quarter of wave length resonance between 700 and 1000 Hz. Frequencies of these absorption peaks may be adjusted by an adequate choice of air gap thickness.

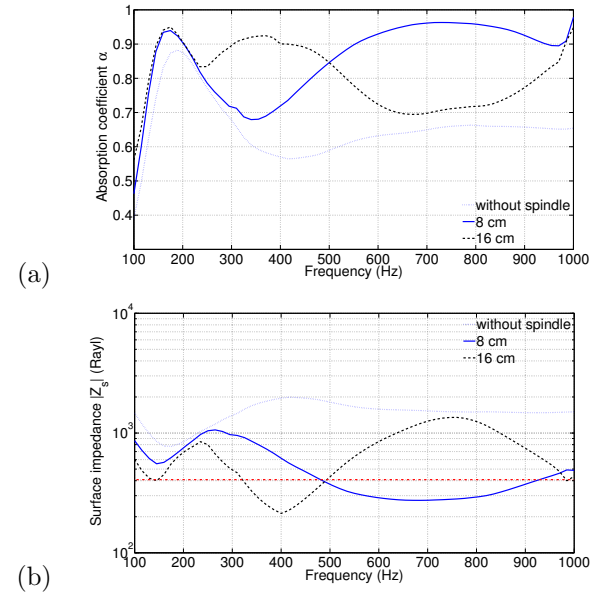


Figure 15: spindle layer of variable thickness atop 16 cm thick perlite layer: (a) absorption coefficient; (b) surface impedance modulus. Red dotted line: air characteristic impedance.

5.4 Sound absorption by type type I modular living wall system

The impact of plant layer thickness on sound absorption is studied for type I modular living wall systems composed of a spindle layer of variable thickness superposed on a perlite layer of constant thickness. Figure 15 displays the absorption coefficients and the surface impedance moduli of three different geometries in rigid backing condition: a 16 cm thick perlite layer, two samples composed of a 8 or 16 cm thick spindle layer placed on top of a 16 cm thick perlite layer. When $d_{so} = 16$ cm, the amplitude of the waves reflected by the backing surface of the perlite sample is small and the physical analysis is simplified. As mentioned in section 4, the absorption peak observed around 166 Hz for the perlite single layer corresponds to a **quarter wavelength** thickness resonance which improves impedance matching with air and facilitates energy transmission into the

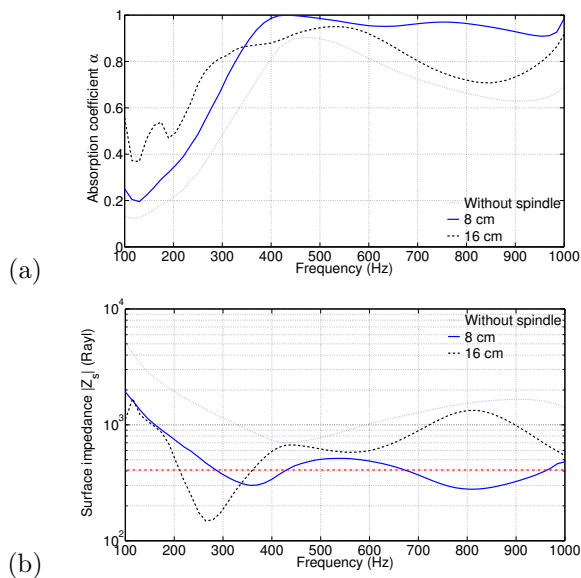


Figure 16: spindle layer of variable thickness atop 8 cm thick perlite layer: (a) absorption coefficient; (b) surface impedance modulus. Red dotted line: air characteristic impedance.

510 sample. When a spindle layer is added, total sample
 511 thickness increases and fundamental **quarter wave-**
 512 **length** resonance slightly shifts down in frequency.
 513 Around this mode, the surface impedance matches
 514 better air characteristic impedance due to the plant
 515 coverage and a higher absorption coefficient is ob-
 516 tained. Additional peaks of absorption coefficient and
 517 minima of sample surface impedance modulus are ob-
 518 served around 730 Hz and 365 Hz for spindle layer
 519 thickness of 8 and 16 cm respectively. At these fre-
 520 quencies, acoustic wavelength in spindle is approxi-
 521 mately four times spindle layer thickness which sug-
 522 gests a quarter-wave transformer effect. **In a quarter**
 523 **wave impedance transformer**, a transmission
 524 line of length one-quarter wavelength is used to
 525 present at its input the dual of the impedance
 526 with which it is terminated. This properties is
 527 obtained when $Z_{trans} = \sqrt{Z_{in}Z_{load}}$ where Z_{trans} ,
 528 Z_{in} and Z_{load} are the characteristic impedance
 529 of the transmission line, the input impedance
 530 and the load impedance respectively. For the
 531 considered case, ($Z_{in} = Z_0 \approx 410$ Rayl) and
 532 ($Z_{load} = Z_{cperlite} \approx 1600$ Rayl). **The character-**
 533 **istic impedance of the impedance transformer**
 534 $Z_{trans} = \sqrt{Z_0 Z_{cperlite}} \approx 810$ Rayl **only differs by**
 535 **20% from characteristic impedance of spindle.**
 536 Therefore, additional peaks in absorption coefficient
 537 may be attributed to the impedance matching be-
 538 tween air and perlite provided by spindle which oper-
 539 ates as a quarter-wave transformer.

540 In the case of a thinner perlite layer, reflection from
 541 backing surface takes place and physical analysis be-
 542 comes more complicated. As an example, absorption

543 coefficients and surface impedance moduli are given
 544 in Figure 16 for 8 and 16 cm thick spindle layers atop
 545 of a 8 cm thick perlite layer in rigid backing condition.
 546 As previously, when adding a plant layer, quarter of
 547 wavelength resonance frequency shifts down from 433
 548 Hz to 360 Hz when $d_{pl} = 8$ cm, and to 273 Hz when
 549 $d_{pl} = 16$ cm. However, the second minima of sur-
 550 face impedance modulus at 810 Hz ($d_{pl} = 8$ cm) and
 551 566 Hz ($d_{pl} = 16$ cm) does not correspond anymore
 552 to a quarter of wavelength in spindle layer due to re-
 553 flection from backing surface. At these minima, the
 554 surface impedance modulus is higher for $d_{pl} = 16$ cm
 555 ($Z_s \approx 590$ Rayl) than for $d_{pl} = 8$ cm ($Z_s \approx 280$ Rayl).
 556 Consequently, the broadband impedance matching
 557 and the absorption coefficient obtained for $d_{pl} = 8$ cm
 558 are degraded when the plant thickness is increased to
 559 16 cm.

560 A more complete representation of the absorption
 561 coefficient of a type I modular living wall system com-
 562 posed of a spindle layer of variable thickness atop of
 563 a 8 or 16 cm thick perlite layer is given in Figure 17.
 564 This green wall system exhibits a much better acous-
 565 tic absorption than green facade and continuous living
 566 wall because of soil layer attenuation. Thus, for a 8
 567 cm thick perlite layer, efficient absorption ($\alpha > 0.9$)
 568 is obtained in the 350-1000 Hz frequency range when
 569 $8 \text{ cm} \leq d_{pl} \leq 10 \text{ cm}$ **under normal incidence. A**
 570 **more realistic sound field conditions such as**
 571 **diffuse field will tend to smooth out the absorp-**
 572 **tion levels over the frequency range and reduce**
 573 **the maximum level of absorption. For a thicker**
 574 **perlite layer ($d_{so} = 16$ cm), efficient absorp-**
 575 **tion is observed in a narrower frequency range**
 576 **and the acoustic absorption coefficient remains higher**
 577 **than 0.5 in the whole frequency range for all plant**
 578 **layer thicknesses.**

5.5 Sound absorption by type type II modular living wall system

580 This section focuses on the effect, on the acoustic ab-
 581 sorption, of an air gap introduced between the plant-
 582 soil bi-layer and the building wall. **A previous work**
 583 **has reported that the addition of a backing air**
 584 **cavity was an efficient way to increase sound**
 585 **reduction index of green roofs [24].** Three dif-
 586 ferent configurations with an air gap of variable thick-
 587 ness are simulated: 8 or 16 cm thick spindle layer atop
 588 of 8 cm thick perlite layer; 8 cm thick spindle layer
 589 atop of 16 cm thick perlite layer. Corresponding ab-
 590 sorption coefficients and surface impedance moduli in
 591 rigid backing condition are given in Figures 18 to 20.
 592 For all cases, the increase of air gap thickness induces
 593 a down-shift of the lowest (quarter of wavelength) re-
 594 sonance frequency with variable effects on absorption
 595 coefficient according to the plant-soil bi-layer geom-
 596 etry. In the first case ($d_{pl} = 8$ cm, $d_{so} = 8$ cm),
 597 initial broadband absorption band tends to split into
 598

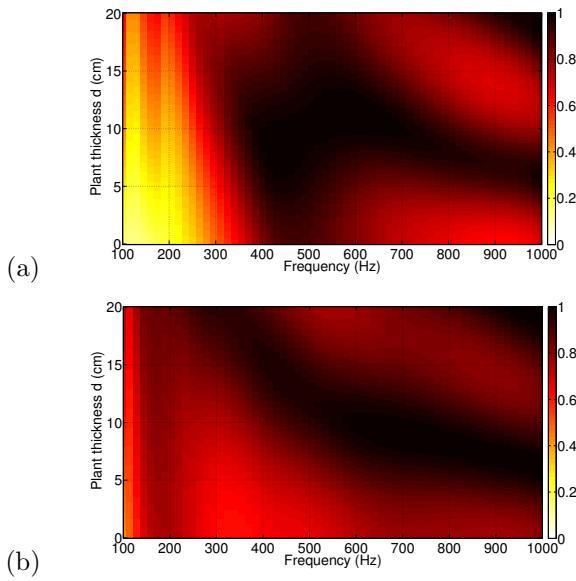


Figure 17: Type I modular living wall system: variation of simulated absorption coefficient at normal incidence versus spindle layer thickness: (a) 8 cm thick perlite layer (b) 16 cm thick perlite layer.

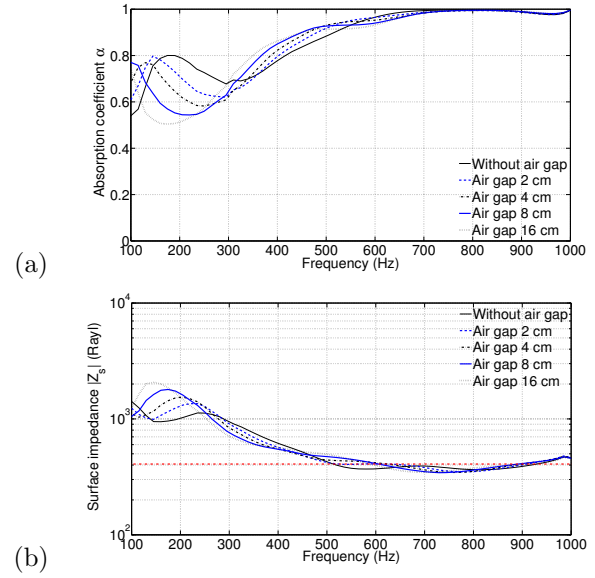


Figure 19: 8 cm thick spindle layer atop 16 cm thick perlite layer with air backing cavity of variable thickness: (a) absorption coefficient; (b) surface impedance modulus. Red dotted line: air characteristic impedance.

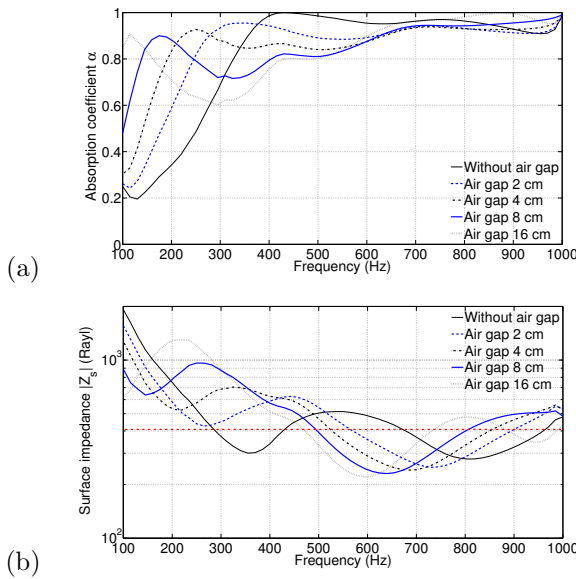


Figure 18: 8 cm thick spindle layer atop 8 cm thick perlite layer with air backing cavity of variable thickness: (a) absorption coefficient; (b) surface impedance modulus. Red dotted line: air characteristic impedance.

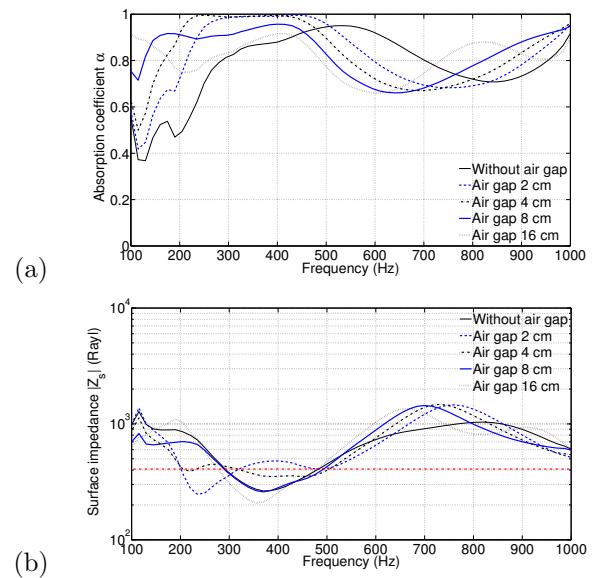


Figure 20: 16 cm thick spindle layer atop 8 cm thick perlite layer with air backing cavity of variable thickness: (a) absorption coefficient; (b) surface impedance modulus. Red dotted line: air characteristic impedance.

599 two separate absorption peaks with increasing air gap
 600 thickness (Fig. 18a). Absorption is degraded between
 601 these two peaks due to the increase of the surface
 602 impedance modulus (Fig. 18b). In the second case
 603 ($d_{pl} = 8$ cm, $d_{so} = 16$ cm), only the low frequency ab-
 604 sorption peak slightly shifts down in frequency with
 605 increasing air gap thickness (Fig. 19a). Above 300 Hz,
 606 the absorption coefficient and the impedance surface
 607 modulus (Fig. 19b) are not affected by the air gap.
 608 The last case ($d_{pl} = 16$ cm, $d_{so} = 8$ cm) is character-
 609 ized by a low frequency broad absorption peak which
 610 shifts down in frequency with increasing air gap thick-
 611 ness (Fig. 19a). **Maximal** absorption is obtained be-
 612 tween 300 and 470 Hz for a 2 cm thick air gap and
 613 between 230 and 430 Hz for a 4 cm thick air gap.

614 The variation of absorption coefficient frequency
 615 spectrum with air gap thickness is displayed in Figure
 616 21 for the three considered plant-soil configurations.
 617 The second configuration ($d_{pl} = 8$ cm, $d_{so} = 16$ cm)
 618 is characterized by a high absorption coefficient above
 619 400 Hz for any air gap thickness. The third config-
 620 uration ($d_{pl} = 16$ cm, $d_{so} = 8$ cm) displays a broad
 621 absorption peak below 450 Hz for 2 cm $\leq d_{pl} \leq 8$ cm.
 622 Thus, a high absorption coefficient may be obtained
 623 in a broader frequency range between 200 and 1000
 624 Hz by combining these two configurations in a single
 625 modular living wall system.

626 5.6 Summary and conclusion

627 Measurement of the effective acoustic properties of
 628 plants and soils have been combined with transfer
 629 matrix method to simulate the acoustic absorption
 630 coefficient by different types of green walls. Results
 631 show that an adequate choice of constituents and ge-
 632 ometry may result in an efficient absorption of sound
 633 in a broad frequency range due to two main mecha-
 634 nisms: **the** thickness resonances of the wall structure;
 635 the quarter wave transformer effect provided by the
 636 plant layer between air and soil layer. Among differ-
 637 ent green wall types, modular living wall systems dis-
 638 play higher sound absorption performance than con-
 639 tinuous living wall systems or green facades with an
 640 absorption coefficient larger than 0.9 in a frequency
 641 bandwidth that may reach 600 Hz. The proposed
 642 approach could also be used to simulate the effect of
 643 environmental (moisture content) or seasonal (decidu-
 644 ous, semi-deciduous or semi-evergreen plants) changes
 645 on sound absorption.

646 Acknowledgement

647 Support of this work by ADEME, Yncrea Group and
 648 “Hauts-de-France” region is greatly acknowledged.
 649 The authors would also like to thank the anonymous
 650 reviewers for their helpful and relevant comments.

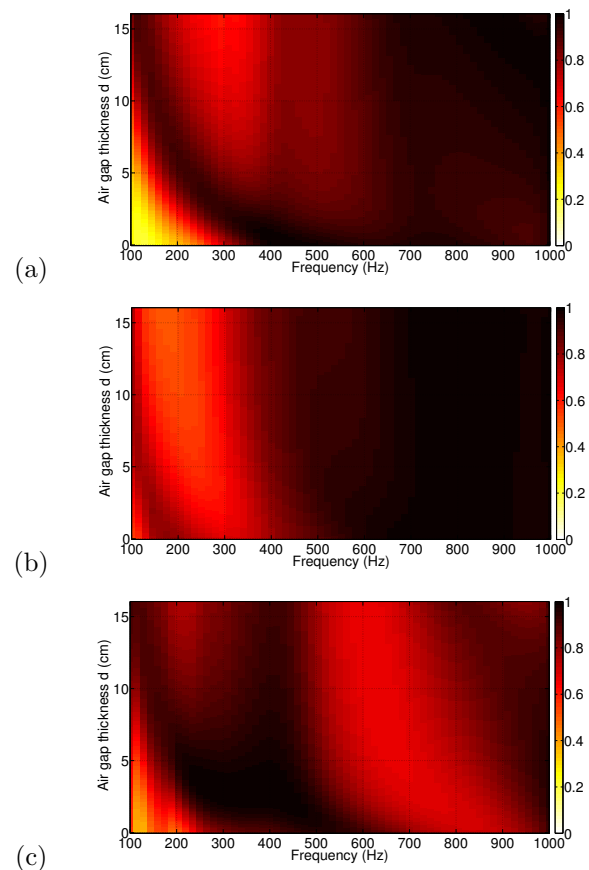


Figure 21: Type II modular living wall system: variation of absorption coefficient at normal incidence versus air gap thickness: (a) 8 cm thick spindle layer atop of 8 cm thick perlite layer; (b) 8 cm thick spindle layer atop of 16 cm thick perlite layer; (c) 16 cm thick spindle layer atop of 8 cm thick perlite layer.

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