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Experimental evaluation and modelling of the sound absorption properties of plants for indoor acoustic applications

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ABSTRACT

In this paper the sound absorption properties of two types of plants for indoor applications are analyzed. The aim of this research is to investigate the feasibility of using *Nephrolepis Exaltata* (Boston Fern) and *Helxine soleirolii* (Baby Tears) in green walls for indoor applications, in order to improve the acoustic quality of indoor environments. The normal incidence sound absorption coefficient of ten specimens of Fern and three of Baby Tears was measured in presence and in absence of a substrate. The chosen substrate is made of coconut and perlite soil, commonly used in hydroponics; its composition allows to obtain high porosity values. The sound absorption coefficient spectra were measured in the frequency range of 50–1600 Hz using a vertically mounted impedance tube with a diameter of 100 mm; measurements were carried out in accordance with ISO 10534-2 method. After measuring the normal incidence sound absorption coefficient with impedance tube, the equivalent fluid model for sound propagation proposed by Miki was used to deduce non-acoustical properties of the samples. The inverted Miki's model allowed to find the theoretical tortuosity (α_∞) and the flow resistivity (σ). These non-acoustic properties were then related to morphological characteristics of specimens. It is shown that the leaf area density is closely related to flow resistivity, at least for Boston Fern; the data allowed to identify a semi-empirical relation between them. Finally an application of the developed green system for the acoustic treatment of a real case study is reported.

1. Introduction

There are various types of construction systems of green walls, even if two main typologies can be identified: green façades and living walls [1]. In green façades plants climb wall surface but root on the ground. Living walls can be further differentiated in two categories: the first one uses geotextile felts as growing panel, there is no substrate in this technology and the plants are fed as in hydroponics.

In the second kind of living walls technology, the plants root in the substrate which is contained inside modules (boxes), made of different materials and hooked to a vertical bearing texture fixed to the building façade. The present paper is focused on the second type of green walls, because an adequate selection of a porous substrate can give an important contribution to the acoustic absorption of the system.

As far as the propagation of sound waves in presence of vegetation, three main mechanisms of attenuation can be found. The dissipative effect caused by soil by means of destructive interference of sound waves, named "ground effect", occurs for frequencies below 500 Hz [2]. A second mechanism arises from the reflection and scattering effects of plant elements (trunks, branches, sprigs, leaves). When a dense vegetation layer is placed between source and receivers, it leads to a drop of sound pressure levels due to reflection and scattering, particularly at middle and high frequencies [3]. The present paper is focused on the last of three mechanisms, i.e. the acoustic absorption of vegetation. Foliage is able to absorb an important amount of sound energy, up to 50% of incident sound wave, depending on the morphological parameters of the plant [4]. When the sound wave hits the plants a vibration of its elements occurs and produces a dissipation by converting sound energy into heat. Furthermore a contribute to absorption is given by dissipation caused by thermo-viscous friction at the boundary layer at high frequencies [5]. The studies found in the literature are basically focused on green systems for outdoor acoustic applications such as street canyons, courtyards and noise barriers and on the influence of vegetation on the perception of the sound environment [6,7]. The present work studies vertical green systems for application as acoustic treatment of indoor spaces, as an alternative

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to traditional or sustainable acoustic materials [8]. The aim is to use the green wall as a sound absorbing element to control the acoustic quality inside confined environment, replacing traditional man-made acoustic absorbers. The scientific literature about this topic is very limited. Vertical green systems are important elements for interior design because of their aesthetic value; moreover they can provide further benefits, such as improving air quality as well as restorative, neuropsychological effects and even improved cognitive performance [9]. The stress recovery in four different environments (urban street, urban park, kept woods, unkept woods) was studied and the results showed that green environments have positive effects on the recovery in comparison to the urban environment whereas there are not significant differences among the different green spaces [10]. A similar experiment was conducted in a workplace on a sample constituted by 51 healthy workers in presence and absence of indoor plants in their office. It was found that the discomfort symptoms average was 23% lower during the period in presence of plant and the coughing and fatigue complaints decreased by 37% and 30% respectively [11]. Cognitive performance was investigated by Raanaas et al. [12], showing that the presence of natural elements in an office environment affects positively cognitive performance during a fatigue task.

The fundamental difference between indoor and outdoor green walls is basically in the selection of the green species. Species of plants able to survive in indoor climatic conditions should be selected, i.e. plants able to (i) live in thermo-hygrometric conditions typical of indoor spaces (temperature $\cong$ 20 °C and relative humidity $\cong$ 50%), (ii) to root in horizontal position and (iii) to live without direct sunlight illumination. The present work is the prosecution of a previous research by the same authors [13]: a summary of the results is reported in Section 3.

2. Literature review

2.1. Early studies

Early studies concerning the acoustic properties of plants were focused on the acoustic influence of tree belts and plantations on propagation of sound waves in free fields. A work of Aylor in 1972 [3] analyzed the transmission of sound through dense corn, dense hemlock plantations, green belts of pines, dense hardwood brush and over cultivated soil. Aylor deduced early prediction models of the sound attenuation. In particular he observed that leaf area density increases the sound attenuation especially at higher frequencies, whereas the ground effect (interferences between direct waves and waves reflected from the ground) is predominant in the frequency range 200–1000 Hz. In another paper Aylor showed that sound attenuation increases with increasing values of leaf area density, leaf width and frequency [14]. A later study by Martens [15] investigated the vibration of four different plant leaves using a laser-Doppler-vibrometer. This instrument allowed to measure the leaf vibration velocity without mechanically loading the plant leaves. The tested samples were leaves of *Ligustrum regelianum* (Privet), *Betula verrucosa* (Birch), *Corylus avelona* (Hazel) and *Quercus robur* (Oak). The measurements showed that single leaves are able to convert a small quantity of acoustic energy into heat by vibration. A similar study was conducted by Tang et al. some years later [16]. In the paper the normal mode vibrations of leaves were analyzed in a controlled situation and then the results were used as parameters in a computer-simulation (Monte Carlo technique) to calculate the contribution of six tested leaves to the attenuation of sound waves of different frequencies propagating though foliage. The Monte Carlo simulations gave results comparable to those obtained by Martens, i.e a single leaf is able to absorb acoustic energy, especially at high frequencies, although the values of acoustic energy absorbed could be affected by the bulk of the accelerometer, which could mechanically overload the leaves.

2.2. Outcomes of the Hosanna Project

More recently the European 7th FP Hosanna Project (2009–2013) has provided an important boost to this research field [17]. Hosanna (Holistic and Sustainable Abatement of Noise by optimized combinations of Natural and Artificial means) aimed at discovering novel solutions for noise pollution reduction in urban environments by using natural and recycled materials, or a combination of both. The main findings of the project can be found in Ref. [18]. One of the novel solutions proposed in Hosanna was to use vertical green walls as sound absorbing elements in different urban environments, such as courtyards, roadsides or street canyons. In the framework of the project several researches concerning the evaluation of the acoustic absorption by means of the foliage were performed.

Smyrnova et al. studied the acoustic behavior of low growing evergreen bushes and typical bedding plants, easy to find in cities [19]. The selected samples were the followings: *Viola x wittrockiana* (Pancy), *Primula vulgaris* (Primrose) and evergreens *Buxus Sempervirens* (Buxus). During the tests, the specimens were put in pots with soil. The results obtained in the reverberation chamber, both for evergreen and bedding plants, showed an important reduction of reverberation time (RT) for frequencies ranging between 250 and 1600 Hz: a drop caused by the soil absorption occurs for frequencies below 500 Hz, whereas for frequencies between 500 and 1600 Hz the reduction is caused by the vegetation absorption. For frequencies above 1600 Hz the RT drop is relatively small and probably due to mechanism of reflection and scattering. Moreover the authors observed that RT decreases as the density of foliage increases, except for Buxus. The analysis of absorption coefficients showed a different behavior between the two types of specimens: the absorption of bedding plants is significantly higher than evergreen plants.

Following works under Hosanna Project analyzed the influence of three fundamental variables on the acoustic absorption of vegetation systems [20]. These are soil depth, water content and vegetation coverage. The sound absorption coefficients of different types of soil were measured in the reverberation chambers of the University of Sheffield (USFD, United Kingdom) and of the Hanyang University (HYU, South Korea). Three types of soil were tested: sandy soil, a mixture of sandy soil and leaf mold and topsoil. The results highlighted that the absorption is not influenced only by the thickness of the soil, but also by its porosity and compactness; as a consequence topsoil provides the highest absorption due to its porosity. The influence of the water content on the sound absorption properties of sandy soil and topsoil was also investigated. In general, the outcomes showed that the more water content of soil increases, the more absorption coefficient decreases. The effect is due to the decrease in porosity. It can be observed that the reduction of absorption occurs basically at middle and high frequencies. It was also observed that the behavior of the different types of soil is very different, depending on the percentage of water content. Water content does not affect sandy soil at low frequencies. Observing the results of the researches, it can be concluded that reduction of absorption caused by water content is larger in topsoil compared to that in sandy soil.

Lastly the research investigated the effect of vegetation coverage on sound absorption. In the measurements with sandy soil and boxtrees, the absorption coefficient showed a slightly drop as the coverage percentage increases. Whereas in the other tests with topsoil and different plants, the acoustic absorption increases as the coverage increases, especially at middle and high frequencies. Such different result can be explained by the morphological differences