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► **To cite this version:**

Emmanuel Attal, Nicolas Côté, Takafumi Shimizu, Bertrand Dubus. Analysis of environmental and seasonal effects on sound absorption by green wall systems. 23rd International Congress on Acoustics, ICA 2019, Sep 2019, Aachen, Germany. hal-03019117

HAL Id: hal-03019117

<https://hal.science/hal-03019117>

Submitted on 23 Nov 2020

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Analysis of environmental and seasonal effects on sound absorption by green wall systems

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ABSTRACT

Buildings and roads are made of acoustically rigid materials which reflect sound emitted from many sound sources and contribute strongly to acoustic environment. In that context, green systems (roofs and walls) used for building envelope greening were found to be efficient solutions for acoustic protection in cities when applied in a significant urban scale. Green wall systems are usually composed of plants, soils and/or air gaps. Below 1000 Hz, sound attenuation is high in soils but much lower in plants and air. Thus, sound absorption by green systems varies with the arrangement of plants, air and soil and an efficient broadband absorption is only obtained when the arrangement is optimized. In this work, environmental (moisture content) and seasonal (leaves fall) effects on absorption coefficient are studied for a green wall system. Effective properties of plants and soils are measured in an impedance tube using three-microphones-two loads method between 100 and 1000 Hz under controlled moisture content for soils and porosity for plants. Sound absorption coefficient at normal incidence is then calculated using matrix manipulation. Variation of absorption coefficient with moisture and porosity is provided for a green wall system composed of Japanese spindle and coconut peat.

Keywords: acoustic absorption, green wall

INTRODUCTION

Buildings and roads are made of acoustically rigid materials which reflect sound emitted from many sound sources and contribute strongly to acoustic environment. In that context, green systems (roofs and walls) used for building envelope greening were found to be efficient solutions for acoustic protection in cities when applied in a significant urban scale [1-3]. Acoustic characterization of green noise barriers performed in situ [1, 3-7] or in reverberation rooms [5, 6] revealed their good sound absorbing properties. Laboratory measurements showed that soil substrates used in green walls to provide nutrients to the plants, may have a high absorption coefficient with a particular dependence to substrate composition [8-11] and moisture content [10, 11]. Plants and foliage display a smaller absorption coefficient usually negligible below 400 Hz [8, 9, 12]. A recent work showed that adequate choice of constituents and geometry of a green wall system may result in an efficient sound absorption in a broad frequency range [13]. The impact of environmental and seasonal effects such as humidity and presence of plants, on the acoustic absorption was studied for vegetated roofs [14].

This last question is addressed in this work. The following approach is used: measurements are carried out in an impedance tube on different plant and soil samples in order to determine their effective speed of sound and characteristic impedance under controlled plant porosity (to account for leaves fall) or moisture content (to account for variation of air humidity). These experimental results are then used to calculate the theoretical absorption coefficient at normal incidence of a composite sample made of a plant layer atop a soil substrate. Effect of plant porosity and moisture content on absorption coefficient is discussed and related physical phenomena are analyzed.

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MEASUREMENT METHOD AND SAMPLE PREPARATION

Acoustic characterization of plant and soil samples is performed in an impedance tube using the three-microphone two-load method [15-17]. A specific tube of large diameter (192 mm) is used to have a sample size significantly larger than sample heterogeneities (leaves, stones... [12, 13]. Sample transfer matrix parameters are obtained in the 100-1000 Hz frequency range. Assuming a symmetrical and homogeneous material, transfer matrix is written as

$$[T] = \begin{bmatrix} T_{11}(\omega) & T_{12}(\omega) \\ T_{21}(\omega) & T_{22}(\omega) \end{bmatrix} = \begin{bmatrix} \cos(kd) & jZ_c \sin(kd) \\ \frac{j \sin(kd)}{Z_c} & \cos(kd) \end{bmatrix}, \quad (1)$$

where k and Z_c are respectively the effective wave number and characteristic impedance of the the sample medium. c is the effective speed of sound in the sample, ω the circular frequency and d the thickness of the sample. Z_c and c are deduced from measured $[T]$ matrix using

$$[Z_c](\omega) = \sqrt{\frac{T_{12}(\omega)}{T_{21}(\omega)}}, \quad (2)$$

$$c(\omega) = \frac{\omega d}{\arccos(T_{11}(\omega d))}. \quad (3)$$

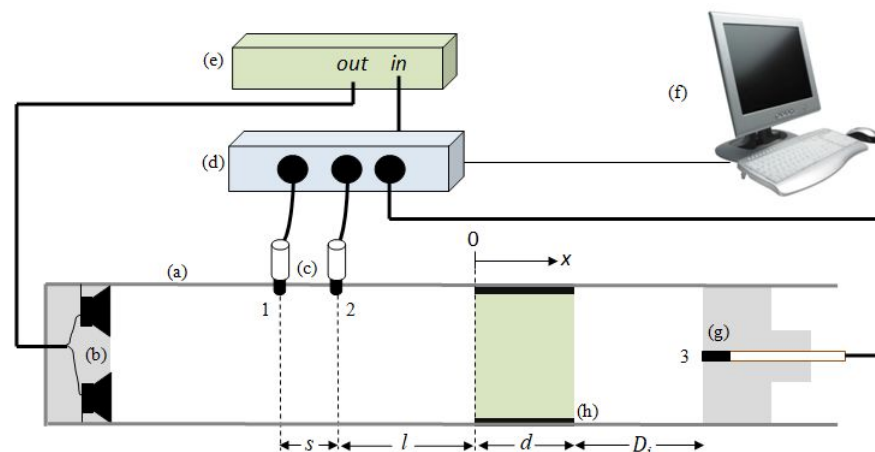


Figure 1 – Schematic view of the experimental setup: (a) stainless steel tube; (b) cylindrical PVC disk integrating 4 loudspeakers; (c) microphones; (d) sound card; (e) amplifier; (f) computer; (g) flush mounted microphone on movable piston; (h) sample holder containing the sample.

The plant considered in this work is Japanese spindle, an evergreen small shrub with oval leaves which are about 5 cm long and 3 cm wide. Porosity of plant sample is evaluated by dividing the total volume of the plant (obtained by submerging branches and leaves in a graduated cylinder filled with water and measuring the water level variation) by the internal volume of the sample holder. Branches and leaves are then dried and introduced into the sample holder (Fig. 2a). A piece of tulle stretched at the top and bottom ends of the sample holder is used to maintain the plant-air interfaces perpendicular to the axis of the tube. Acoustic measurements are made for four different arrangements of the same branches and leaves in the sample holder.

The soil of interest is coconut peat, a residual waste of coconut processing produced from the bark. It contains more lignin than other plant fibers, which makes it more resistant and slows down its decomposition. Coconut peat has several other interesting properties: high aeration even wet; good water retention, capacity to absorb nine times its own volume of water without being soggy,

very fast absorption of water when it is dried, uniformity of the spread of water. Coconut peat is first dried in an oven at 130°C. Then, a controlled amount of water is added to the dry soil. Moisture content is defined as the ratio of the mass of added water to the mass of the dry soil. Finally the wet soil is placed in the sample holder (Fig. 2b) and tulle nets are stretched on the top and bottom ends of the sample holder to maintain the soil-air interfaces perpendicular to tube axis. Acoustic measurements are made for four different samples.

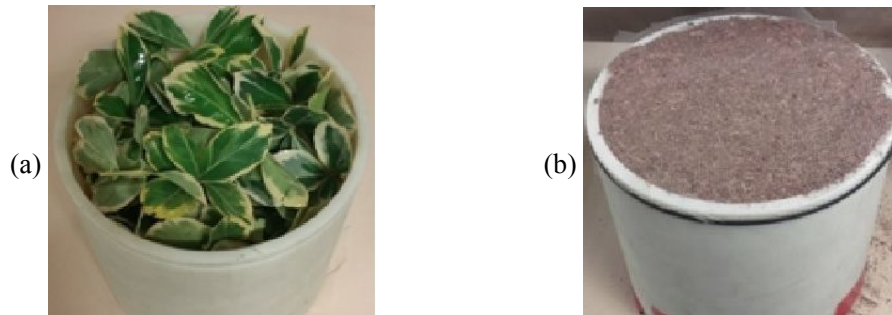


Figure 2 – (a) Japanese spindle sample (porosity of 95%); (b) dry coconut peat sample.

EFFECT OF POROSITY ON PLANT EFFECTIVE PROPERTIES

Figure 3 displays the real part of effective speed of sound, the imaginary part of acoustic wavenumber and the characteristic impedance versus frequency of a 8 cm thick dry spindle sample for different porosities. For any porosity, the sample behaves as a non dispersive medium having almost constant speed of sound and characteristic impedance the 250-1000 Hz frequency range. For porosities decreasing from 0.99 to 0.95, mean value of speed of sound decreases from 300 m.s⁻¹ to 240 m.s⁻¹ and mean value of characteristic impedance increases from 510 to 620 Rayl. Above 250 Hz, attenuation increases monotonically for all porosities but remains weak with a maximum value of 1 Np/m at 1000 Hz. Standard deviation between measurements becomes high below 200 Hz. At these frequencies, some elements of $[T]$ get close to zero when $kd \approx n\pi/2$ due to weak attenuation. Therefore inversion procedure becomes sensitive to small changes in sample geometry or small errors on phase measurements. Experiments made on wet samples show that effective properties of spindle are not significantly modified by moisture.

EFFECT OF MOISTURE CONTENT ON SOIL EFFECTIVE PROPERTIES

Figure 4 displays the real part of effective speed of sound, the imaginary part of acoustic wavenumber and the characteristic impedance versus frequency of a 8 cm thick coconut peat sample for different moisture contents.

For the dry sample, real part of effective speed of sound increases monotonically with from 60 to 100 m/s in the 100-1000 Hz frequency range. Dry coconut peat behaves as a dispersive medium with a speed of sound 3.5 to 5.6 times smaller than those of air in that range. Attenuation in dry coconut peat is high and increases from 7 to 30 Np/m between 100 and 1000 Hz. Real part of characteristic impedance decreases monotonically with frequency with values ranging between 2.5 and 5 times the characteristic impedance of air.

Experimental results obtained with wet samples show that coconut peat is highly sensitive to moisture. Compared to the dry sample, speed of sound is divided by about 2 for a moisture content of 15% (Fig. 4a). This variation is not uniform with frequency, a transition taking place around 700 Hz. No significant change is observed when increasing moisture content to 30%. Attenuation increases by approximately 60% for moisture contents of 15% and 30% and exhibit also a transition near 700 Hz (Fig. 4b). Finally characteristic impedance of coconut peat increases at low frequencies and decreases above 600 Hz (Fig. 4c) in the presence of moisture.

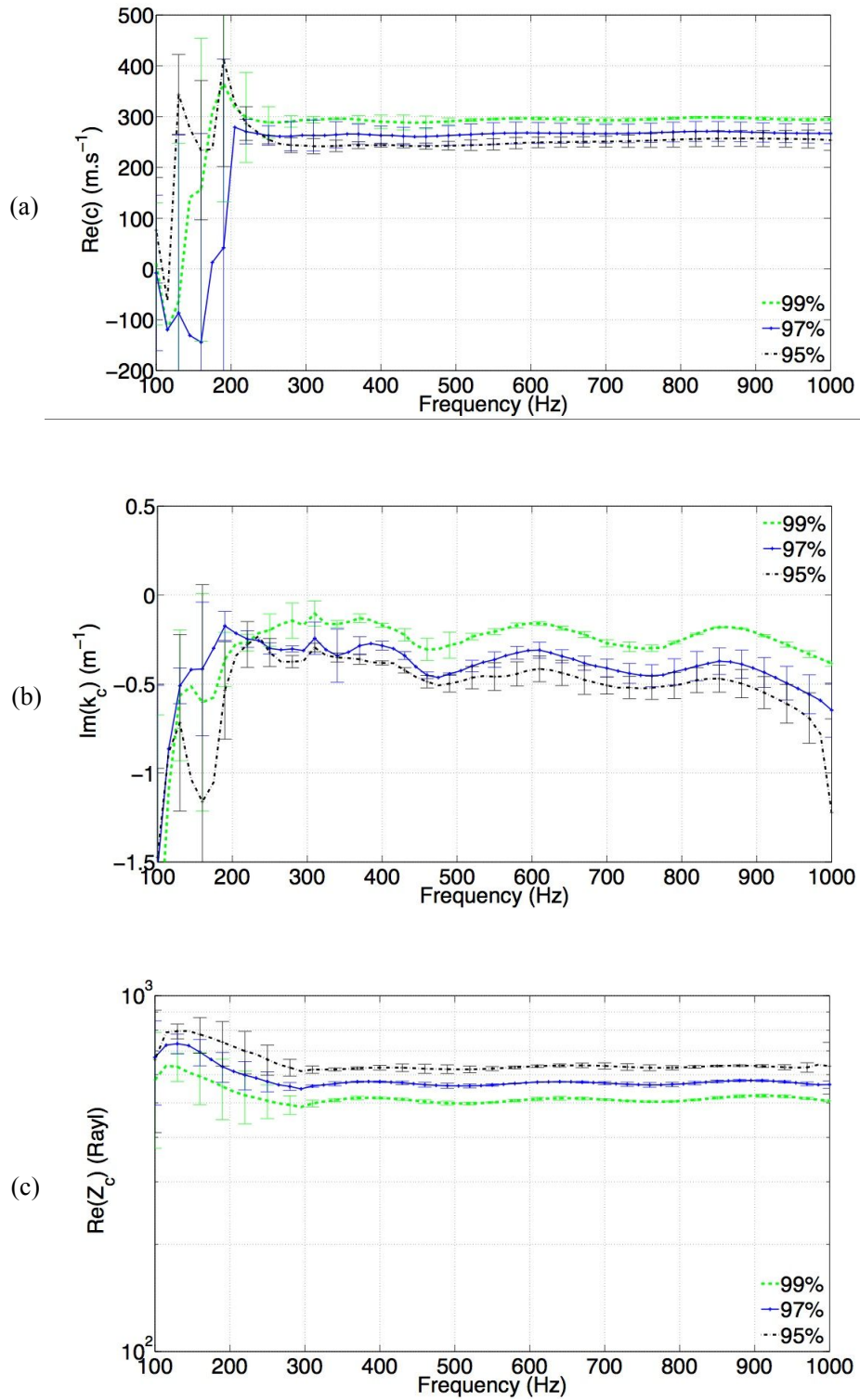


Figure 3 – 8 cm thick plant samples of different porosities: (a) real part of effective speed of sound; (b) imaginary part of effective wavenumber, (c) real part of characteristic impedance.
 Full line: average value; error bars: standard deviation.

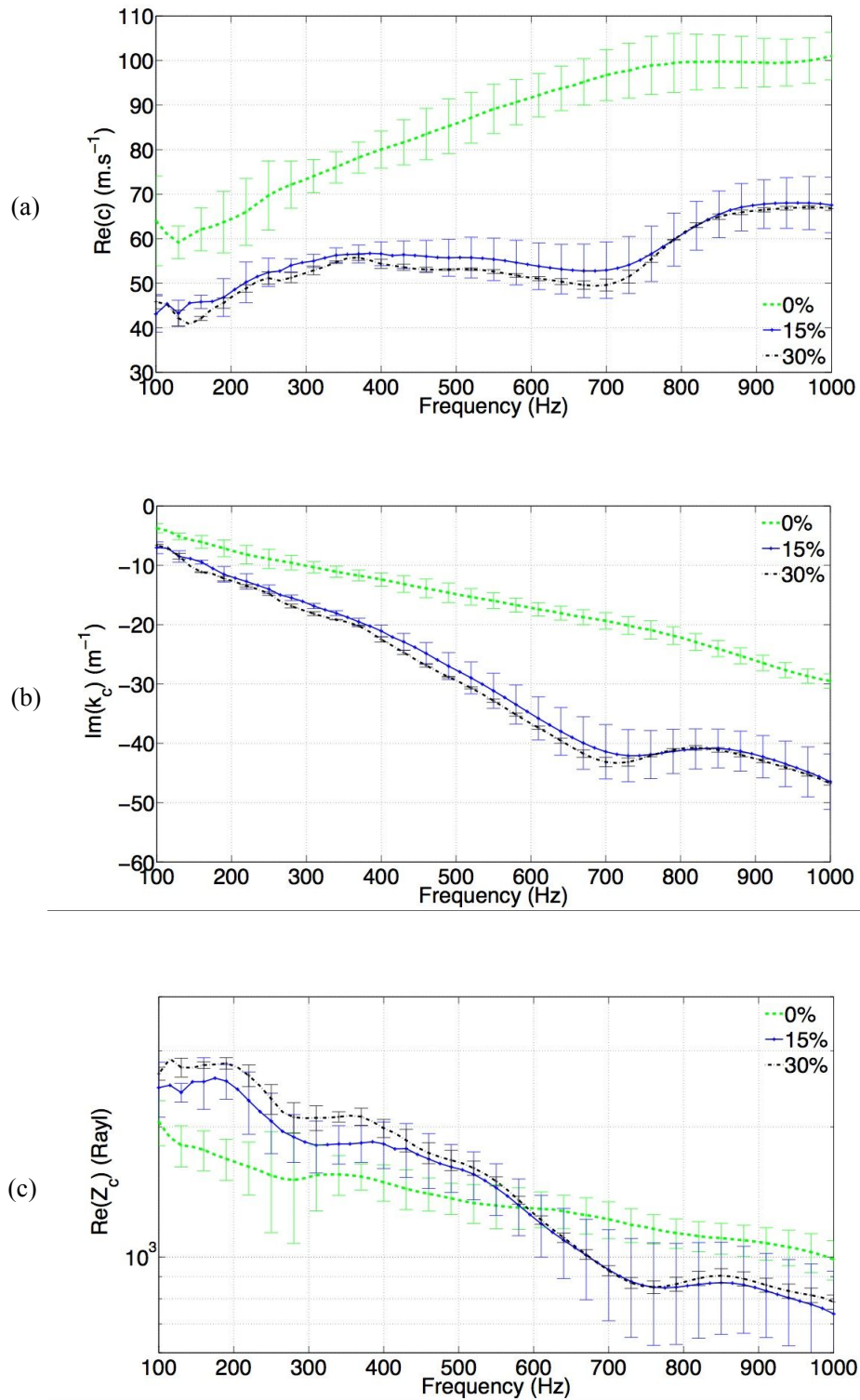


Figure 4 – 8 cm thick coconut peat samples of different moisture contents: (a) real part of effective speed of sound; (b) imaginary part of effective wavenumber, (c) real part of characteristic impedance.

Full line: average value; error bars: standard deviation.

VARIATION OF SOUND ABSORPTION COEFFICIENTS BY A GREEN WALL SYSTEM VERSUS PLANT POROSITIES AND SOIL MOISTURE CONTENTS

To evaluate the impact of porosity or humidity variations on the acoustic performance of a green wall system, simulations are conducted on a composite sample constituted by a 8 cm thick layer of spindle atop a 8 cm thick layer of coconut peat using previous experimental results and transfer matrix method. Details of the method may be found in [13].

Figure 5 displays the variation of absorption coefficient and surface impedance of the composite sample in rigid backing condition for 0% moisture content and various plant porosities. In the absence of plant (100% porosity), absorption coefficient is approximately constant around 0.7 between 200 and 1000 Hz. Surface impedance shows that this behavior is the consequence of the impedance mismatch between air and soil : approximately 25% of incident energy is reflected on air-soil interface. Most of transmitted energy is then dissipated in the coconut peat layer in which the acoustic wave is highly attenuated. The presence of plant layer of increasing porosity improves impedance matching and absorption. This improvement reaches an optimum when the plant layer behaves as a quarter-wave transformer [13] around frequency $f = c/4d$ i.e. 937, 812 and 750 Hz for porosities equal to 0.99, 0.97 and 0.95 respectively. The quarter-wavelength resonance of the sample around 200 Hz, which constitutes the lower bound of the absorption band, is not affected by plant porosity.

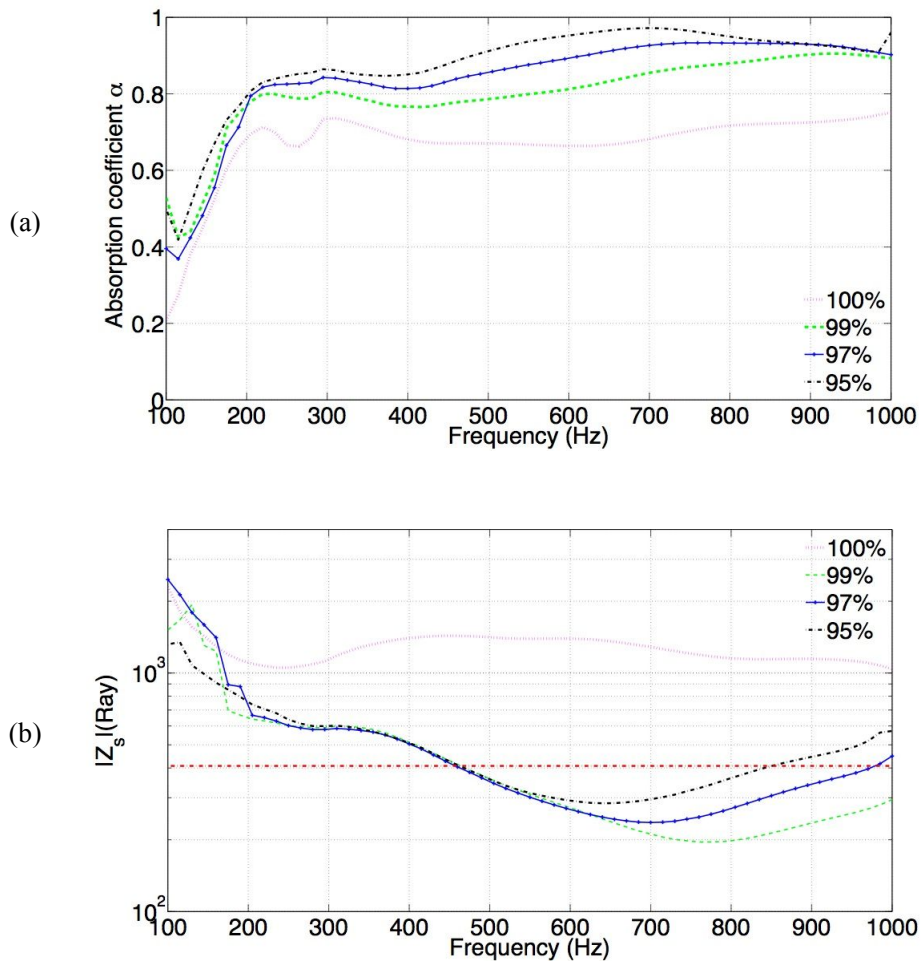


Figure 5 – 8 cm thick spindle layer atop 8 cm thick coconut peat layer in rigid backing condition for 0% moisture content and different plant porosities: (a) absorption coefficient; (b) surface impedance.

Red dotted line: air characteristic impedance.

Figure 6 displays the variation of absorption coefficient and surface impedance of the composite sample in rigid backing condition for 95% plant porosity and various moisture contents. The case of the dry sample (0% moisture content), already presented in Fig. 5, is characterized by a high (above 0.8) and broadband (between 200 and 1000 Hz) acoustic absorption coefficient due to the impedance matching between air and soil provided by the plant layer. A different behavior is observed in the presence of moisture. The slow-down of the wave in the coconut peat shifts down the quarter-wavelength resonance of the sample below 100 Hz. Therefore, the anti-resonance peak, observed near 200 Hz on surface impedance curve, increases impedance mismatch between air characteristic impedance and sample surface impedance. A larger amount of incident energy is thus reflected by sample surface and acoustic absorption decreases. Similar behavior was observed previously in plant-soil systems with air-backed cavity [13]. It may be noted that change of soil effective properties due to moisture does not affect much the quarter-wave matching effect provided by the plant layer.

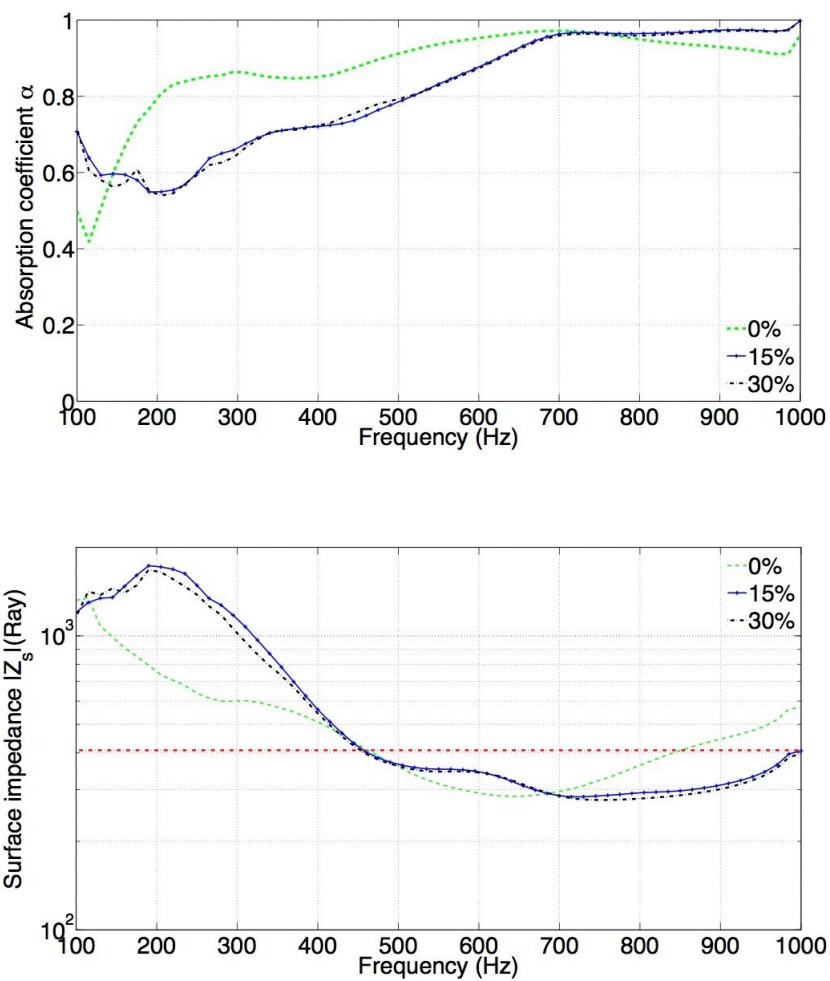


Figure 6 – 8 cm thick spindle layer atop 8 cm thick coconut peat layer in rigid backing condition for 95% porosity and different moisture contents: (a) absorption coefficient; (b) surface impedance.

Red dotted line: air characteristic impedance.

CONCLUSIONS

The effect of plant porosity and soil moisture contents on the sound absorption by spindle-coconut peat composite samples at normal incidence has been analyzed using experimental characterization of effective properties and calculation using transfer matrix method. It is found that both the variation of porosity and the variation of moisture contents affect significantly the frequency spectrum of the absorption coefficient: 1) the increase of plant porosity induces a degradation of impedance matching (between air and soil) provided by the plant layer and therefore a decrease of sound absorption between 200 and 1000 Hz; 2) the increase of moisture content causes a shift of wall thickness to lower frequencies which lowers absorption coefficient between 150 and 700 Hz. The latter problem could be addressed by replacing coconut peat by a soil mixture less sensitive to moisture.

ACKNOWLEDGEMENTS

Supports of this work by ADEME, Yncrea Hauts-de-France and “Hauts-de-France” region are greatly acknowledged.

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