Experimental characterization of foliage and substrate samples by the three-microphone two-load method

Emmanuel ATTAL[1]*; Nicolas CÔTÉ[1]; Gérard HAW[1]; Geoffrey POT[1] ; Clément VASSEUR[1]; Takafumi SHIMIZU[2] ; Christian GRANGER[1]; Charles CROËNNE[1]; Bertrand DUBUS[1]

[1] Institut d'Electronique, de Microélectronique et de Nanotechnologie, UMR CNRS 8520, ISEN 41 Boulevard Vauban, 59046 Lille, France

[2] Central Research Laboratory, Daiwa House Industry Co., Ltd. 6-6-2 Sakyo, Nara 631-0801, Japan

ABSTRACT

In addition to their aesthetic aspect, green walls can help decreasing noise pollution in the environment due to their acoustic properties. Green walls mainly contain two components: the substrate which feeds the plants and the foliage. Some authors have shown that, for a given leaf density on a specific substrate, acoustic absorption can be improved with respect to the bare substrate. Although acoustic measurements have already been carried out on leaves and substrates, few studies have given information about the effective characteristics (sound speed, characteristic impedance) of substrate and foliage. Here, we propose to determine those characteristics from measurements performed in an impedance tube with the three-microphone two-load method. This method consists in measuring transfer functions between three microphones, two of them located in front of the substrate and the third one behind the sample, mounted on a movable hard termination. From the measured transfer functions, it is possible to establish the transfer matrix of the sample, which allows to determine its effective properties. The experimental setup and measurement method are described. Measured intrinsic properties of foliage and substrate are presented. Acoustic absorption coefficients of slabs made of foliage, substrate and foliage-substrate superposition are also provided.

Keywords: Measurement of properties of materials I-INCE Classification of Subjects Number(s): 72.7

1. INTRODUCTION

Green walls, which are implemented in cities for aesthetic reasons can also improve air quality, foster bio-diversity and decrease noise pollution. A green wall is constituted by a living plants cover, a soil including recycled or fibrous materials to feed the plants, a metallic structure ensuring the bearing of the soil and living plants and an irrigation system. An air gap is generally inserted between the green wall and the backing wall for natural ventilation and structural decoupling.

Acoustic properties of substrates, foliage or combination of both, have been studied in the HOSANNA project (1,2,3) using different characterization techniques such as standard measurement in impedance tube (4) and reverberant room (5). Thus, Horoshenkov et al (6) have established a porous model combining substrate and foliage properties to describe the absorption coefficient of foliage and Yang et al (7) have measured absorption and scattering coefficients of substrates and plants, separated and combined, as a function of humidity. Recent works on intrinsic properties of plants cut in small pieces (porosity, bulk modulus, density and absorption) have been carried out by Chabriac et al (8) using an equivalent fluid model and impedance tube measurements. Azkorra et al (9) analyzed building insulation improvement provided by green walls according to the ISO standard 10140-2(10). Shimizu et al (11) performed sound transmission measurements on green walls made of a mixture of organic and inorganic soil covered with foliage and elaborated a BEM model to predict the effect of diffraction.

In this work, intrinsic acoustics characteristics of substrate (perlite) and foliage (Japanese spindle)

[1] emmanuel.attal@isen.fr

are characterized using the three-microphone two-load method developed by Salissou et al (12,13). Experimental setup and measurement method are presented in section 2. Measured intrinsic properties of substrate and foliage are displayed in section 3. Direct measurements of acoustic absorption coefficients are also compared to simulations using intrinsic properties for slabs made of foliage, substrate and foliage-substrate superposition.

2. EXPERIMENTAL PROCEDURE

2.1 Experimental setup

Experimental setup is displayed in Figures 1 and 2. The impedance tube is made of stainless steel with a circular cross section (length 1.90 m, inner diameter 192 mm, radial thickness 15 mm). Four broadband loudspeakers (type Visaton FRS) are mounted in the PVC front disk located at tube front end. A movable Teflon piston (axial thickness 61 mm) is located at the other end. The Teflon sample holder (axial thickness 16 cm) contains foliage or substrate maintained by two pieces of textile net.

Acoustic pressure measurements are performed with three Sennheiser microphones (type MKE 2P; 3.8 mm diameter). Two of these microphones are located in front of the sample at 80 and 90 cm from tube front end respectively. They are used to measure absorption coefficient according to the ISO standard 10534-2 (10). The third microphone is located at the center of the hard piston behind the sample. All three microphones are used to obtain [T] transfer matrix parameters according to the three-microphone two-cavity method (11,12). The sound card (RME-Fireface 802) control inputs and outputs of the system. The excitation signal is a step by step sine.

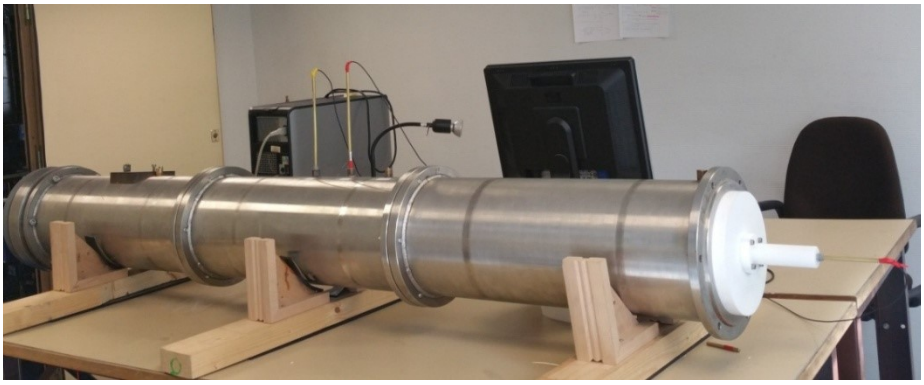

Figure 1 – Impedance tube used for acoustic characterizations of substrate and foliage samples

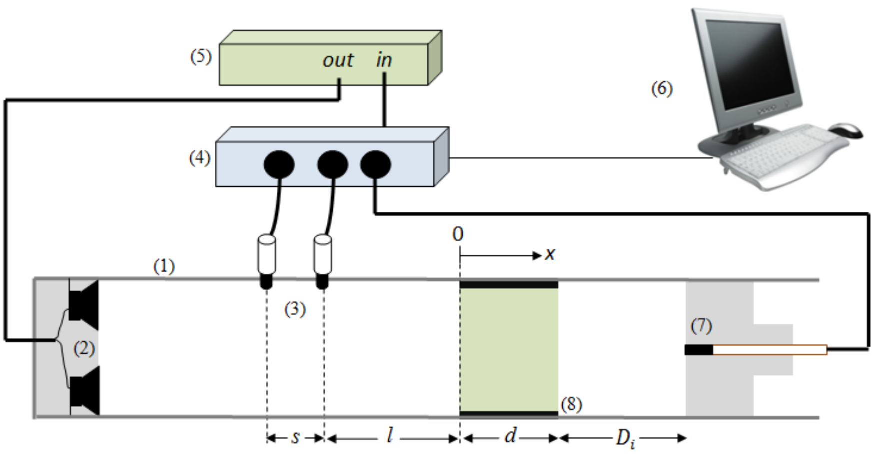

Figure 2 – Schematic view of the experimental setup: (1) stainless steel tube; (2) cylindrical PVC disk integrating 4 loudspeakers; (3) microphones; (4) sound card; (5) amplifier; (6) computer; (7) flush mounted microphone on movable piston; (8) sample holder containing the sample

2.2 Measurement Method

Measurement method relies on plane wave hypothesis in a frequency range extending between 100 and 1000 Hz. Experimental procedure begins with the correction in magnitude and phase of the three microphones according to the standard ISO 10534-2 (10). After calibration, sample is placed at a constant position l from the second microphone and $l+s$ from the first microphone. H_{12a} , H_{13a} and H_{12b} , H_{13b} which are respectively complex pressure transfer functions between microphones 2 and 1 and microphones 3 and 1, are measured for two backing cavity lengths D_a and D_b. Then, acoustic pressure $p_i(x)$ and velocity $v_i(x)$ on sample front (x=0) and back (x=d) surfaces are calculated from transfer functions for each cavity size (i=a) and (i=b): $p_a(0)$, $p_a(d)$, $v_a(0)$, $v_a(d)$, $p_b(0)$, $p_b(d)$, $v_b(0)$, $v_b(d)$. Transfer matrix elements are obtained from equations (1) to (4):

$$T_{11} = \frac{p_a(0)v_b(d) - p_b(0)v_a(d)}{p_a(d)v_b(d) - p_b(d)v_a(d)} \tag{1}$$

$$T_{12} = \frac{p_b(0)p_a(d) - p_a(0)p_b(d)}{p_a(d)v_b(d) - p_b(d)v_a(d)} \tag{2}$$

$$T_{21} = \frac{v_a(0)v_b(d) - v_b(0)v_a(d)}{p_a(d)v_b(d) - p_b(d)v_a(d)} \tag{3}$$

$$T_{22} = \frac{p_a(d)v_b(0) - p_b(d)v_a(0)}{p_a(d)v_b(d) - p_b(d)v_a(d)} \tag{4}$$

The transfer matrix of a symmetrical and homogeneous material thickness d is given by

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} \cos(k_{mat}d) & jZ_{mat}\sin(k_{mat}d) \\ \dfrac{j\sin(k_{mat}d)}{Z_{mat}} & \cos(k_{mat}d) \end{bmatrix} \tag{5}$$

where k_{mat} and Z_{mat} are respectively the effective wave number and characteristic impedance of the material. These parameters, invariant whatever the thickness of the sample, are obtained by inverting the T_{11} and T_{12}

$$k_{mat} = \frac{\cos^{-1} T_{11}}{d} \tag{6}$$

$$Z_{mat} = \sqrt{\frac{T_{12}}{T_{21}}} \tag{7}$$

Effective speed of sound in the material is deduced k_{mat} by the following equation from:

$$c_{mat} = \frac{2\pi f}{k_{mat}} \tag{8}$$

Absorption coefficient in rigid backing condition is also directly calculated using equation (9)

$$\alpha = 1 - \left|\left(\frac{T_{11} - Z_{air}T_{21}}{T_{11} + Z_{air}T_{21}}\right)\right|^2 \tag{9}$$

2.3 Test samples

Experimental results are reported for two types of samples: a 8 cm thick of Japanese spindle foliage sample with a density of 3% and a 8 cm thick perlite substrate sample. Pictures of these samples are displayed in Figure 3. Acoustic characterization is performed for each sample separately and then for the superposition of the two samples. Each acoustic measurement is performed for four geometrical arrangements of the sample.

Figure 3 – Japanese spindle foliage sample, perlite substrate sample and superposition of foliage and substrate sample

3. EXPERIMENTAL RESULTS

3.1 Acoustics measurements on foliage

Figures 4 and 5 display effective speed of sound and characteristic impedance versus frequency for a 8 cm thick foliage sample with 3% density. Real part of effective speed of sound keeps an almost constant of 270 m/s in the 200-1000 Hz frequency range. The foliage appears as a non dispersive medium having a speed of sound 20% smaller than those of air in that range. Internal losses are evaluated by the imaginary to real part ratio of the effective speed of sound. They vary between 2% and 5%. Mean value of characteristic impedance real part is 560 Rayl in the 250-1000 Hz, a value corresponding to a 37% increase with respect to air. Imaginary to real part ratio of characteristic impedance varies between 0 and 2%.

Foliage transfer matrix is then used to calculate absorption coefficient of foliage slabs in rigid backing conditions using equation (9). Calculated values for 8 cm and 16 cm thick slabs (Fig. 6) shows that increased thickness leads to higher absorption coefficient mainly in the lower part of the frequency spectrum. Comparison between calculated and measured absorption coefficients is also provided (Fig. 6). A good agreement is found, .the difference between calculated and measured values being much smaller than the variations between foliage arrangements over the whole frequency range.

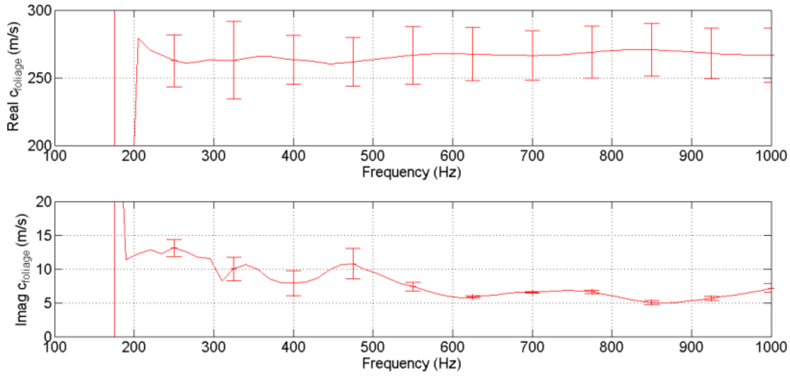

Figure 4– 8 cm thick Japanese spindle foliage sample with 3% density. Real and imaginary parts of foliage effective speed of sound versus frequency. Full line: average value for 4 arrangements. Error bars: maximum and minimum values among arrangements

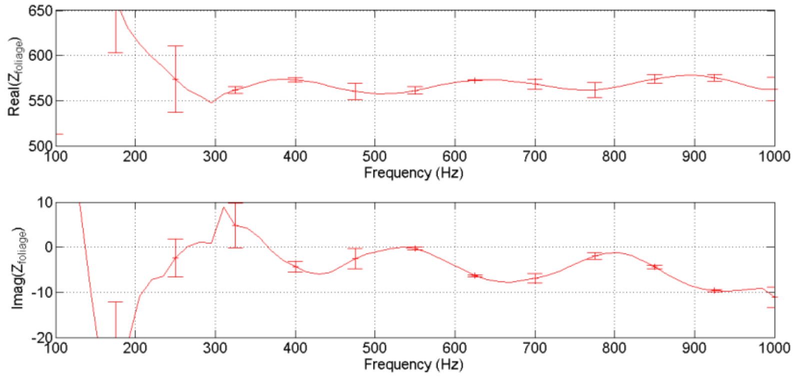

Figure 5 – 8 cm thick foliage sample with 3% density. Real and imaginary parts of foliage effective characteristic impedance versus frequency. Full line: average value for 4 arrangements. Error bars: maximum and minimum values among arrangements

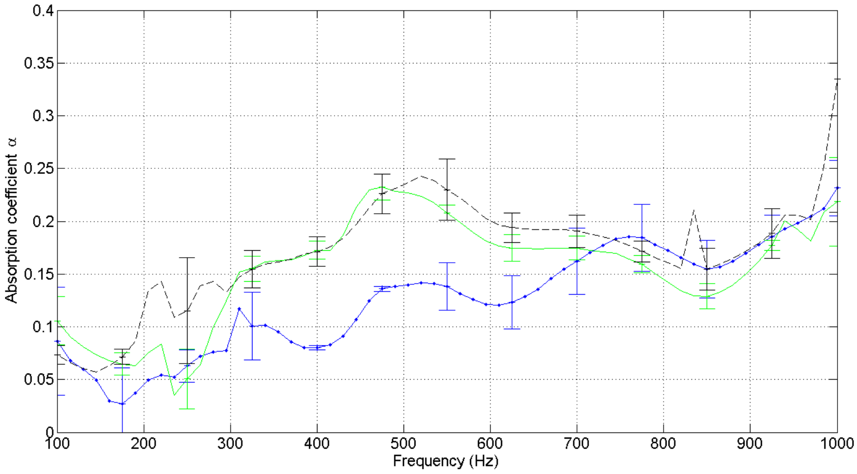

Figure 6 –Absorption coefficient of foliage samples with 3% density versus frequency in rigid backing condition. 16 cm thick sample: measurement (full line) and calculation (dashed line). 8 cm thick sample: calculation (dotted-dashed line). Line: average value for 4 arrangements. Error bars: maximum and minimum values among arrangements

3.2 Acoustics measurements on substrate

Figures 7 and 8 display effective speed of sound and characteristic impedance versus frequency for a 8 cm thick perlite sample having a mass density of 317 kg.m^{-3}. Real part of effective speed of sound increases monotonically from 100 of 142 m/s in the 100-1000 Hz frequency range. The substrate behaves as a dispersive medium with a speed of sound 3 to 4 times smaller than those of air in that range. Large internal losses are also observed with imaginary part to real part ratio varying between 45% and 55%. Calculated absorption coefficient versus frequency is displayed in Fig.9 for 8 cm and 16 cm thick substrate samples for rigid backing condition. Variations between arrangements are much smaller for substrate sample than for foliage samples. A resonance of the absorption coefficient is found at 430 Hz (resp. 200 Hz) for 8 cm (resp. 16 cm) thick sample. It corresponds approximately to a quarter-of-wavelength thickness resonance of substrate sample.

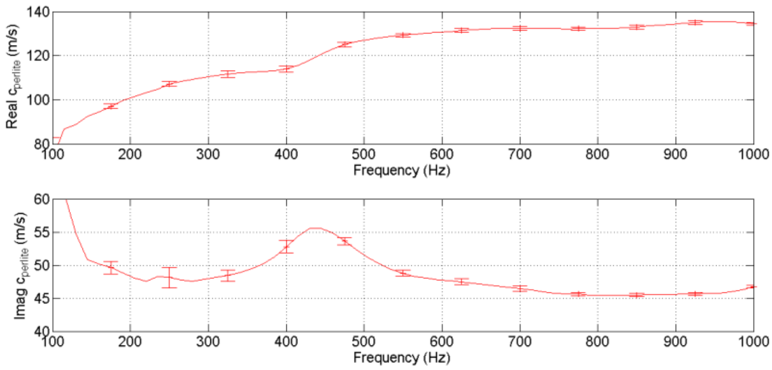

Figure 7 – 8 cm thick perlite sample. Real and imaginary parts of effective speed of sound versus frequency. Full line: average value for 4 arrangements. Error bars: maximum and minimum values among arrangements

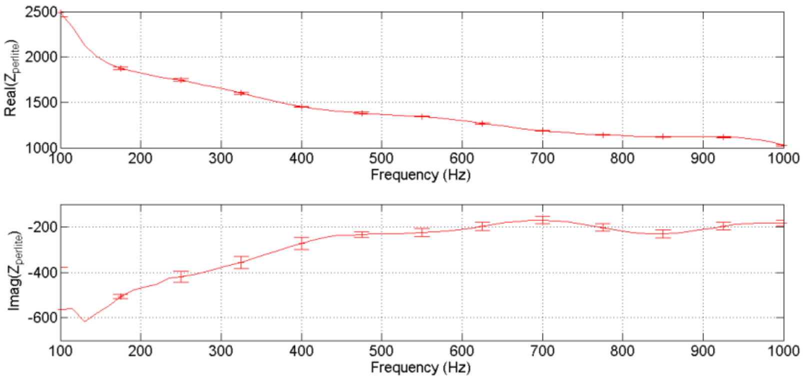

Figure 8 – 8 cm thick perlite sample. Real and imaginary parts of effective characteristic impedance versus frequency. Full line: average value for 4 arrangements. Error bars: maximum and minimum values among arrangements

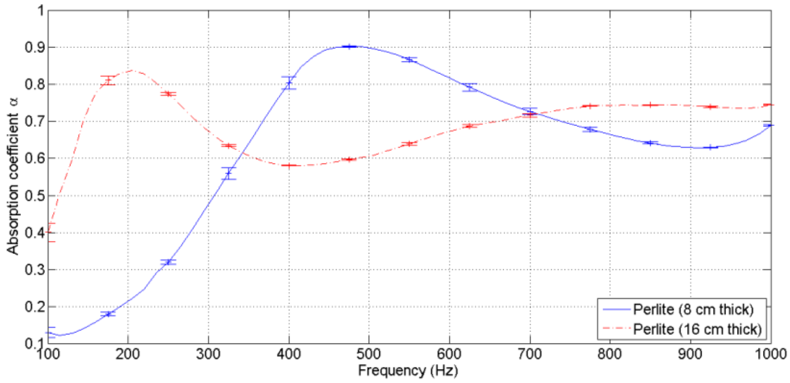

Figure 9–Absorption coefficient of perlite sample versus frequency in rigid backing condition. Full line: 8 cm thick sample; dashed line 16 cm thick sample. Line: average value for 4 arrangements. Error bars: maximum and minimum values among arrangements

3.3 Acoustics measurements on foliage-substrate superposition

The case of a 16 cm thick sample constituted by the superposition of a 8 cm thick spindle foliage sample with 3% density and 8 cm thick perlite substrate is considered. Figure 10 compares calculated values of absorption coefficient versus frequency for the foliage-substrate sample in rigid backing condition using two methods: 1) by multiplying $[T]$ matrices of obtained for isolated foliage and substrate samples and then by using the coefficients of the product in equation (9); 2) by measuring $[T]$

of foliage-substrate superposition and then using equations (9). Results provided by both methods are in good agreement on the whole 100-1000 Hz frequency range. This results shows that separate characterization of foliage and substrate effective properties can be used to predict and optimize acoustic properties of green walls.

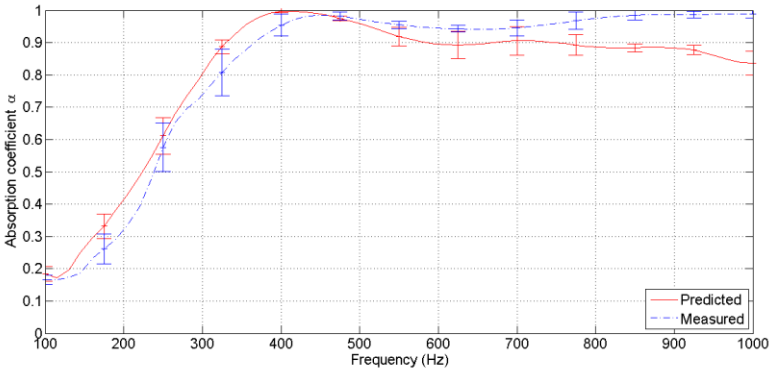

Figure 10 –Calculated absorption coefficient of foliage-substrate sample versus frequency in rigid backing condition. Dashed line: method 1; full line: method 2. Line: average value for 4 arrangements. Error bars: maximum and minimum values among arrangements

4. CONCLUSIONS

An experimental setup using an impedance tube has been designed and developed for characterizing effective speed of sound and characteristic impedance of foliage and substrate samples. In the 200-1000 Hz frequency range, spindle foliage is found to be a non dispersive media with reduced speed of sound and increased characteristic impedance compared to air. Perlite substrate is dispersive with speed of sound (resp. characteristic impedance) 3 to 5 times smaller (resp. larger) compared to air. Internal losses reach a few per cent in foliage and a few tens of per cent in substrate. As expected, they are inversely related with absorption coefficients of foliage and substrate samples with rigid backing conditions. A good agreement is found in the whole frequency range between measurements and calculation (from [*T*] matrices) of absorption coefficient for foliage and foliage-substrate samples. Thus, [*T*] matrix characterization of single foliage and substrate samples can be used to predict, optimize and tailor the absorption coefficient of green walls in the audible frequency range.

ACKNOWLEDGEMENTS

This study was supported by the French Agency ADEME, the HEI-ISA-ISEN Group and the Nord Pas-de-Calais region.”

REFERENCES

1. J. Y. Jeon, .P. J. Lee, Y. H. Kim, Technical Report on Identification of acoustic properties of ground and vegetation, HOSANNA project report (2011).
2. T. V. Renterghem, B. Altreuther, J. Defrance, K. Attenborough, S. Taherzadeh, I. Bashir, Y. Smyrnova, C. Cheal, H. Yang, J. Kang, K. Horoshenkov, A. Khan, Technical Report on Acoustical shielding by edges and shrubs; HOSANNA project report (2012).
3. K. Horoshenkov, .H. Benkreira, A. Khan, S. Taherzadeh, J. Kang, T. V. Renterghem, H. Yang, Y. Smyrnova, C. Cheal, D. Botteldooren, L. Ding, Technical Report on Theoretical models and/or empirical formulae for predicting acoustic performance of vegetation relating to application in an urban context, HOSANNA project report (2013).
4. International Standard ISO 10534-2: Determination of sound absorption coefficient and impedance in Impedance tube, Part 2: Transfer-function method, (1998).
5 International Standard ISO 354: Measurement of sound absorption in a reverberation room, (2003)

6. K.V. Horoshenkov, A. Khan, H. Benkreira, Acoustics properties of low growing plants, J. Acoust. Soc. Am. 133, 2554-2565 (2013).
7. H. Seok, J. Yang and C. Cheal, Random-incidence absorption and scattering coefficients of vegetation, Acta Acust. United Acust. 99, 379-388 (2013).
8. P. A. Chabriac, E. Gourdon, P. Gle, A. Fabbri, H. Lenormand, Agricultural by-products for building insulation: Acoustical characterization and modeling to predict micro-structural parameters, Construct. Build. Mater. 112, 158–167 (2016).
9. Z. Azkorra, G. Pérez, J. Coma, L.F. Cabeza, S. Bures, J.E. Álvaro, A. Erkoreka, M. Urrestarazu, Evaluation of green walls as a passive acoustic insulation system for buildings, Appl. Acoust.89, 46–56 (2015).
10. International Standard ISO 10140-2: Laboratory measurement of sound insulation of building elements - Part 2: Measurement of airborne sound insulation, (2010).
11. T. Shimizu, T. Matsuda, Y. Nishibe, M. Tempo, K. Yoshitani and Y. Azumi, Suppression of diffracted sounds by green walls, Noise Control Engr. J. 64, 142-152 (2016).
12. O. Doutres, Y. Salissou, N. Atalla and R. Panneton, Evaluation of the acoustic and non-acoustic properties of sound absorbing materials using a three-microphone impedance tube, Appl. Acoust. 71, 506-509 (2010).
13. Y. Salissou, R. Panneton, O. Doutres, Complement to standard method for measuring normal incidence sound transmission loss with three microphones, J. Acoust. Soc. Am 131, 216-222, (2012).