The Absorption and Scattering Characteristics of Interior Living Walls

Mahsa Akbarnejad

A Thesis

In the

Building Science Graduate Program

Presented in Partial Fulfillment of the Requirements for the Degree of Master of Applied Science in Building Engineering/ Building Science

At the

British Columbia Institute of Technology

Burnaby, British Columbia, Canada

British Columbia Institute of technology

Date (January, 2017)

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1. ABSTRACT

Installation of interior living walls is increasing rapidly due to their beauty, biophilic design and their potential contribution to indoor environmental quality. However, there is little understanding of the specific effect they have on the acoustics of a room.

To advance the state of practice, this interdisciplinary study explores the acoustical characteristics of interior living walls to determine how they can be used to positively benefit room acoustic by reducing excess noise and reverberation. Specifically, the objective of the research is to measure the acoustical characteristics of the interior living wall in order to determine their absorption coefficient, scattering coefficient, and the parameters that most significantly impact these coefficients.

First, a series of measurements are carried out in a reverberation chamber to examine random-incidence absorption by considering parameters such as carrier type, moisture content, vegetation type, and substrate. In addition, both absorption and scattering coefficients are examined by considering various vegetation types and coverage. The findings from empirical measurements facilitate a sensitivity analysis, with the use of the commercial software Odeon, of the absorption and scattering coefficients.

Next, the empirical absorption and scattering coefficients are used on a model, developed in the commercial software Odeon, to see the effect of interior living walls on room acoustics. The aim of this study is to evaluate the application of interior living walls as a sustainable and acoustically beneficial material for buildings of any kind.

Keywords: acoustical characteristics of interior living walls, sound absorption coefficient, sound scattering coefficient, Odeon software, room acoustics, living wall

2. INTRODUCTION

Noise … is one of the chief drawbacks to the enjoyment of modern urban living.

- Dr. Vern O. Knudsen, 1967

This quote highlights the profound effect of noise on the quality of urban life. Therefore, it is imperative to come up with practical acoustical measures to reduce unwanted noise in living, studying and working environments. This research will determine if the new technology of living walls can reduce noise and whether the improvement of room acoustics can be truly considered a benefit of the modern technology.

To meet the acoustical criteria for rooms a wide range of building materials are available for use inside of the rooms. Using interior green walls, which address multiple issues in the sustainability discussion, may be an efficient option for the design team. The acoustic characteristics must first be quantified in terms of absorption and scattering properties.

In order to determine the acoustical impact of using living walls in a room and to make it possible to predict their effect in room design (layout of the room), the absorption and scattering characteristic of systems should be empirically evaluated and the impact of the most effective components of the interior living wall systems must be understood and defined.

Additional to the potential acoustic impact of living walls, introducing a plant to the living space breaks the roughness, the coldness, and disciplinary aesthetic nature of urban architecture (Figure 1). Plants also act as natural air-conditioners, removing carbon dioxide and other pollutants such as toxic volatile organic compounds from the air and releasing oxygen, and contributing to a comfortable relative humidity of 45-65 percent and temperature of 20^{o}-22^{o}C [23].

Figure 1. Interior living wall installation [9]

The interior living wall system is composed of three major components: carrier panel, substrate and plants (leaf, stem and root). Each plays a specific role in absorbing and scattering sound. Therefore, it is necessary to characterize the effect of each component separately as well as the combined effects.

The carriers are made in many forms from a variety of materials such as stainless steel, plastic, and polypropylene fabrics. The substrate can vary in terms of percentage of organic matter, aggregate type and range of moisture content. Plants can differ in terms of physiology, structure and the density of wall coverage. Interior living walls are supported with an automatic, closed circuit irrigation system, some with an in-line fertilizer and some with a water reservoir. Interior living walls need about 5 to 10 μmole/m^2/s of light, which can be provided naturally with standard size windows in the room. Natural daylight is the best choice to provide interior living wall systems with necessary light for plant growth and leaves. In situations where that is not possible, a lighting system can be installed.

Specific objectives of this research are primarily to measure the acoustical characteristics of the interior living wall in order to determine their normal and diffuse absorption coefficient, scattering coefficient, and the parameter, which most significantly impact these coefficients. A secondary objective is to use the measured absorption and scattering coefficient data to model the effects of the interior living walls using the commercial software Odeon and investigate the model`s sensitivity to the measured data.

3. LITERATURE REVIEW

Noise, also known as invisible pollution by acoustical experts, has a great impact on happiness, and the physical and mental health of human beings. The World Health Organization (WHO) identified low-frequency sound as a particular environmental noise problem, its annoyance rising with increasing sound level [1].

Figure 2. Interior living wall installation in commercial buildings [10]

The influence of contact with nature on the health and psychological well-being of humans is represented in numerous literatures. An examination of the effect of being close to greenery illustrated a relief from stress, which can help to improve different aspects of well-being [1]. However, limited research on interior greenery is available.

The literature supporting this thesis focuses on three main topics: acoustical characteristics and parameters of vegetation, acoustical characteristics and parameters of substrates, effect of material absorption and scattering in room acoustics.

3.1. Acoustical characteristics and parameters of vegetation

Previous studies have shown that leaves of plants attenuate sound by reflecting, refracting and absorbing acoustic energy in small amounts. Martens evaluated sound propagation through a modeled forest in an anechoic chamber, and found that plants act as a low-pass filter [19]. He also studied acoustic reflection characteristics of deciduous plant leaves, and showed the importance of leaf dimension and leaf mass for sound reflection [18]. Another investigation by Martens examined reverberation pattern and sound energy absorption of four types of plant leaves in a sound field using a Laser-Doppler-Vibrometer system over a wide frequency range (0-100 Hz) [20]. In another investigation, he measured sound reflection off a plant leaf as a function of leaf mass using pulsed and pure tones. The result of this study showed the importance of the dimensions of a plant leaf, especially at high sound frequencies, and the mass of the leaf tissue on the reflection of sound waves [21].

Attenborough's measurements of leaf vibration induced by sound showed that absorption by leaves is important at high frequencies above 1 kHz, whereas below 1 kHz there is little sound absorption by leaves [3]. This kind of study was done with the aim of understanding the mechanisms of reflection, diffraction and absorption of sound waves around plant leaves.

In the study by Azkorra, two different standardized laboratory tests were conducted on the contribution of vertical greenery systems to noise reduction [21]. Findings indicated a weighted sound reduction index (Rw) of 15 dB and a weighted sound absorption coefficient (a) of 0.40 attributed to the modular-based systems. Comparing Azkorra's results with those of previous studies, it can be concluded that the introduction of the green walls into the reverberation room results in a reduction in the reverberation time from 4.2 to 5.9, highlighting and quantifying the sound absorption capacity of this construction system[21].

The leaves of plants absorb the vibration of sound waves [23]. A complete study on the acoustic and mechanical characteristics of plant leaves still needs to be specified for use in interior green walls.

Vander Heiden investigated the complexity of the plant and soil interface and possible effects of vegetation on the acoustical properties of soil surfaces such as porosity and soil structure. His research indicated great influence of vegetation on the porosity, inorganic and organic matter content, water content and soil temperature [26]. The results also indicated a correlation between the penetration of roots into the soil, and the porosity of soil.

In an experiment by Aylor, sound attenuation in vegetated areas with different configurations of plants and ground conditions was examined. He considered the effect of area, width, thickness and surface-area density of the leaves, as well as stem diameter and density and ground impedance. He described the relationship between absorptive capacity of the plant material and sound attenuation [4]. Aylor's results indicated that foliage reduces sound transmission, especially at high frequencies mainly by stems, and more efficiently with increasing leaf density, leaf width and leaf thickness, as shown in Figure 3.

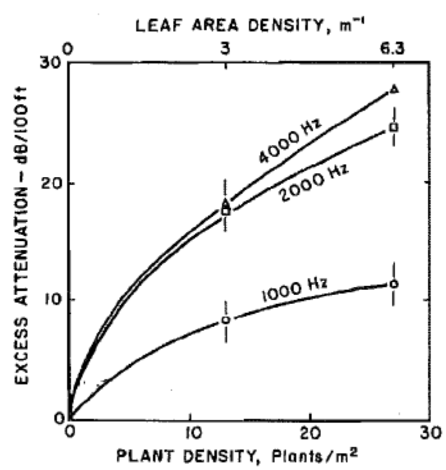


Figure 3. Excess attenuation vs. plant density (Plant/m^2) and leaf area density (m^{-1}) at different frequencies [4]

Wong examined the sound absorption coefficient of vertical greenery systems in the reverberation chamber to show the attenuation throughout the frequency spectrum for varying Leaf Area Index (LAI) (Figure 4). Figure 5 illustrated the average sound absorption coefficient relative to coverage. However, his study didn't define the effect of scattering coefficient. Diffraction is a concern because it significantly affects the sound pressure level (SPL) at low frequencies [29]. Additionally, Wong carried out insertion loss experiments on 8 systems of living walls in Hort Park. The frequency-dependent average SPL readings and insertion loss due to the different plant characteristics in each zone are shown in Figure 6 and Figure 7.

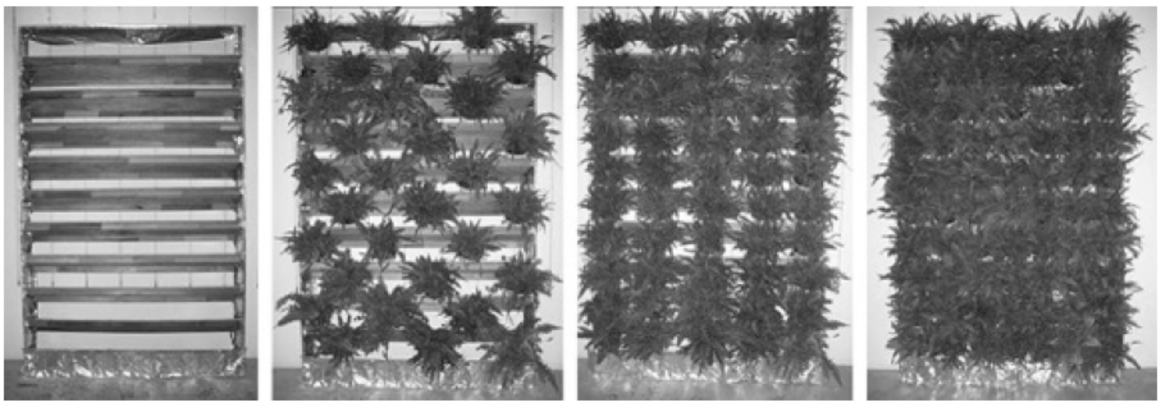


Figure 4. Vertical greenery system with empty, 43%, 71% and 100% greenery coverage densities in reverberation chamber (from left to right) [29].

The results of the study by Price showed the stronger attenuation in insertion loss at low to middle frequencies that is due to the absorbing effect of the substrate. Furthermore the sound absorption coefficient increased with increasing frequency and greater greenery coverage. It was shown that vertical greenery systems are effective in reducing sound levels as well as absorbing sound energy and found that scattering by leaves can contribute to noise attenuation especially above 1 kHz [17].

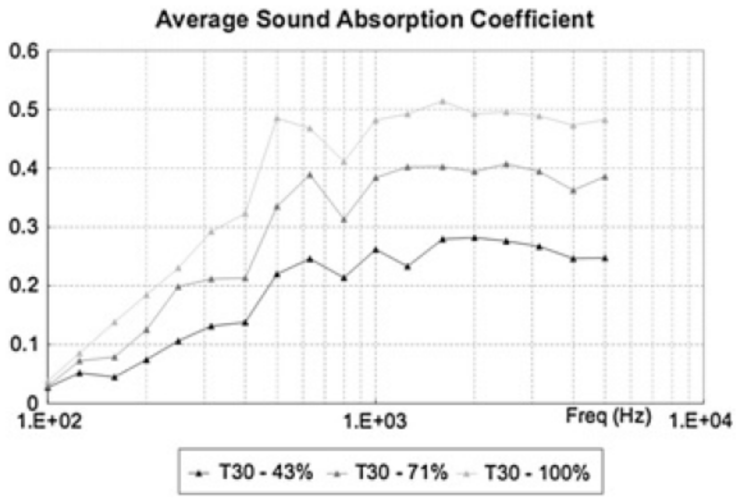


Figure 5. Average sound absorption coefficient relative to coverage [17].

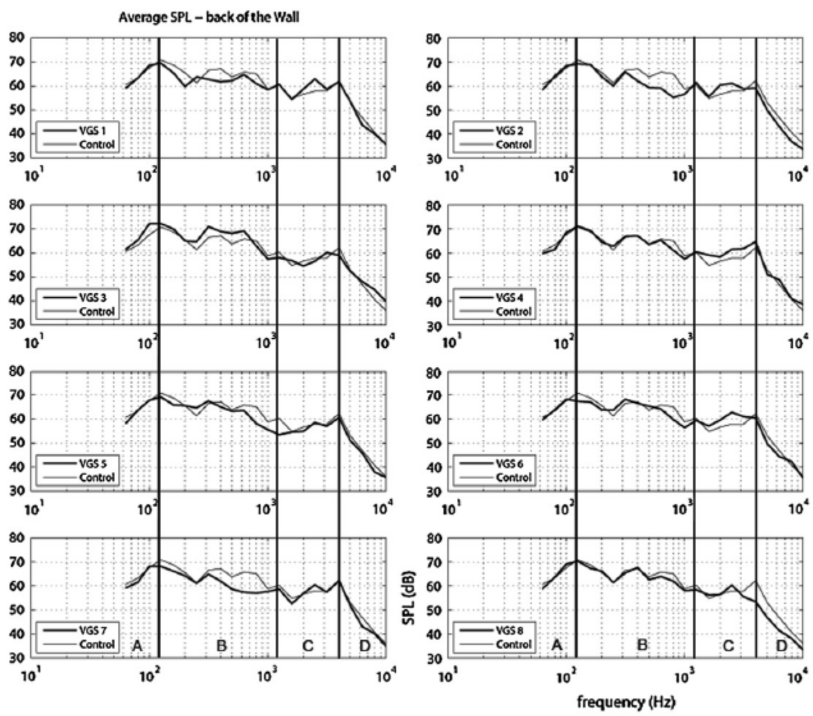


Figure 6. Average SPL readings at the back of the entire eight vertical greenery systems during the acoustics experiments in Hort Park [17]

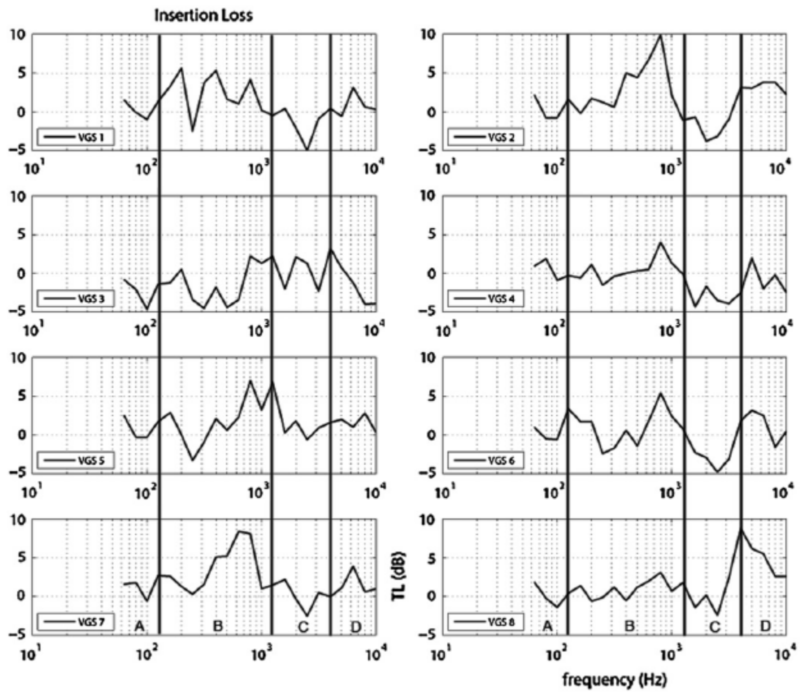


Figure 7. Average insertion loss for the entire eight vertical greenery systems (VGS) during the acoustical experiments in Hort Park [17]

Yang examined random incidence absorption coefficient for soil without vegetation, soil with vegetation, above-ground components of plants and green wall without vegetation. He also measured random incidence scattering coefficients of above-ground components of plants such as leaf and stems in a reverberation chamber [11]. The absorption and scattering coefficients of different installations of vegetation were determined in the reverberation chamber in order to illustrate the influence of factors such as soil depth, soil water content, plant size, level of vegetation coverage and the like.

With increased soil moisture content, a strong decrease in absorption coefficient was reported, since the application of water to soil results in a decline in pore space.

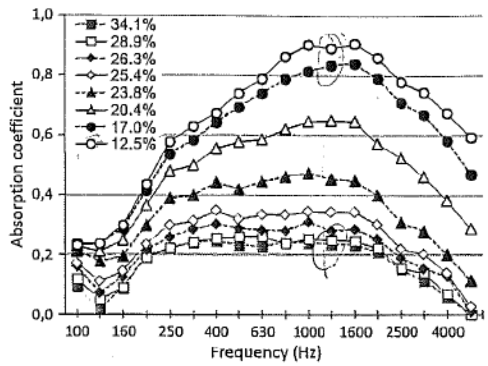


Figure 8. Absorption coefficient of 200 mm topsoil with different soil moisture content [11]

An investigation of the effect of the combined soil substrate and low-growing vegetation on absorption coefficient showed better absorption at low and mid frequencies (rather than high frequencies above 2000 Hz) with increasing vegetation density. This likely happens due to viscous friction losses and the inertia effect of vegetation on sound absorption at low and mid frequencies [11].

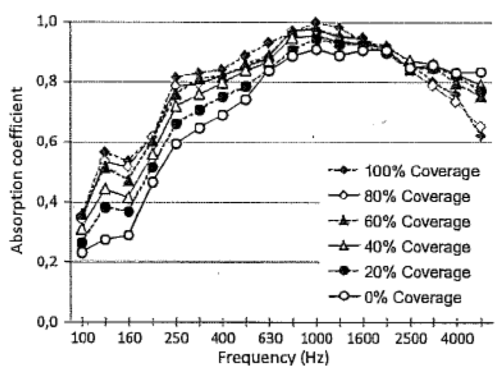


Figure 9. Absorption coefficient of top soil with different level of vegetation coverage [11]

Looking separately at the absorption and scattering coefficient of the above ground components, for different types of vegetation such as Buxus and Ivy with various levels of vegetation coverage, showed that generally the absorption coefficient increases with increasing vegetation density and leaf size.

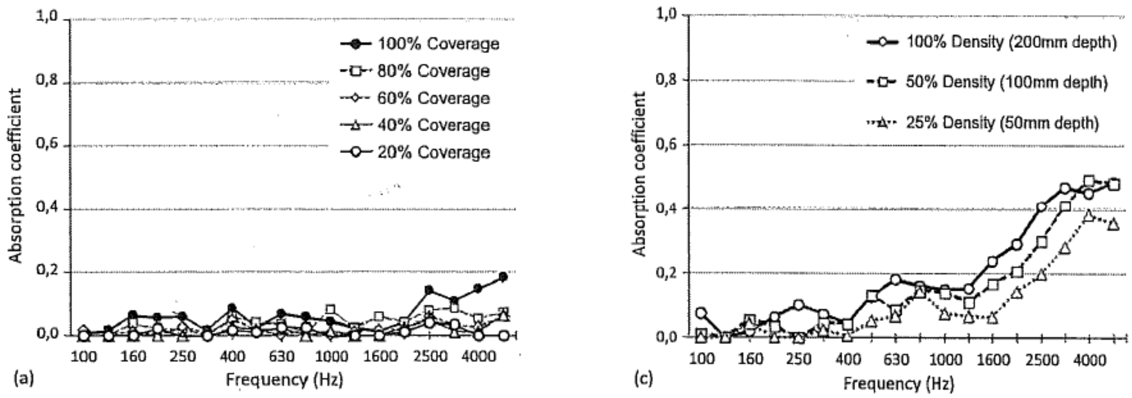


Figure 10. Absorption coefficient of vegetation with different level of vegetation coverage/density. (a) Buxus, (c) Ivy[11]

In Figure 11 it can be seen that, just like absorption coefficient, the scattering coefficient increases with increasing levels of vegetation and leaf size for both types of plants.

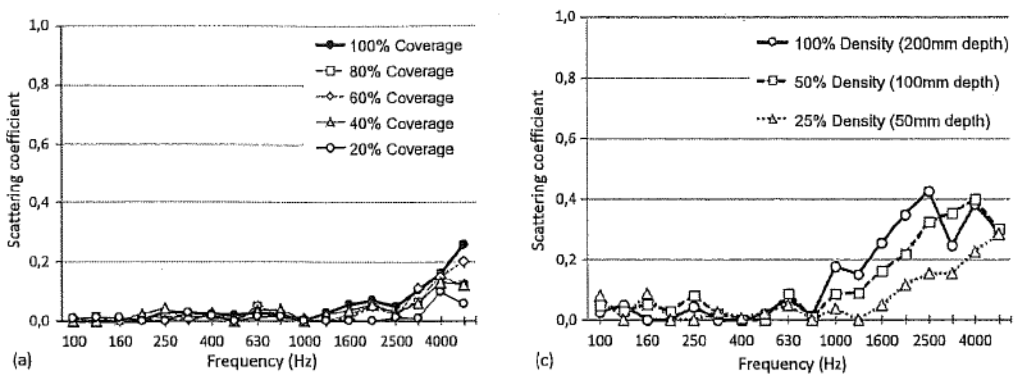


Figure 11. Scattering coefficient of vegetation with different levels of vegetation coverage/ density. (a) Buxus, (c) Ivy [11]

From investigations on a green wall without vegetation, it was reported that a green wall with highly porous substrate maintained a high absorption coefficient even with high moisture content Figure 12 [11].

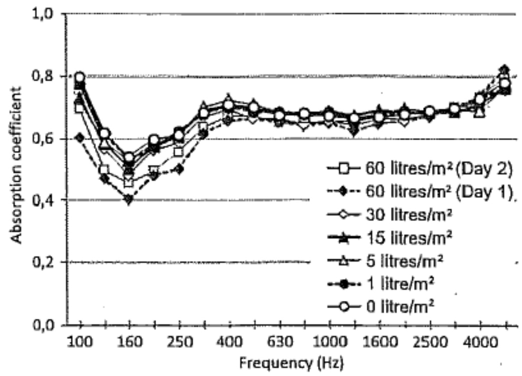


Figure 12. Absorption coefficient of the green wall with different levels of substrate moisture content [11]

There is also a study by Horoshenkov based on impedance tube measurements, which evaluated the influence of leaves on the acoustic absorption of soil, plants, and their combination. The result showed that the presence of plants with a particular type of leaf could result in a considerable improvement in the absorption coefficient of a green wall at certain water saturation levels in comparison with the wall without vegetation [25].

In the study by Alessandro the normal incidence sound absorption coefficient of ten specimens of Fern and three specimens of Baby Tears were measured in the presence and in absence of a substrate [47]. The sound absorption coefficient were measured in the frequency range of 50 -1600 Hz using a vertically mounted impedance tube with a diameter of 100 mm. The measurements were carried out in accordance with UNE-EN ISO 354-2 standards. The soil substrate used for the measurements were made of 70% coconut fibers and 30% expanded perlite. The morphological parameters of the plants, such as area of a single leaf, number of leaves in a plant, height of a plant, predominant angle of leaves orientation, were also measured. The measurements results confirmed that plants are able to absorb a considerable amount of acoustic energy, particularly in presence of the soil substrate. The soil substrate is able to absorb up to 80% of acoustic incident energy, at frequencies above 1000 Hz [47].

3.2. Acoustical characteristics and parameters of substrates and porous materials

A number of studies have been done on the substrate properties that have an effect on acoustical response. A study by Tittmann [24] illustrated the influence of saturation on the speed and attenuation of compressional and shears waves in porous materials.

Attenborough's model took into consideration the physical properties of materials to formulate a theory for sound propagation in porous materials. Knowing a number of physical parameters such as flow resistivity, porosity, layer thickness and structure shape factors, the acoustical properties of rigid porous materials can be predicted using Attenborough's theory [3].

A previous study by Oelze, O'Brien, and Darmody determined the acoustical attenuation coefficient and the speed of sound propagation to be a function of soil type (six soil types were classified) and different moisture contents. The results illustrated that, generally, the attenuation coefficients increase with compaction and water content [33].

Delany and Bazley determined the acoustical properties of a number of fibrous absorbent materials using transmission-line analysis. Their aim was to provide the expected value of the flow-resistance for materials [8].

Aylor's study on soil attenuation characteristics showed (Figure 13) better sound attenuation at low frequencies for the softer and more porous the soil surface [4].

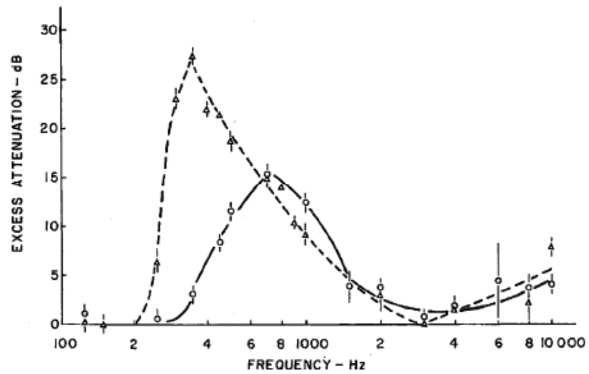


Figure 13. Excess Attenuation for a fine sandy loam (o) and for the soil after disking (Λ) vs. frequency [4]

The result from the recent study by Vander Heiden indicated that a thin soil layer provides a significant absorption coefficient, but increasing the soil depth more than 90mm did not result in a large change, Figure 14 [26]. Therefore, it can be understood that soil effects on absorption coefficient depend more on characteristics such as porosity and flow resistance rather than depth.

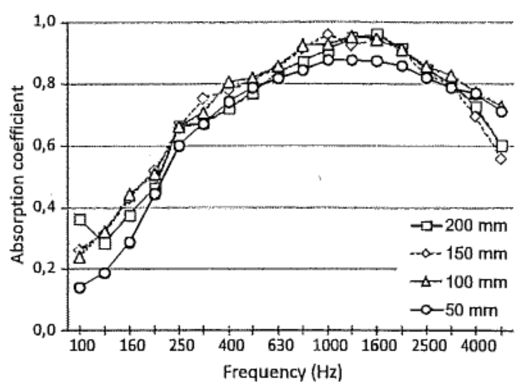


Figure 14. Absorption coefficient of top soil with different soil depth [26]

Examining the acoustical characteristics of green roof, it was confirmed by Connelly that there is a relationship between the plant community and sound absorption as well as between soil depth and absorption [44]. Connelly measured the absorption coefficient of vegetated roofs on a rooftop experimental set-up for three plant communities with a range of depths of substrates. The three different plant communities were selected based on their aerial biomass (foliage above substrate) and root system as structural differences in examining the absorption potential of green roofs. The results, shown in Figure 15, illustrate the increase in absorption coefficient of the substrate (without vegetation) with depth and frequency.

Figure 15 shows the absorption coefficient of the substrate on the rooftop. Absorption coefficient increases with frequency up to 1250 Hz then it stays constant at higher frequencies up to 4000 Hz. It also can be inferred that the absorption coefficient increases with depth [44].

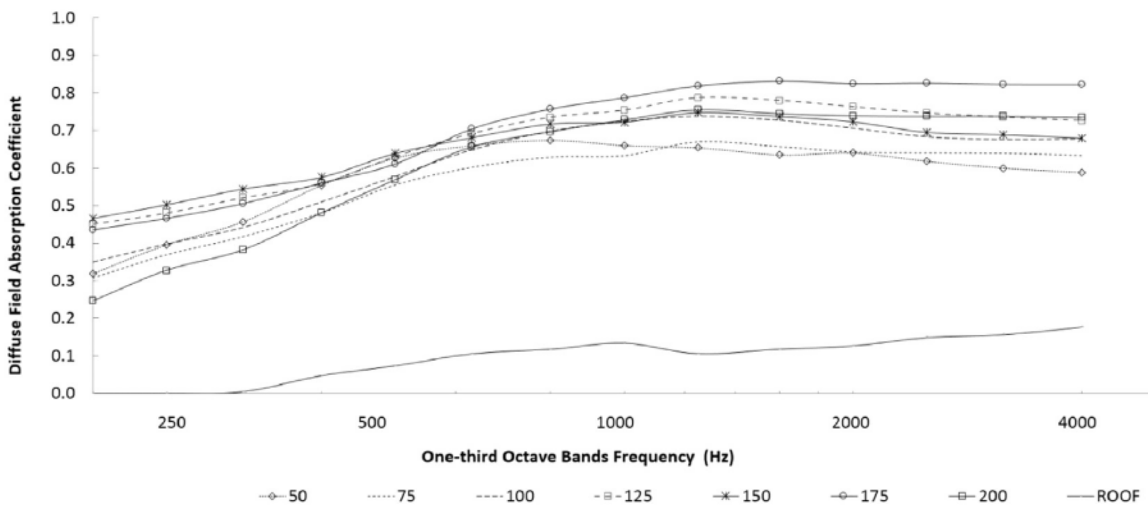


Figure 15. Measured third-octave diffuse-field absorption coefficients of reference roof and substrates of 50- to 200-mm depth in rooftop test plots. [44]

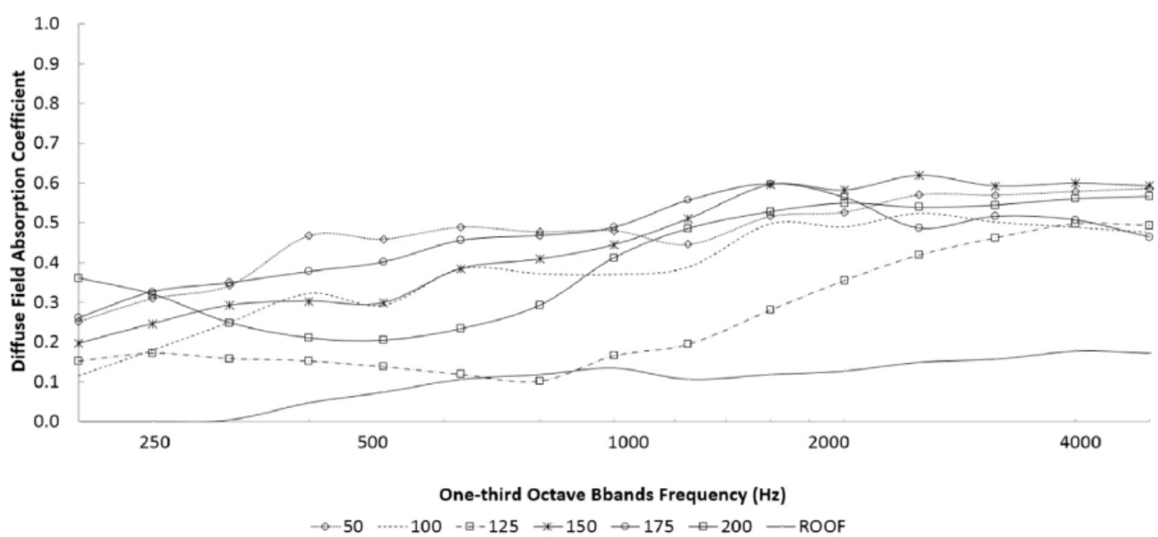


Figure 16. Measured third-octave-band diffuse-field absorption coefficients of rooftop test plots planted with sedums (P1). [44]

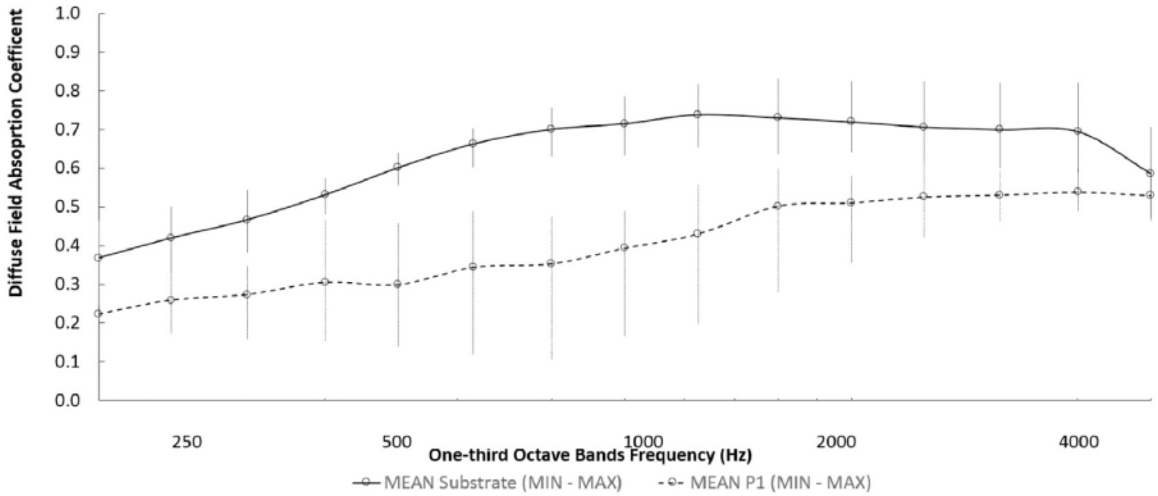


Figure 17. Measured third-octave-band diffuse-field coefficients of substrate and sedums (P1) in rooftop test plots. [44]

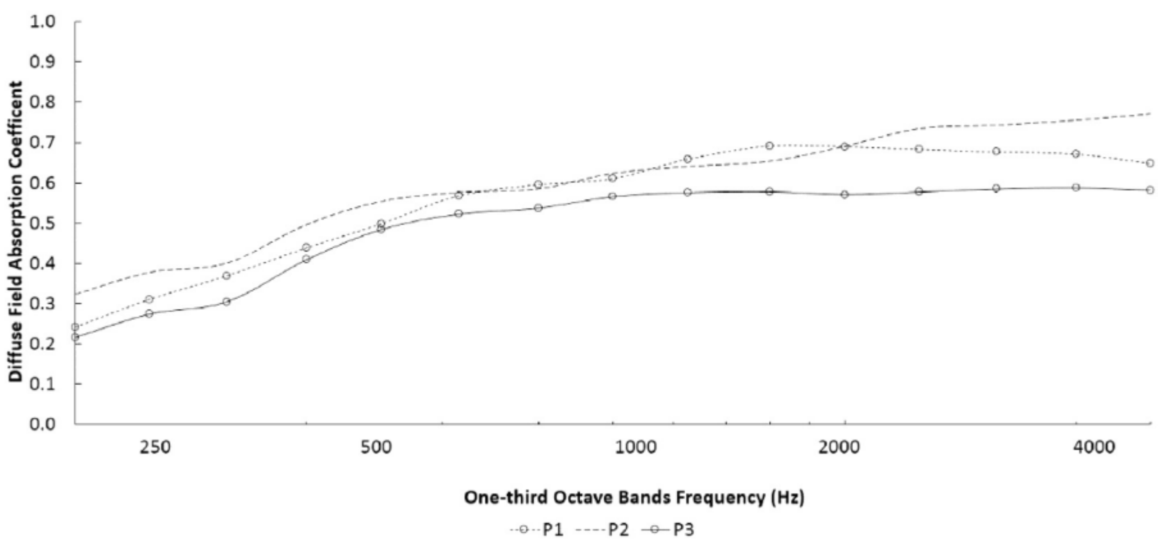


Figure 18. Measured third-octave-band diffuse-field absorption coefficients of 3 plant communities (substrate depths 125e200 mm) after 2 seasons of establishment [44].

Figure 16 and 17 from the same study [44] showed that with vegetation (established P1 community of planted sedum album and moss) the absorption coefficient trend of increase with soil depth was the same as the substrate only. Generally speaking plots with community P1 were less absorptive than the substrate plots. While the changes in absorption with frequency is similar for both (Figure 17).

Figure 18 shows that after two years of establishment 3 different plant communities have similar absorption trends. However, the range of absorptivity between three communities overlapped at some frequencies.

The study by Connelly showed that: the absorptivity of vegetated roof (living roof) is a function of substrate depth, establishment of plant community and moisture content of substrate [34].

Further research on the relationship of plant root structure to porosity and substrate mass, as the vegetation establishes over time, is required in order to measure and fully understand the impact of plant establishment on the effective absorption of the vegetated roof and wall material layer, substrate and established plant communities.

There has been little work completed on similar effects associated with soil depth, moisture and plant type in living walls. However, we can take some guidance from research on green roofs.

3.3. Material absorption and scattering; effect on room acoustics

All surfaces of the room absorb and reflect sound energy. Absorption removes sound energy from a room. Therefore, many factors such as ceiling height, room volume, surface types of all materials and any equipment in a room have a direct impact on the room's total sound level and sound absorption. Materials have sound absorption and scattering properties that can be quantified with frequency-dependent sound absorption and scattering coefficients.

Acoustical absorption results from friction and resonance phenomena. Absorption through friction is possible when using porous and fibrous materials, working best in the mid and high frequencies. If the above-mentioned material types are of adequate thickness or backed by air, they can be efficient in low frequencies as well. Resonant absorbers are efficient at low frequencies [31].

Neubauer and Kostek reviewed and compared several different reverberation models and their derivations, beyond Sabine (Equation 1), include Erying (Equation 2), Millington-Sette (Equation 3), Fitzroy (Equation 4) and Fitzroy-Kuttruff (Equation 5) [22]. In Figure 19, it can be observed that the values calculated using Tohyama and Eyring's model differ considerably with the result from the other formulae. It can be seen that Tohyama, Fitzroy, Arau tends to over predict the RT. It also showed that the new formula mentioned in the paper matches well with the measured reverberation time (RT).

Sabine's formula

$$T_{60} = 0.161\ V/A \qquad \textit{Equation 1}$$

Eyring's formula

$$T_{60} = (0.161\ V) / (-S \ln(1-\alpha)) \qquad \textit{Equation 2}$$

S - total surface area (m^2) .
α - average absorption coefficient.

Millington-Sette's formula

$$T_{60} = (0.161\ V) / (\Sigma(-S_i \,.\, \ln(1-\alpha_i)) \qquad \textit{Equation 3}$$

S_i - surface area of the material
α_i - its actual absorption coefficient.

Fitzroy's formula

$$T_{60} = 0.16\ V/S^2\ [(-x/\ln(1-\alpha_x))+(-y/\ln(1-\alpha_y))+(-z/\ln(1-\alpha_z))] \qquad \textit{Equation 4}$$

x, y, z - total areas of two opposite parallel walls in m^2,

α_x, α_y, α_z - average absorption coefficients of a pair of opposite walls,
S - total surface area of the room in [m^2],
V - total volume of the room [m^3].

Fitzroy-Kuttruff's formula

$$T_{60}= (0.32\ V/S^2)\ (h\ (1+w)\ /\ \alpha^*\ L.w\ /\ \alpha^*_{cf})$$ *Equation 5*

V, S - volume in [m^3] and total surface area of the room in [m^2],
h, w, l - room dimensions: height, width and length in [m],
α^*_{Lw}, α^*_{cf}- average effective absorption exponent of walls, ceiling and floor.

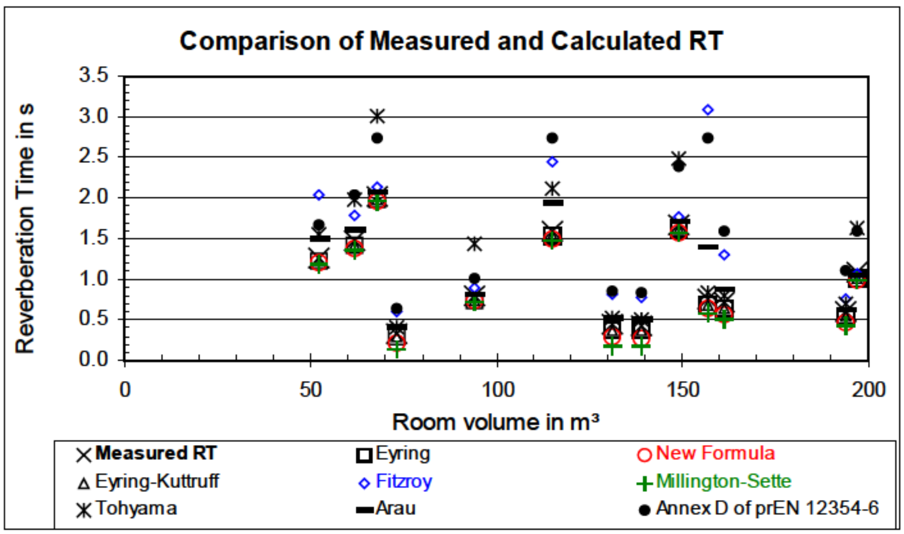


Figure 19. Comparison of measured and predicted reverberation time values for a room with a volume range of 50-200

Measurements by Ducourneau & Planeau showed that the change in average acoustical absorption depends on the relative distance between the sound source and the absorbent panels [14].

The currently used formulas to calculate the reverberation radius have been derived by the classic theories of Sabine or Eyring. However, these theories are only valid in perfectly diffused sound fields; thus, only when the energy density is constant throughout a room. Nevertheless, the generally used formulas for the reverberation radius have been used in any circumstance, regardless of the uniformity of the distribution of absorption. Arau-Puchades and Berardi has written the expression of the reverberation time as:

$$T = (0.16V/A_x)^{Sx/S} . (0.16V/Ay)^{Sy/S} . (0.16V/Az)^{Sz/S} \qquad \text{Equation 6}$$

The Arau-Puchades's formula shows that Fitzroy's theory was not completely correct, as it was only valid when the reverberation times in each direction (Tx , Ty , Tz) are equal, or approximately equal. A tendency for co- incidence of the Fitzroy's formula with the Sabine's and Eyring's formulas may occur depending on the closeness of the average absorption coefficients in every direction. However, whenever the reverberation times are well differentiated among the directions, then the Fitzroy's formula diverges significantly from theoretical results as recently shown in some round robin tests (Mehta, Mulholland , 1976; Istafa, Bradley , 2000; Ducourneau, Planeau , 2003). The new formula Equation 6 covers diffuse and non-diffuse sound fields, and appears as a general formulation of the theory of reverberation [46].

According to the data from Cavanaugh, it can be concluded that well–placed, correct amounts of absorptive materials in the room can control the reverberation characteristics of the room [31]. The study by Bistafa and Bradly validates this finding through changing the location and amount of absorptive materials in a classroom [5]. They also determined that spreading the absorptive materials around the room surfaces is more effective in controlling reverberation rather than putting them in one area. This work was followed up with further study that noted and ranked absorption surface design variations and their impact on producing a diffuse sound field [5]. These findings are very relevant to the potential effects of the living wall in that, living walls are typically installed on a limited wall area in a room

Acoustical scattering results from the roughness of the material, known as diffusing and diffraction due to edge and a limited surface size. Scattering does not remove the sound energy from a room but reduces specular reflection. Scattering from diffusion is not well understood. Scattering from diffraction is also not fully understood but is known to be dependent on incidence path lengths and angle of incidence. Vorlander and Mommertz introduced the scattering coefficient and defined it as: the total reflected energy minus Specular reflected energy [27]. Vorlander and Mommert's research on scattering has provided the methodology by which to define and measure the scattering coefficient for various materials. They compared the scattering coefficient of random incidence from the measurement of impulse responses from a free-field method and a reverberation chamber method for various orientations on a sample surface. The research identified the reverberation chamber method to be more consistent for measuring the scattering of reflective surfaces [27].

Sauro & Michael's research confirmed that all the energy from an incident sound wave is reflected as specularly reflected and scattered energy. In addition, the amount of scattered and specular energy depends on the wavelengths of the incident energy [40].

The study by Christensen and Rindel investigated the scattering of reflected sound, s_d (by diffraction, due to surface dimensions, angle of incidence, incident and reflected path-lengths), and surface scattering, s_s (roughness of surface material) [6]. A decreased sensitivity of rooms to the scattering coefficient of materials is due to increased sound field diffusivity.

Most numerical models look at absorption in terms of specular reflection only and ignore scattering.

Odeon software was developed for simulating the interior acoustics of buildings, using image-source method combined with ray tracing. Given a set of geometry and surface properties and absorption and scattering coefficients, the acoustics can be predicted, illustrated and analyzed. In Odeon surface diffraction and diffused diffraction are combined to estimate the reflection-based scattering. The scattering coefficient is defined as the amount of scattered sound energy in different directions over the total reflected sound energy, Figure 20.

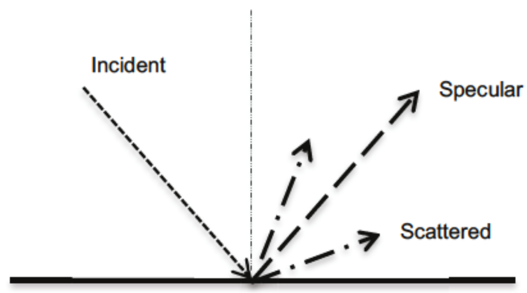


Figure 20. Vector base scattering

Most acousticians and designers have ignored the importance of scattering. This may be because of the fact that the scattering coefficient normally is not used in numerical algorithms. Measuring the total scattering coefficient in real life is difficult, and unless accurate it is not valid in software models such as Odeon and CATT-Acoustic. Previous research, such as the investigation by Navarro, et al showed a greater effect of scattering on the reverberation time for materials with a lower absorption coefficient. It showed a greater effect of the scattering coefficient on the reverberation time if the standard deviation of the average absorption coefficient is high [38]. Designers might jump to the conclusion that scattering can be ignored, and that they can resolve the room acoustics by using more absorptive materials, and by using materials with similar absorption coefficients throughout all the surfaces in the room. It also should be mentioned that the main barrier for using the scattering coefficient is the lack of determination on the scattering values of materials.

The focus of the research by Wang and Rathsam [16] was on the impact of the choice of scattering coefficients, location of absorption and amount of absorptive materials in the room on the predicted sound field using Odeon software in an empty room. The result of the study illustrated that if the model had mirrored reflective surfaces, it is more sensitive to scattering coefficients. Therefore, if a room has a large area of mirrored reflective surfaces, it will have a greater disparity of materials and a lower average absorption coefficient. In rooms with non-mirrored reflective surfaces, the area of absorption is the determining factor in its sensitivity to scattering coefficients. Sensitivity increases as the average absorption coefficient is decreased.

Huber and Bednar [35] studied the effect of the scattering coefficient on the reverberation time through simulation results from computer models (CATT-Acoustic v8.0f). First, they found that CATT was in good agreement with the reverberation time calculations according to Sabine and Eyring's algorithms with respect to absorption coefficient only. The results of their study illustrated that the low scattering coefficients produce high reverberation times in the simulation. Reverberation time is increased when the absorption coefficient is not uniform. From their results, it also can be understood that the influence of the scattering coefficient on the reverberation time increases with larger differences between the absorption coefficient of the different surfaces of the room and decreases with increasing the average absorption coefficient of the room. This study illustrated and summarized the significant influence of the scattering coefficient on the reverberation time.

Navarro, et al [38] evaluated the predicted values for reverberation time, absorption and scattering coefficients, from a geometrical acoustic model and the diffusion equation model. They were able to establish a range in which the predicted values, for absorption and scattering, from the mentioned models are in good agreement. Comparing the results, it was determined that the values from the diffusion equation model are closer to the values of the Ray-tracing software for homogeneous rooms with a scattering range greater than 0.6 and an absorption of less than 0.45. Therefore, it can be used to predict reverberation time in that range. The simulation results also showed a greater impact of scattering on reverberation time for smaller values of absorption.

Farina completed a series of experimental measurements of the scattering coefficient based on the wave field synthesis method [37]. The comparison of the results from her work was in good agreement with the numerical simulations. Her work described the extension of a numerical simulation, which becomes possible by development to the pyramid-tracing algorithm. Her technique makes it possible to derive the values of the scattering coefficient. The scattering coefficient was introduced as a new concept in ISO 17497-1, standard (2013) [12]. Which is an international standard for measurement of the random-incidence scattering coefficient in a reverberation room and will be reviewed in section 3.4.

To measure normal-incidence coefficients, absorption and scattering, Tetsuya, Hyojin and Kashiwanoha developed an alternative to Farina's method. However, it is not sufficiently developed yet for this research. Also, they developed a numerical simulation to determine the absorption coefficient and scattering but have only applied it to simple surfaces rather than the complex surfaces such as plants [36].

Shtrepi, et al research investigated the effect of scattering on six acoustical parameters of the room, reverberation time (T_{30}), clarity (C_{80}), strength (G), Early Decay Time (EDT), definition (D_{50}) and Lateral energy Fraction (LF) using Catt-acoustic software. Six different scattering values s= 10, 30, 50, 60, 70, & 90% was applied to room surfaces (ceiling, side and rear walls) to consider scattering variation in the measurement. From the results it can be illustrated that the distance between source and receiver greatly affect the acoustical parameters. From the findings it can be understood that by increasing the scattering coefficient value T_{30}, C_{80}, G and D_{50} values are decreasing. It was also found that LF and EDT are not affected by scattering [39].

A preliminary evaluation was done last year at BCIT in classroom 317 (NE1 building) as shown in Figure 18, with different configurations of newly planted living walls installed. A reduction in low frequency reverberation was observed according to the study results Figure 22. Absorption and scattering coefficient were not known and modelling was not validated [30].

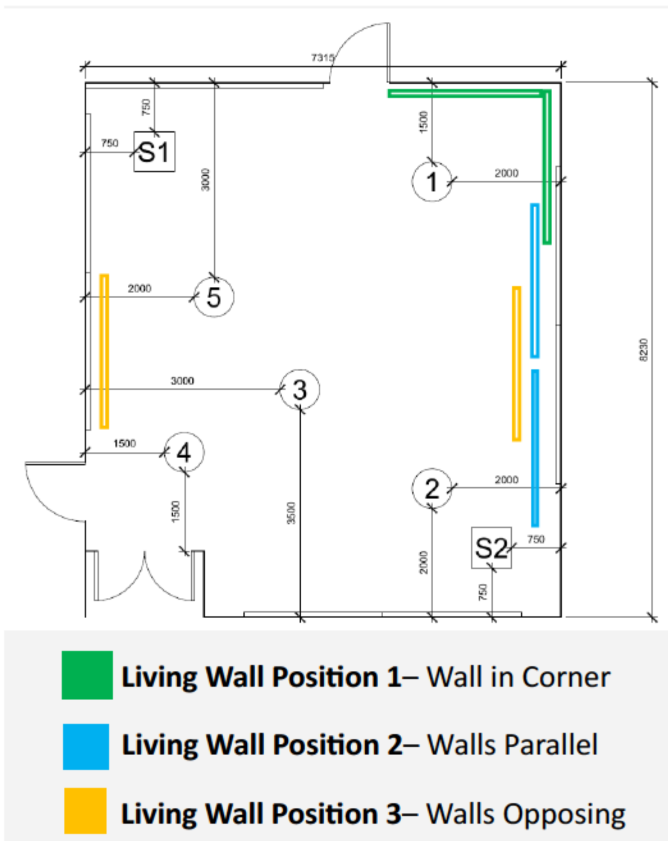


Figure 21. Putting ILW in different configuration in the classroom [30]

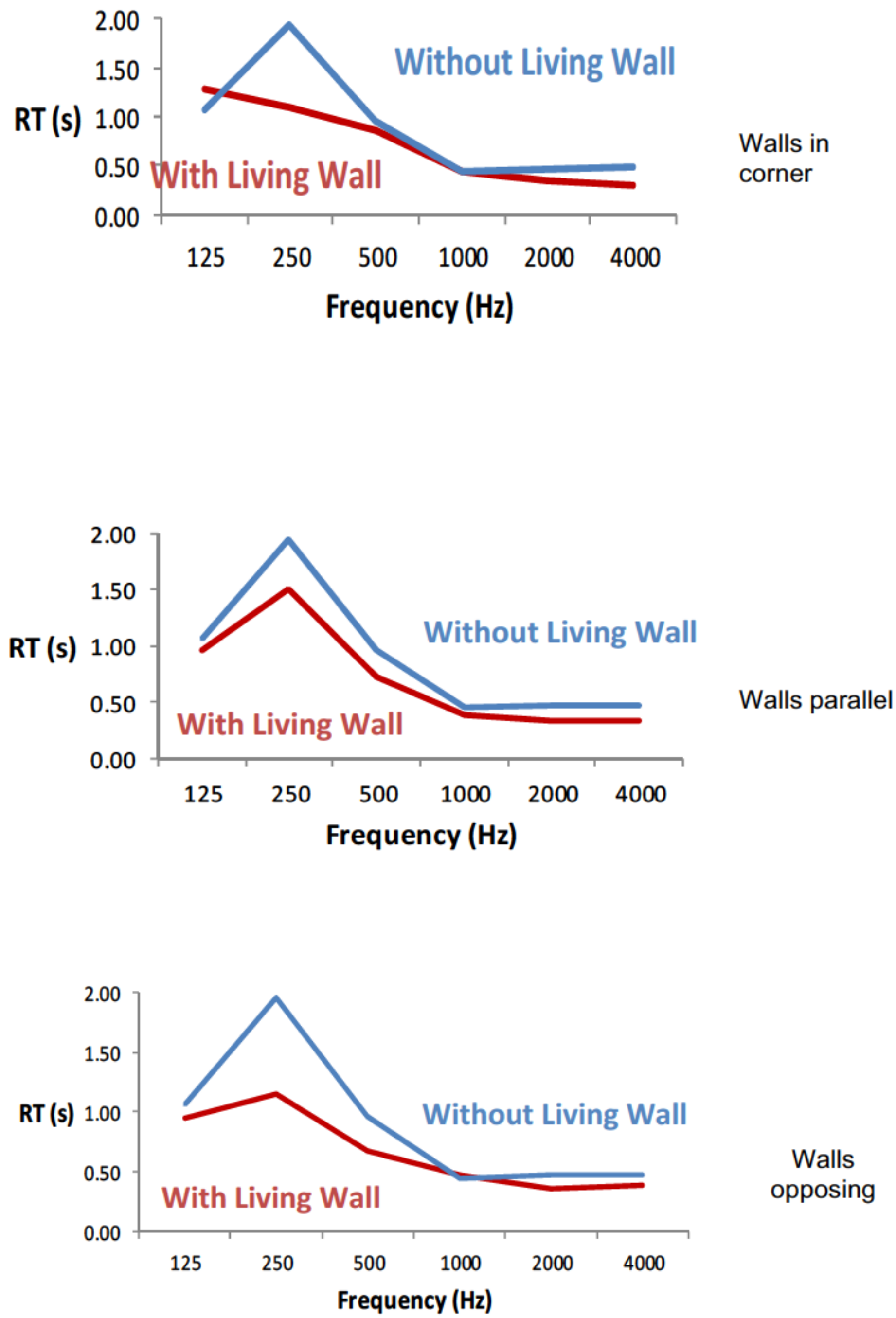


Figure 22. Reverberation time of the room with different configuration of living walls [30]

3.4. Experimental methods

3.4.1. Absorption

A number of methods used in previous studies relevant to this research can be mentioned: random-incidence absorption coefficient according to ISO 354[13] and random-incidence scattering coefficient based on ISO 17497-1 [12]. Van der Heijden measured free field sound pressure level and found absorption based on impedance tube methods [26]. Martens used Laser-Doppler-Vibrometer system for measuring the vibration velocity of small areas on the plants over a wide frequency range (0-100 Hz) [20]. Wong determined an absorption coefficient through insertion loss experiments in a reverberation chamber [29].

3.4.2. Scattering

Ronald and Michael provide suggestions to modify requirements and method recommendations by ISO-17497-1 standard in order to gather more accurate data. Their measurements on hundreds of full sized material samples illustrated that the shape and size of the samples are important in collecting the data. It is recommended that the structural depth of the sample for measurements should be less than 1/16 of the total sample diameter. And the diameter of the sample should be longer than 3.5 meter (137.8 inches) at full scale in order to get the more accurate measurements at low frequencies. The chamber door should be closed for 15 minutes before starting the measurements to let air movement in the chamber stabilize. During the measurement for each set, the temperature cannot change more than two degrees Celsius, also the relative humidity of the chamber must be constant and above 50%. The selected stimulus should have less sensitivity to temperature, humidity and air movement such as pink noise. The test samples on the turntable should be constantly rotated more than 3 complete turns. Because of the requirements of the simulation programs the frequency range should be extended from 100Hz to 10kHz [40].

Choi, et al used a scale model to investigate issues and ambiguities of random-incidence scattering coefficient measurement based on ISO 1749-1 [41]. They considered three parameters: the air gap below the turn table, the diameter of the turn table and test sample absorption. The results from their work showed that diameter of the turn table has an effect on the scattering coefficient values of the base plate at the high frequency bands between 1 kHz and 5 kHz. Increasing the air gap under the turntable to 50 mm leads in a higher scattering coefficient of the base plate. Also, changing the absorption of the test sample did not change the scattering coefficient significantly.

3.4.3. Reverberation time

The literature by Jambrosic, et al reviews three different methods of reverberation time empirical measurement in the field [32]. The methods are: the interrupted noise method, the integrated impulse response method and the burst method. Balloons were used in the burst method evaluation and an Omni-directional sound source was used for the two other experiments. The different methods were used to measure two rooms. The first room is a 230m^3 rectangular room, containing a number of acoustic materials, and the second room is an 800m^3 L-shape hallway with hard and reflective surfaces. The reverberation time measurements for the first room were more consistent compared with the second room. Figure 23 and 24 illustrate a better agreement at frequencies above 125 Hz in the rectangular room and above 1000 Hz in the L-shaped room. From this result, it can be concluded that all the mentioned methods for measuring reverberation time are usable in the experiment as long as there is powerful excitation to provide sufficient dynamic range. Limited measurements have been carried out on vertical greenery systems, such as, the study by Wong [29]. These findings will support the method of evaluation of living walls.

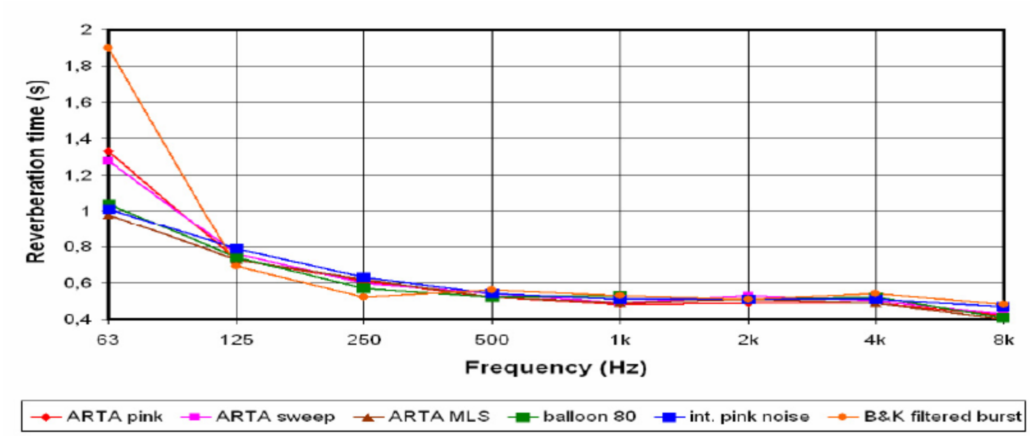


Figure 23. Room 1 at position 1 [32]

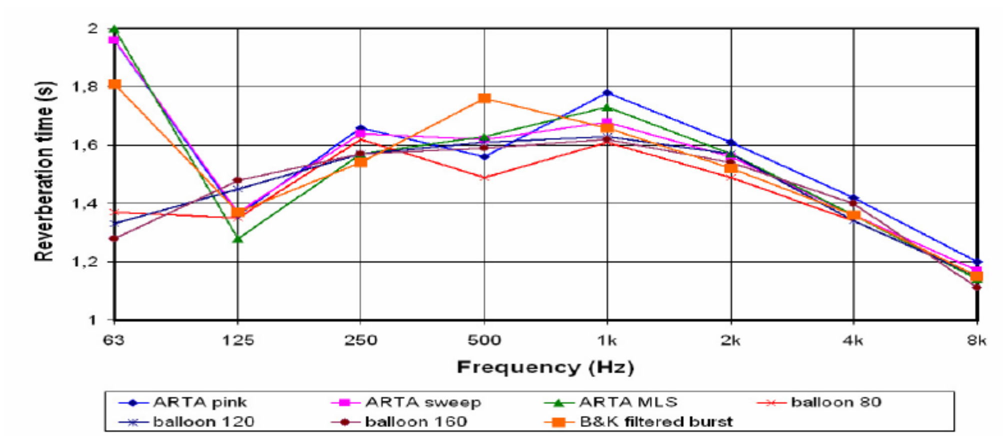


Figure 24. Room 2 at position 1 [32]

To investigate the acoustical benefits of interior living walls systematically, more details about the soil surface, the foliage, diffusion and absorption characteristics are needed.

3.5. Room criteria

There are commonly adopted criteria for background noise level, speech intelligibility index and reverberation time in different interior spaces. ASHRAE has many criteria for all uses and occupancies.
ASHRAE, LEED (Leadership in Engineering and Environmental Design) and ANSI S12.60 are guidelines for appropriate acoustics in school areas. These standards take into consideration the background noise, speech intelligibility, and reverberation time (which has an effect on the other criteria). Background noise level (BNL) can be identified by noise criteria (NC) curves. According to LEED (LEED for school-2009 IEQc9) the minimum acoustical performance recommended by the criteria in the classroom is NC 30-40 for spaces bigger than 20,000 SF, ASHRAE[1] recommends NC-30. Reverberation time should be less than 1.5 seconds and NRC (Noise Reduction Coefficient) rate of 0.7 in order to meet the LEED requirement or it should have T_{60} between 0.6 to 0.7 on the basis of the ANSI standard S12.60-2012 (Part 1).

Appropriate, strategically-placed materials and room geometry effect reverberation time, and a quiet HVAC system can decrease the background noise level. According to the study by Kang, appropriate absorptive characteristics of the room surfaces can improve speech intelligibility in the room. In internal spaces with acoustic defects such as echoes and long reverberation, selecting suitable scattering properties of boundaries is also important to improve speech intelligibility [15]. For high speech intelligibility, SII must be higher than 0.75, while for high speech privacy, it must be less than 0.2. The considered acoustical standards and criteria in this research are listed in appendix A.

[1] ASHRAE Handbook, Chapter 47, Control background noise levels in core learning space

4. METHODOLOGY

4.1. Scope and Hypotheses

The scope of this interdisciplinary research is focused on the absorption and scattering characteristics of living walls. The empirical data collection includes full scale absorption measurements of the constituent parts - carrier, substrate and plants for three available living wall systems, full scale absorption measure of fully established living wall systems. Plants were evaluated over time to establish the 1/3 scaled species, 1/3-scale absorption and scattering measurement of six different plant species.

From the findings of the literature review, it is expected that the substrate is the most significant component of living walls in terms of absorption, and plants are the most significant in terms of scattering. Additionally, the sound scattering of living walls significantly impacts the reverberation time and cannot be neglected in modelling. The plant coverage density is also important in terms of absorption and scattering, while the carrier type will not be significant. The interior living wall and its location, as a sound absorptive and sound scattering material, given the typical size of interior living walls will have an effect on reverberation time in rooms.

Parameters of substrate mixture, moisture content, and overall plant coverage investigated. Then the sound absorption and scattering coefficients from the reverberant chamber will be used to investigate the sensitivity of room modelling to the measured data.

4.2. Materials

The purpose of having three significantly different living wall systems is to see the effects of organic attributes like substrate and plants on the absorption and scattering of a broad representational range of market-established living wall systems. Of the three systems, two systems have soil-based substrates, while the third system has a fibrous wool-based substrate.

Figure 25. interior living wall system dimension. (Carrier Type A)

Figure 26. interior living wall system. (Carrier Type B)

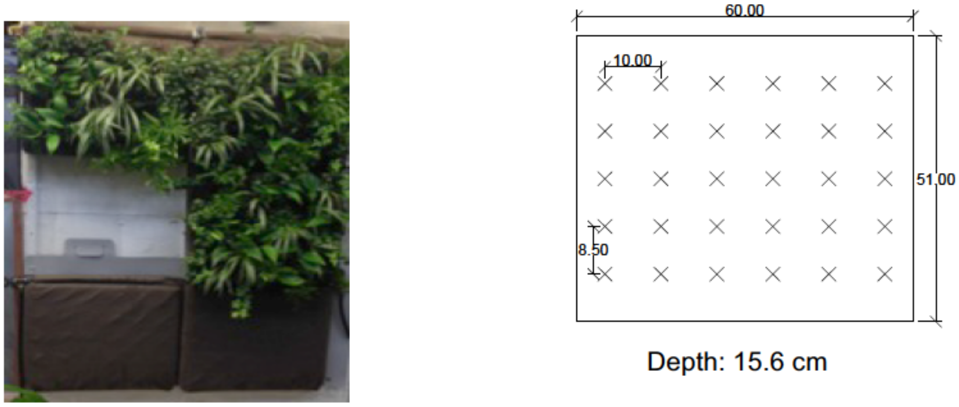


Figure 27. interior living wall system. (Carrier Type C)

System 1-Carrier A Figure 25**:** This is a soil-based living wall system with relatively low water consumption (about 220L per year/ per m²). The carrier is 100%-recyclable ABS plastic. The self-regulating, low-output drip irrigation network provides for the plants' water needs. Water overflow is drained directly through the bottom edge of the module. The design of the carriers makes it easy to plant and the system provides plenty of space for root development, the form of the carrier holds the substrate and roots securely inside.

System 2- Carrier B Figure 26**:** This system is a soil-based living wall system with relatively low water consumption (about 220L per year/ per m²) and uses a self-regulating, low-output soak hose which provides the plants' water (The panels are planted horizontally, and the soil is exposed). The carrier is made of stainless-steel, and can be used for both interior and exterior purposes. The form of the carrier presents the substrate as the vertical exposed face cannot hold the substrate until after the establishment of the plant roots (30-60 days after planting in a horizontal orientation).

System 3- Carrier C

Figure 27**:** Is a hybrid hydroponic living wall system. Constant irrigation is required to provide sufficient moisture content and nutrients for successful growth of plants

(about 220L per year, per m^2). The primary substrate in this system is mineral wool; however, the potting soil from 2-inch nursery pots inserted into the rock wool provides additional nutrients for the plants.

4.2.1. Substrate

Interior living walls need a specifically engineered and designed substrate that can stay stable in vertical growing situations and provide a healthy support for root growth. It is important that the substrate mix can provide a balance between water retention and drainage, and that the substrate should not compact over time. For the three living wall systems investigated a mix of 70% planting soil and 30% pumice (less than 15 mm in size) is used for the primary substrate. As secondary substrate comprised of 80 % planting soil and 20% pumice was also mixed for evaluation in the two soil-based living wall systems (Figure 28).

Figure 28. Soil Sample

The weight of samples for lab measurements are listed below in Table 1.

Table 1. Weight of the carriers, carriers with 2 different substrate mixture and planted carriers

		Systems		
No.		CTA (weight)	CTB (weight)	CTC (weight)
1	Empty Carrier	6.04 kg	10.92 kg	2.65 kg
2	Carrier with substrate (80% soil-20% pumice)	25.88 kg	32.70 kg	-
3	Carrier with substrate (70% soil-30% pumice)	26.80 kg	34.11 kg	-
4	Carrier with potting soil only	-	-	3.35 kg
5	Carrier with substrate in field capacity (70% soil-30%pumice)	27.30 kg	35.00 kg	3.79 kg
6	Planted carrier, (70% soil-30% pumice) (Mix vegetation)*	Mix_1= 30.20 Mix_2= 32.35 Mix_3= 34. 70	Mix_1= 38.62 Kg Mix_2= 39.44 Mix_3= 41.90	
7	Planted carrier, (70% soil-30% pumice)	-	1. Ivy=36.72 Kg 2. Spider=35.14 Kg 3. Pilea=45.54 Kg 4. Creep. fig= 42.36 Kg 5. Fern=40.74 Kg 6. Gold. Poth.= 43.86Kg	-
Note	CTA: Carrier Type A , CTB: Carrier Type B , CTC: Carrier Type C $Mix_{1,2,3}$ = to measure consistency in measurements I conducted three experiments with three of each carriers having the exact same mixture of plant`s species * All three systems were planted with 40 plants.			

Each panel (Carrier A, Carrier B and Carrier C) was planted using 40 pots, with a mixture of six available species. In order to verify the consistency reliability of the results for each carrier type three sets of experiments were conducted for each of the three test samples. In total 9 sets of experiments were conducted to make sure the results are consistent and repeatable. The results are discussed in section 5.2.2 (Figure 53-55) and show promising consistency.

4.2.2. Plants Description

Six available plants were studied, namely English Ivy (*Hedera helix*), Fern (*Filicophyta*), Golden Pothos (*Epipremnum aureum*), Pilea (*Pilea microphylla*), Spider Plant (*Chlorophytum comosum* 'Variegatum') and Creeping Fig (*Ficus pumila)*. The selected species differ in their properties (leaf thickness (mm), leaf length (mm), leaf area (mm^2), leaf mass live (mg), leaf mass dry (mg), stem diameter (mm), plant height (mm)), and will facilitate the examination of different plant properties' impact on sound absorption and scattering. Figure 29 illustrates each species, figure 30 illustrates the variance in plant structure and figure 31 illustrates the variance in plant leafs. Follow are short plant descriptions;

Short plants description

Ivy

Ivies have dark-green and waxy leaves, alternately arranged along the stems, Ivy grows well in sandy, clay and nutrient-poor soils. It grows to 235 mm in height, with stems up to 1.6 mm in diameter, in height in living wall systems [28].

Fern

Ferns are green flowerless plants with divided leaves that tend to grow in damp, shady areas. It grows to 514 mm height, with stems up to 1.47 mm in diameter in living wall systems [28].

Golden Pothos

Golden Pothos is a popular houseplant in temperate regions. The plant grows to 318 mm height, with stems up to 4 mm in diameter, climbing by means of aerial roots which adhere to surfaces. This plant produces trailing stems and requires little care. [28].

Pilea

Pilea have peculiarly puffy leaves with depressed veins. They required low light levels. Most Pilea (Glauca) grow no more than 299 mm tall, with stems diameter up to 1.1 mm. [28]

Spider Plant

The Spider Plant is one of the most common houseplants. It is easily grown and is especially popular for the ease and speed with which it forms new plants. Spider Plants grow quickly to 475 mm height in living wall systems. [28]

Creeping Fig

Creeping Fig is a woody evergreen vine and popular houseplant in cooler areas. It grows to 262 mm height, with stems diameter up to 1.4 mm. [28]

Figure 29. Images of the various species used for planting the living wall panels.

Figure 30. Six species under investigation (in pot)

Figure 31. Shape of the leaf of each species

4.2.3. Plant Properties

The plant species are characterized in terms of

- Leaf thickness (mm)
- Leaf length (cm)
- Leaf area (mm^2)
- Leaf mass (live) mg
- Leaf mass (dry) mg
- Stem diameter (mm)
- Plant height (mm)
- Leaf area index (LAI), when planted
- Total coverage, when planted

4.3. Measurement procedure of plant properties

Plant properties were determined from an average of three pots of each species type selected randomly from the plants reserved for the research project. The thickness of the leaves was determined using a digital caliper. Leaf area was measured from randomly selected leaves from each species. The leaves were traced and imported to AutoCAD and the area was determined with a polyline. Leaf mass was measured by dry and live weight. For live mass all selected leafs were weighted using a scale with the accuracy of 0.00 g (a 100 … of a gram) and averaged. To determine dry mass, the leaves were blotted to remove existing free surface moisture, dried in an oven overnight (around 105° F) and then weighted. Stem diameter (mm) was measured using a digital caliper. Plant height (mm) was measured with a ruler from the base substrate to the height of the tallest leaf in each pot. Leaf Area Index, defined as the area of leaves over surface area.

Scaled measurements of plants

In order to consider the use of plants for sound scattering measurement of the 1/3 scale model infrastructure, the plant characteristics were measured repeatedly over time, as the plants changed with growth. The results of all measurements were compared to the result of the fully-grown species characteristics. From this investigation, it was determined that it was only possible to scale the plant species in terms of the live leaf mass. In this manner, a 1/3-scaled plant was determined for scaled acoustic measurements.

Figure 32 illustrates the process of the establishment of the plants in the living wall systems.

Figure 32. Preparation phase at the Center for Architectural Ecology (BCIT). The living wall panels were developed as joint experiment set-up with Ivan Cheung (UBC, The impact of living walls on indoor air quality).

4.3.1. Absorption

Absorption coefficient were measured and calculated based on ISO 354 [13] and ASTMC423-08a in a reverberation chamber of 88 m³ at BCIT Figure 33. The chamber width, length, height ratio is 1:1.29:1.56 as per ASTM E 90-98. The room was designed to create a diffuse sound field with a uniform distribution of acoustic energy and random direction of sound incidence over a short time period. According to study by Connelly the low-frequency cut off of the chamber is 177 Hz [7]. Spatial variation of SPL is shown to be within 1.5 dB at all frequencies above 177 Hz.The change of impedance at the boundary of the concrete room surfaces between air and concrete is so large that almost all of the acoustic energy that is incident on the room surfaces is reflected back into the room. Due to the diffused sound field and the use of a broadband sound source, the resulting sound field contains acoustic energy across the whole audible range. The absorption of the room and its content sound field is calculated based on the assumptions that the incident sound field is diffuse before and during decay and that no additional energy enters the room during decay [2]. In this study setup the low-frequency cutoff was determined to be 315 Hz.

Sound absorption are a function of frequency and measurements will be made across a series of frequency bands, in one-third-octave bands from 177 Hz to 4000 Hz. As statistical model the result of each test is from averaging 50 measurements (n=50).

Photo credit: commons.bcit.ca

Figure 33. Reverberation Chamber at BCIT

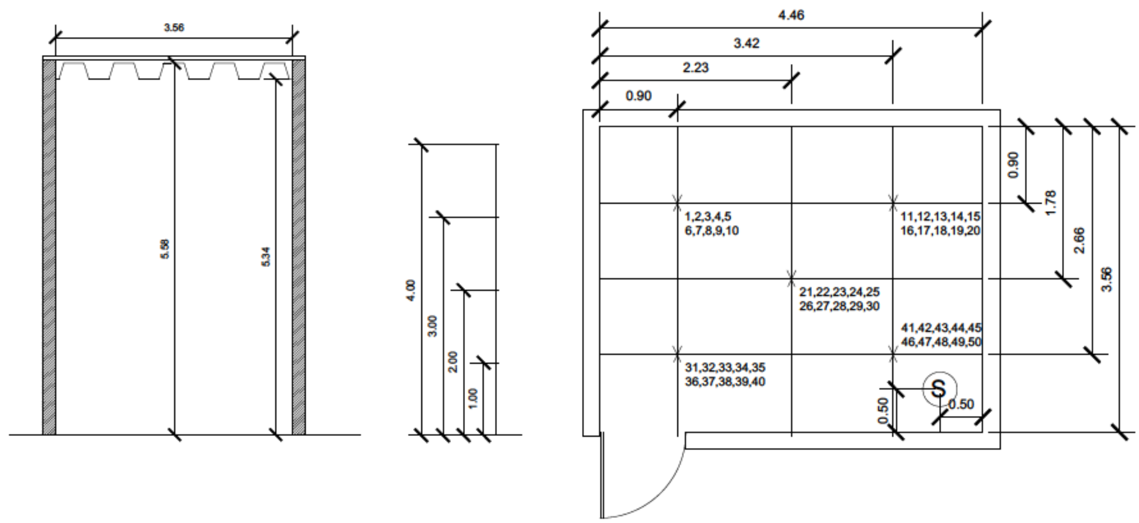


Figure 34. Microphone (X) and source (S) position plan

To find the absorption coefficient, RT was determined with impulse response measurement using WinMLS software. These test methods determine the sound absorption in a reverberation room by measuring decay rate. The sound absorption was measured before and after placing the test specimen in the chamber. According to Bibby`s study changes in temperature and relative humidity during the RT measurements can have a significant impact on the test results [42]. Therefore, all attempts were made for the measurements to be completed under similar climatic conditions, and variance in temperature and RH is accommodated during post-measurement analysis. Sound absorption was also measured in a process of obtaining the scattering coefficient at 1/3 scale and is discussed in the following section. As illustrated in figure 34, absorption of each sample was averaged over 50 measurements; (each set of measurement were taken at five different points, every point has three spots with different height, and the whole measurement at each point was done twice). See Appendix 4 for equipment list and specifications.

Acoustical absorption of each component of the interior living wall was calculated from the Sabine formula (see Equation 1).

$$A = A_2 - A_1 \qquad \textit{Equation 7}$$

A= Absorption of the specimen, m^2

A_1= Absorption of the empty reverberation room, m^2

A_2= Absorption of the room after

$$\alpha = (A_2 - A_1)/S + \alpha_1 \qquad \textit{Equation 8.}$$

In order to access the living wall and investigate the contribution of each component (carrier, substrate, plant) a series of tests were executed. The first series evaluated a single empty panel of each system. The second series evaluate the single panel of each system filled with substrate. The absorption of two different substrate mixes in the Carrier A and Carrier B were evaluated. Also two levels of moisture content were evaluated for the Carrier A and carrier C filled with substrate. The third series of tests evaluated each system with a mix of all six species. Also Carrier B was planted with each of the six species individually to assess the absorption of each plant species (Section 5.2.2 Figure 57). In this series the panels were evaluated individually and in groups of 3 Carrier A panels, 4 Carrier B panels and 8 Carrier B panels in order to consider the effect of panels multiplier in sound absorption (Appendix 5). In that the area does not meet ASTM 423 standard for sample size. The data is presented as comparative in Δ Sabine.

In to access the consistency of the measurements

Each panel (Carrier A, Carrier B and Carrier C) was planted using 40 pots, with a mixture of the six available species. In order to verify the consistency and reliability of the results for each carrier three test samples were established. For each carrier type three sets of measurement were conducted (Mix_1, Mix_2, Mix_3). In total 9 sets of measurement were conducted to ensure that the results are consistent and repeatable. The results are discussed in Section 5.2.2 (Figures 53-55) and show promising consistency. This series of evaluations are summarized in Table 2.

Table 2. Table of test in the reverberation chamber- full scale absorption test

Test No.	Description ASTMC423-08	Species
1	Empty reverberation chamber	-
2	Turning table (1/3 scale)	-
Carrier panel		
3	Carrier Type A (CTA)	-
4	Carrier Type B (CTB)	-
5	Carrier Type C (CTC)	-
Carrier panel with substrate		
6	CTA with Substrate (S_1: mixing rate of pumice / pot soil = 20%/80%)	-
7	CTA with Substrate (S_2: mixing rate of pumice / pot soil = 30%/70%)	-
8	CTB with Substrate (S_1)	-
9	CTB with Substrate (S_2)	-
10	CTC with Substrate (PS)	
11	CTA with Substrate (S_2),field Capacity	
12	CTC with Substrate (PS), Fieled Capacity	
Fully established panels		
13	CTA, S_2 (Sample 1)	Mix_1
14	CTA, S_2 (Sample 2)	Mix_2
15	CTA, S_2 (Sample 3)	Mix_3
16	All three CTA	Mix
17	CTC, S_2 (Sample 1)	Mix_1
18	CTC, S_2 (Sample 2)	Mix_2
19	CTC, S_2 (Sample 3)	Mix_3
20	CTB, S_2 (Sample 1)	Mix_1
21	CTB, S_2 (Sample 2)	Mix_2
22	CTB, S_2 (Sample 3)	Mix_3
23	CTB, S_2	P_1= English Ivy
24	CTB, S_2	P_2= Fern
25	CTB, S_2	P_3= Golden Pothos
26	CTB, S_2	P_4= Pilea
27	CTB, S_2	P_5= Spider Plants
28	CTB, S_2	P_6= Ficus pumila
29	4 CTB	Mix
30	8 CTB	Mix
Note 1	- 10 times in 5 microphone location	

4.3.2. Scattering

Measurements for random-incidence scattering coefficient were carried out according to ISO 17497-1 [12] in the reverberation room. The BCIT reverberation chamber is 88 m^3 therefore, scattering measurements are conducted at 1/3 scale. The 1/3 scaled turning table that was built according to standard as shown in Appendix 3 [45]

A periodic pseudo-random noise signals (MLS) is used to gain the impulse response. RTs in one-third octave bands were averaged over 50 source-receiver positions (Figure 34 and 36). The duration of the measurement for each source-receiver position was equal to one complete rotation of the turntable (60 seconds for one complete rotation of the turntable). The impulse response was evaluated based on ISO 354 (using the calculated values for T_1, T_2, T_3, T_4). Reverberation time of the empty room (T_1) and the reverberation time with the sample in the room (T_2) was measured on a non-rotating turntable. Additionally, the reverberation time when the turntable is rotating (T_3) and while the round table is rotating with the test sample (T_4) was measured.

The scattering coefficient, s, was calculated as follows:

$$\alpha_S = 55.3\ V/S\ (1/c_2 T_2 - 1/\ c_1 T_1) \qquad \textit{Equation 9.}$$

$$\alpha_{spec} = 55.3\ V/S\ (1/\ c_4 T_4 - 1/c_3 T_3) \qquad \textit{Equation 10.}$$

Where:

α_s= random-incidence absorption coefficient

α_{spec} = random-incidence specular absorption coefficient

V = volume of the reverberation room (m^3)

c = speed of sound (m/s)

T_{20} = reverberation time

4.3.3. Scattering Measurements

In order to investigate the impact of the type of species and the density of vegetation in the sound absorption and sound scattering, the series of tests were executed and listed in table 3.

To ensure the accuracy of any sample the scattering coefficient of the base plate was first measured, to confirm that it is lower than the specified maximum frequency-dependent scattering coefficient from 160 to 4000 Hz according to ISO 17497-1 [12]. Figure 35 shows that the scattering coefficient of the base plate is well below the ISO criteria. Figure 36 illustrates the location of the base plate, microphone positions and sound source for the scaled measurements.

Investigation determined that the substrate effect in scattering is negligible therefore it could act as a base plate.

The scattering coefficient of Substrate (30% pumice, 70% potting soil)

In order to calculate scattering from plants foliage while planted in substrate, it was necessary to verify that the substrate conforms with the standard criteria for a base plate (turning table). Illustrated in figure 35. According to ISO 17497-1 [12], the scattering coefficient for a base plate used in measurement should not exceed the maximum plotted in Figure 35. As the figure illustrates the turning table, covered with 100 mm of substrate, meets the standard criterion; as the base plate for all our scattering experiments.

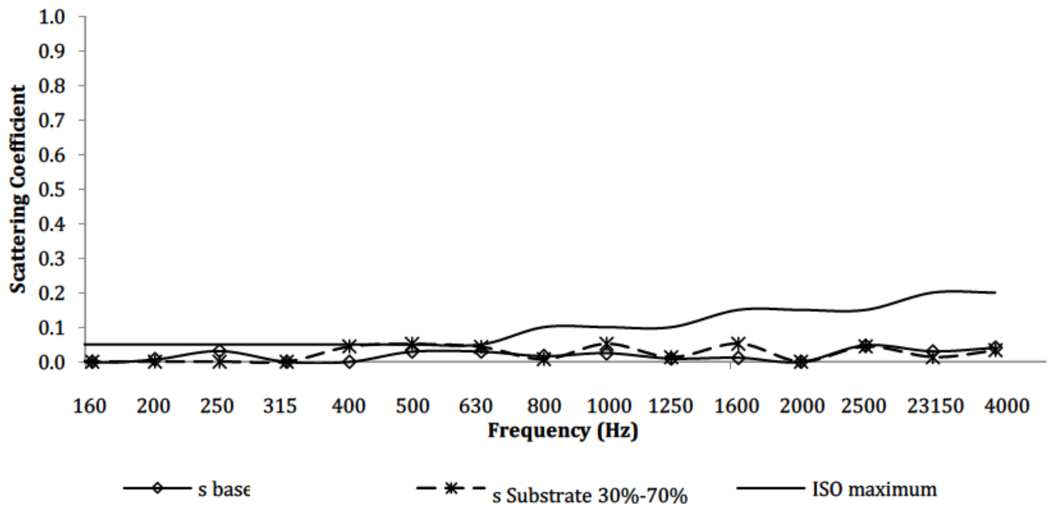


Figure 35. Scattering Coefficient of base plate and substrate (30% pumice, 70% soil)

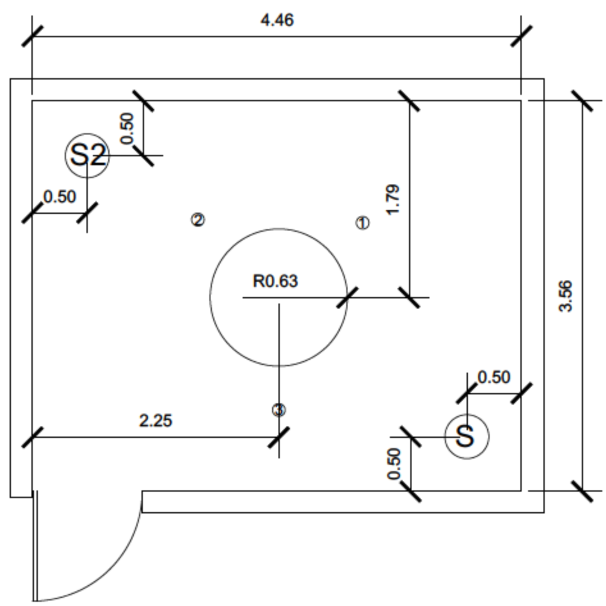


Figure 36. Microphone, turning table and source position plans

When scattering coefficients are determined through scaled measurement, all aspects of the experimental set-up must be scaled, this includes the material under test and the sound wave lengths. The measurements were made from 160 Hz to 3150 Hz. 160 Hz is the low frequency limit of the reverberation chamber, these measurements represent the full scale frequency range of 583 Hz to 10000 Hz.

The plants cannot be scaled, however the plant species evaluated at specific time periods growing with respect to scaling these materials. After full growth the 1/3 scale plant was determined and the measured data was used for analysis.

To examine the effect of vegetation coverage on sound absorption and sound scattering coefficient, coverage was gradually decreased by removing plants while keeping the distribution of plants even across the substrate surface. Sound absorption coefficients and scattering coefficients were measured for three levels of vegetation coverage on top of the turning table: 112 plants planted in 4-inch pots (100% of maximum coverage); 56 plants (50% coverage); and 28 plants (25% coverage) (Figure 37). The section of the sample arrangement on the turning table (base plate) is shown in figure 38.

Table 3. Table of test in the reverberation chamber- 1/3 scaled

Test No.	Description ISO 17497-1	Species
31	Empty Table	-
32	S_2 with	-
33	S_2 -100% cov	P_1= English Ivy
34	S_2 -100% cov	P_2= Fern
35	S_2 -100% cov	P_3= Golden Pothos
36	S_2 -100% cov	P_4= Pilea
37	S_2 -100% cov	P_5= Spider Plants
38	S_2 -100% cov	P_6= Ficus pumila
39	S_2 - 50% cov	P_1= English Ivy
40	S_2 - 50% cov	P_2= Fern
41	S_2 - 50% cov	P_3= Golden Pothos
42	S_2 - 50% cov	P_4= Pilea
43	S_2 - 50% cov	P_5= Spider Plants
44	S_2 - 50% cov	P_6= Ficus pumila
45	S_2 - 25% cov	P_1= English Ivy
46	S_2 - 25% cov	P_2= Fern
47	S_2 - 25% cov	P_3= Golden Pothos
48	S_2 - 25% cov	P_4= Pilea
49	S_2 - 25% cov	P_5= Spider Plants
50	S_2 - 25% cov	P_6= Ficus pumila
Note	- In 50 microphone location - S_2: Substrate with mixing rate of pumice / pot soil = 30%/70%	

Data of table 1 & 2 collected at each above test.

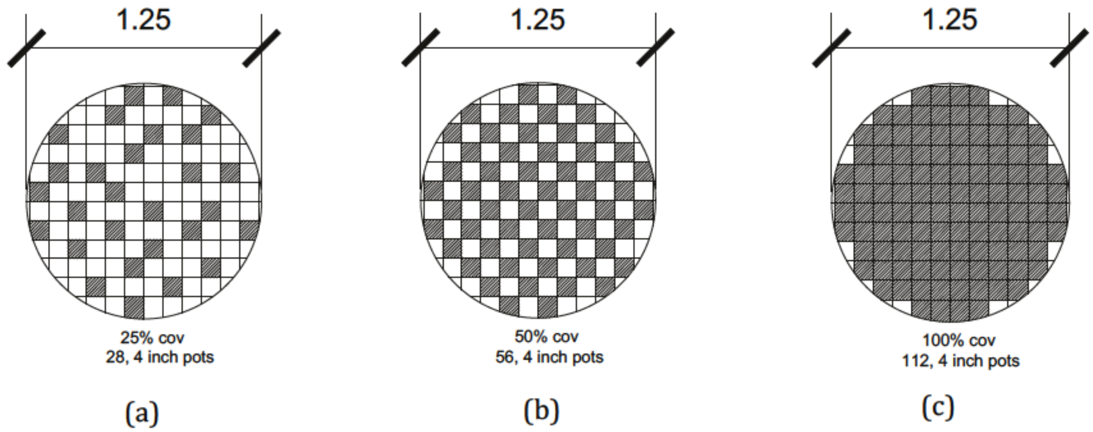


Figure 37. The section of the plant sample arrangement on the round table.

Figure 38. Vegetation coverage percentage for 1/3 scale measurement on turntable.

Measurement Accuracy

The measurement of each sample used to determine the scattering and absorption coefficients is from the average of the measurements taken from several microphone positions. In order to change the microphone position, opening of the door, to enter the chamber creates changes in temperature and humidity. Measurement is highly sensitive to temperature and relative humidity factors, especially at high frequencies [44]. Given uncertainty in the measurements which comes from the limited control over the temperature and humidity in the reverberation chamber, the accuracy of the measurements was increased by waiting for approximately 30 min after closing the door to allow the test specimens to adjust to the temperature and humidity in the reverberation chamber.

5. Result

5.1. Plant properties (Physical properties of the plants studied)

The Tables 4, 5 and 6 illustrate the plant properties of each species based on plant growth during 6 months. Plant properties were evaluated 4 times over 6 months as described in methods section, the time-determined plant properties are listed in Table 4.

By comparing the measurements of the plant properties measurements (leaf thickness, leaf length and etc.) over 6 months (T_1, T_2, T_3) with fully grown plant property measurements (T_4) it was determined that the species were at 1/3-scale of the fully grown species at time T_2. Comparing the plant properties for full-scale (at T4) and 1/3-scale (at T2) sets of measurements in Table 4, indicates that the mass of the plants scaled equally with time for all 6 species and that there was no correlation between the properties other than their live and dry mass. The Leaf Area Index (LAI) has been measured only for 1/3-scale species (T_2), as all measurements at turning table was done at 1/3-scale.

The sound absorption measurements for the living walls and the LAI calculations (Table 6) were carried out only for the full scale species (at T_4).

Table 4. The characteristics of plant leaf specimen

No.		Plant`s characterization							
	Plant Species	Leaf thickness (mm)	Leaf length (cm)	*Leaf area Index (LAI)	Leaf area Average (mm^2)	Leaf mass (live) mg	Leaf mass (dry) mg	Stem diameter (mm)	Plant height (mm)
10	English Ivy -T_1	0.34	3		0.0009		0.01	1.19	124
11	English Ivy -T_2 (1/3 scale)	0.379	3	154.54	0.001	0.09	0.02	1.36	177.96
12	English Ivy -T_3	0.391	43	-	0.0012		0.03	1.52	184
13	English Ivy –T_4	0.4	5	-	0.0013	0.22	0.04	1.6	235
14	Fern -T_1	0.3	4	-	0.005		0.007	1	109
15	Fern -T_2 (1/3 scale)	0.338	5.5	505.48	0.007	0.08	0.01	1.073	199.92
16	Fern -T_3	0.666	1	-	0.001		0.02	1.321	228
17	Fern -T_4	0.68	1.5	-	0.002	0.21	0.03	1.47	514
18	Golden Pothos -T_1	0.52	6	-	0.0019		0.042	2.221	176
19	Golden Pothos -T_2 (1/3 scale)	0.582	7.7	48.29	0.003	0.52	0.06	2.942	240
20	Golden Pothos -T_3	0.63	9.2	-	0.0038		0.09	3.6	291
21	Golden Pothos -T_4	0.65	1	-	0.004	1.26	0.15	4	318
22	Pilea -T_1	0.45	1	-	0.00017		0.013	1	120
23	Pilea -T_2 (1/3 Scale)	0.492	1.7	814.57	0.0002	0.04	0.02	1.02	135.9
24	Pilea -T_3	0.527	2.2	-	0.00022		0.034	1.612	237
25	Pilea -T_4	0.53	2.5	-	0.00023	0.11	0.04	1.1	292
26	Spider Plants -T_1	0.44	1.1	-	0.003		0.02	-	166
27	Spider Plants -T_2 (1/3 Scale)	0.495	18.8	141.66	0.0034	0.79	0.06	-	216.45
28	Spider Plants -T_3	0.741	3.9	-	0.004		0.15	-	383
29	Spider Plants -T_4	0.9	5	-	0.0048	2.44	0.19	-	475
30	Creeping Fig -T_1	0.31	1	-	0.00036		0.081	1.197	98
31	Creeping Fig -T_2 (1/3 Scale)	0.319	2	643.93	0.00040	0.04	0.01	1.215	135
32	Creeping Fig -T_3	0.331	2.7	-	0.00052		0.016	1.35	195
33	Creeping Fig -T_4	0.34	3	-	0.00056	0.07	0.02	1.4	262
	Note	- T_1, … T_n (max; n=4) to be determine base on plant growth during 6 months period *Leaf Area Index of each species at the turning table							

Table 5. Full scale and 1/3 scale plant properties

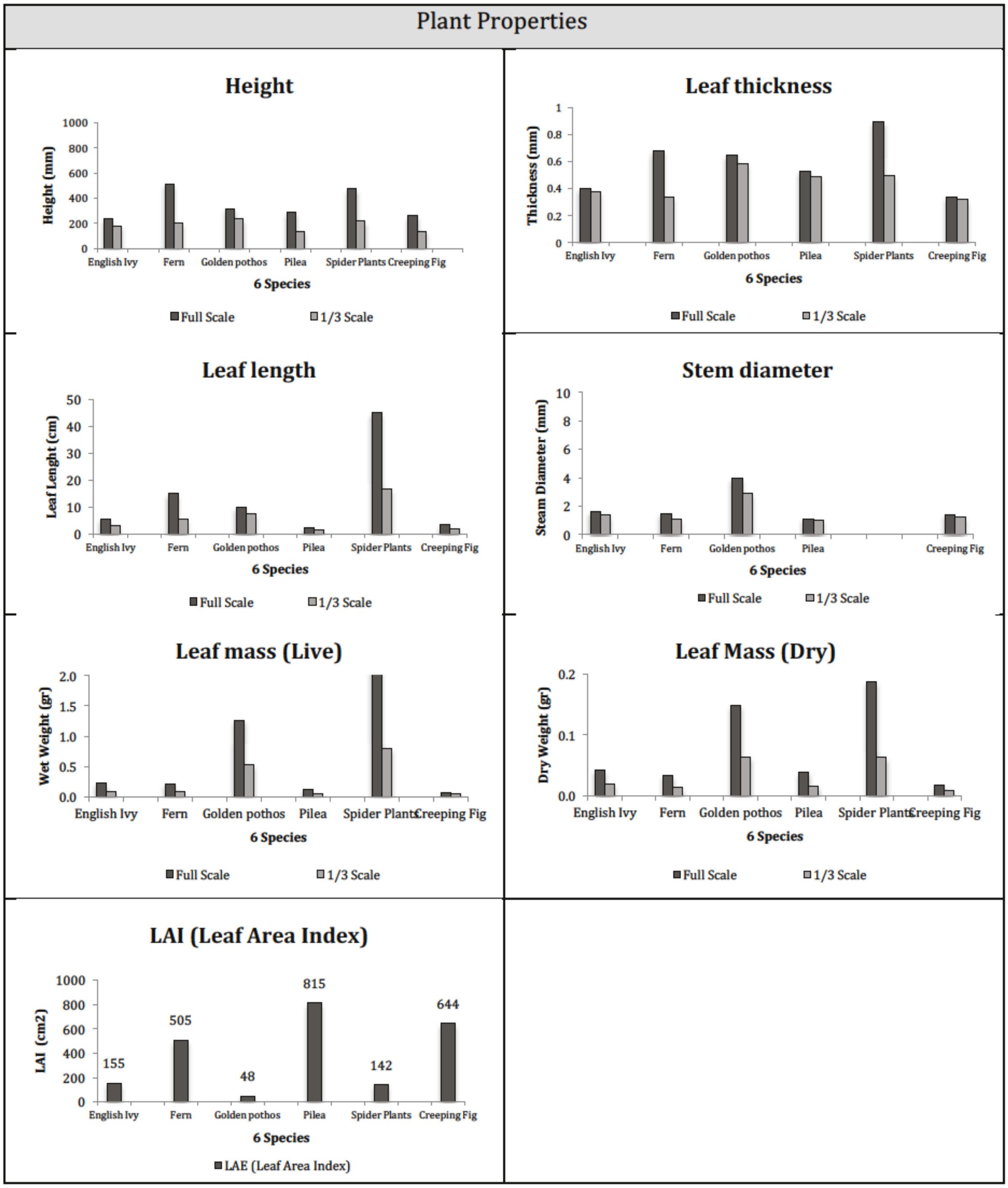


Table 6. The Characteristics surface area of plants

No.	Sample	Leaf area Index (LAI) of planted carriers
1	CTA (Carrier Type A) , mix plants	224
2	CTB (Carrier Type B), mix plants	561
3	CTC (Carrier Type C), mix plants	652
4	CTB, S_2 with P_1 (English Ivy)	574
5	CTB, S_2 with P_2 (Fern)	1744
6	CTB, S_2 with P_3 (Golden Pothos)	583
7	CTB, S_2 with P_4 (Pilea)	678
8	CTB, S_2 with P_5 (Spider Plants)	1699
9	CTB, S_2 with P_6 (Ficus pumila)	894
Note	S2 : Substrate with mixing rate of pumice/ poting soil = 30%/70%	

5.2. Absorption and Scattering

5.2.1. Absorption of Empty Room:

The chamber is highly reverberant and absorption of the chamber increases insignificantly with increasing frequency. Figure 39 shows absorption total in Sabine of the empty reverberation chamber. The sound absorption of the reverberation chamber (Figure 39) is less than 0.08 Sabine for frequencies between 177 and 4000 Hz.

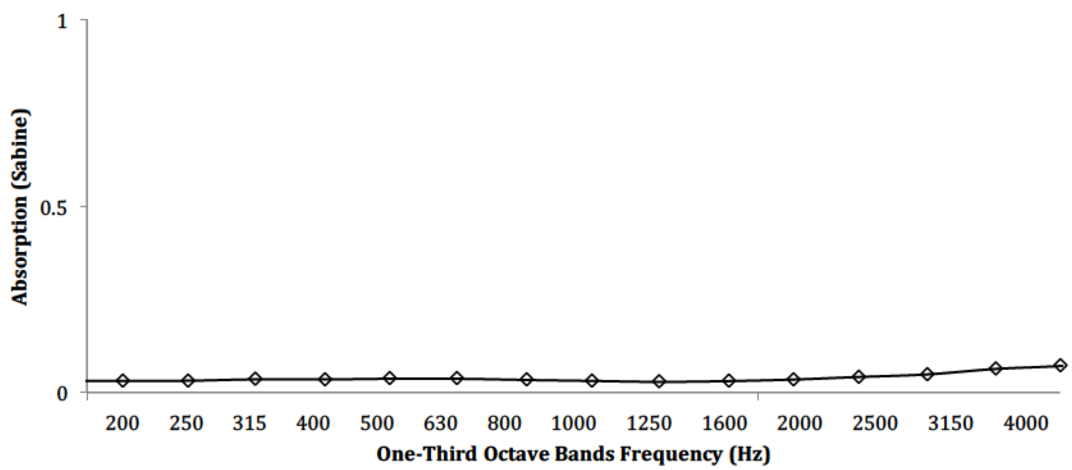


Figure 39. Absorption (Sabine) of empty reverberation chamber

5.2.2. Absorption of living wall systems:

The absorption for all full scale measurements are in Sabine units. The first set of results is for a single panel of each carrier type (Figure 40), the second set is of the single panel of each carrier type with two different mixtures of substrates (Figure 43), and third set is of the fully established vegetated living wall systems of each carrier type (e.g. Figure 48). It should be mentioned that with the high absorptive sample in the room the room is no longer diffuse around 315 Hz which generated artificial results.

Empty living wall Carrier panel

Figure 41 compares the absorption of three empty panels constructed with various materials and geometry: Carrier A, Carrier B and Carrier C. The overall trend is the same for all; the absorption rises slightly from low to high frequency. The empty Carrier C has a higher absorptivity than Carrier A and Carrier B at frequencies below 1600 Hz. The absorption of Carrier A and Carrier B follows the same trend, while the Carrier B system is more absorptive at frequencies above 500 Hz and its absorption increases with frequency.

(a) (b) (c)

Figure 40. The measurement condition of random-incident Absorption of three different empty living wall panels; (a) Carrier A, ((b) Carrier B (c) Carrier C

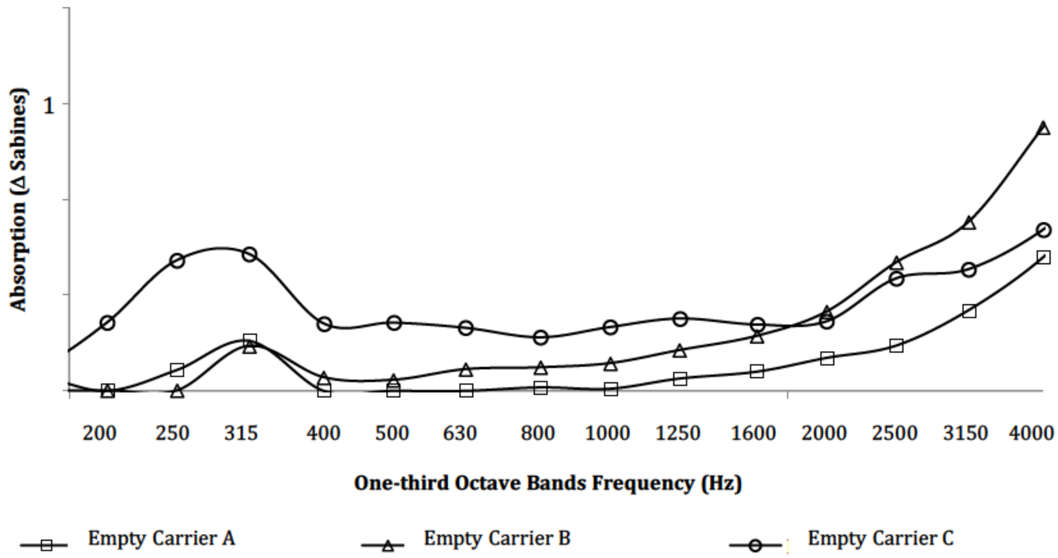


Figure 41. Comparison of absorption (Δ Sabine) of empty carriers

Living walls carrier panel with substrate

The presence of substrates significantly affects the absorptive capacity of the carrier. Figure 42 illustrates absorption of the living wall carriers filled with substrate. The overall trend shows increasing absorption with frequency. At mid frequency the system has similar absorption. At frequencies above 1770 Hz, the carrier B is the most absorptive. The trend of the graphs of Carrier A and Carrier B are similar to each other starting at 800 Hz. While following the same trend, the absorption coefficient of Carrier A is about 0.2 more than Carrier C at all frequencies from 800 Hz to 4000 Hz. Recall that Carrier C is a hydroponic system. This system has a nominal amount of potting soil in it, which is only the soil that comes with the plants from the 2-inch pots. (Refer to Section 4.4 for detailed specifications of each carrier system.)

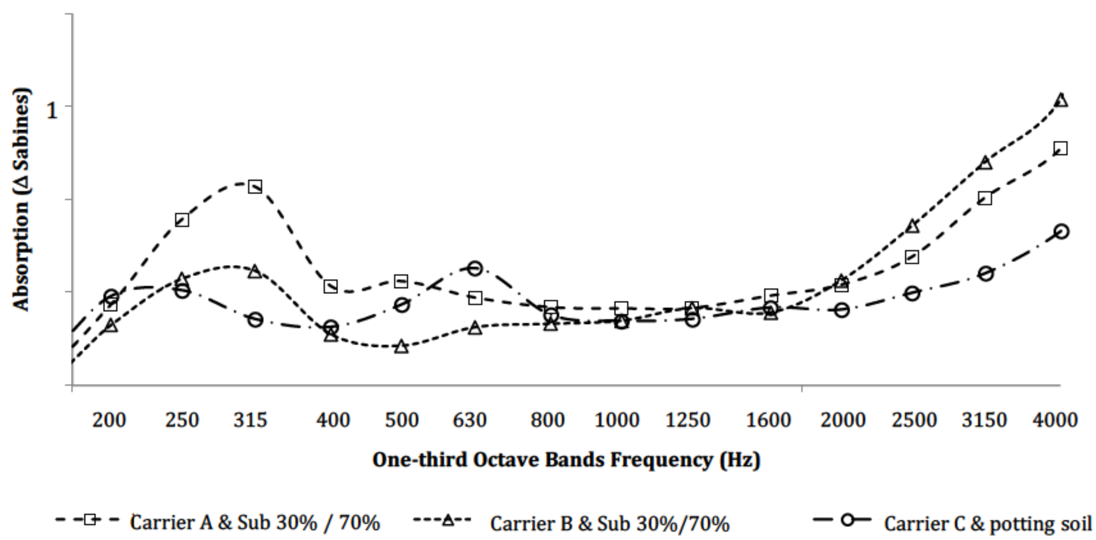
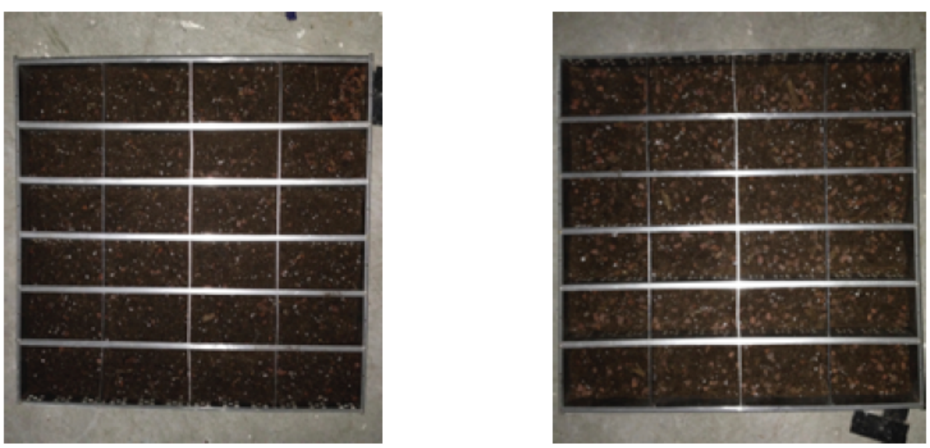


Figure 42. Comparison of absorption (Δ Sabine) of carriers filled with substrate

Carriers with a different mixture of substrate

The random-incidence absorption of two mixtures of substrates was measured: (a) 20% pumice and 80% potting soil, (b) 30% pumice and 70% potting soil (Figure 43). Figure 44 & Figure 45 illustrate overall increase in absorption due to the substrate mixtures in Carrier A and B. The Carrier C was not evaluated with different mixtures of substrate. As previously explained in Section 4.4, it is not possible to add substrate to Carrier C. In all cases, the absorption of the empty carrier is shown as the baseline.

It should be noted that the volume of the carrier panels are not same. The percentage of moisture in the substrate mixtures was the same but was not quantified. However, the difference in the mixture of the substrate does not make a noteworthy difference in terms of absorption of Carrier A. In Carrier B the addition of substrate increased absorption by approximately 0.5 Sabins. The absorption of the mixture with a higher percentage of soil (80%) is only slightly more than the absorption of the second mixture (70% soil) for most frequencies (Figure 45).



(a) (b)

Figure 43. The measurement condition of random-incident Absorption of two different mixtures of substrate ; (a) 20% pumice, 80% potting soil, (b) 30% pumice, 70% potting soil)

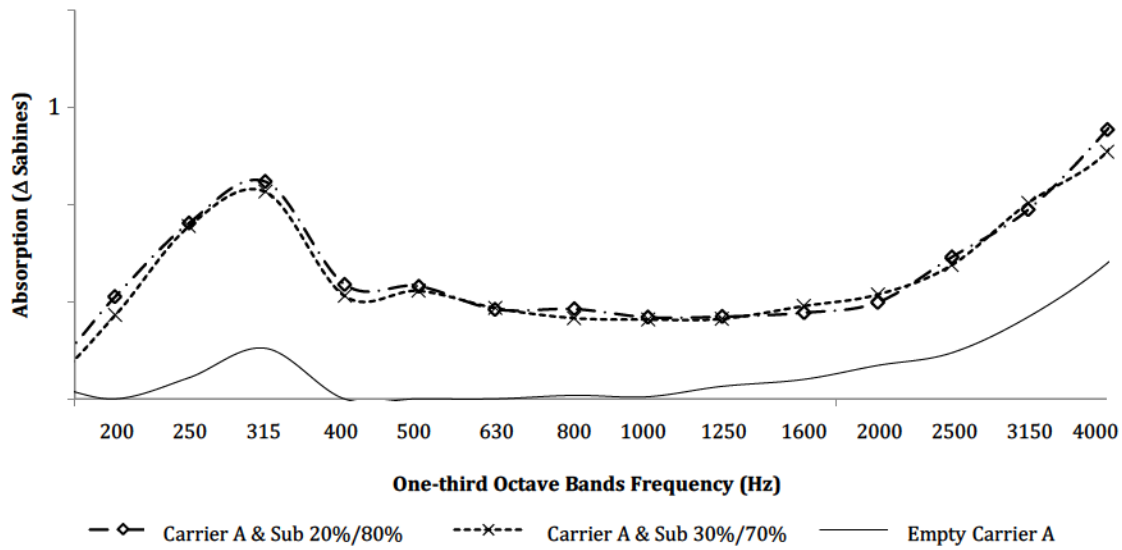


Figure 44. Comparison of absorption (Δ Sabine) of carrier A filled with substrate

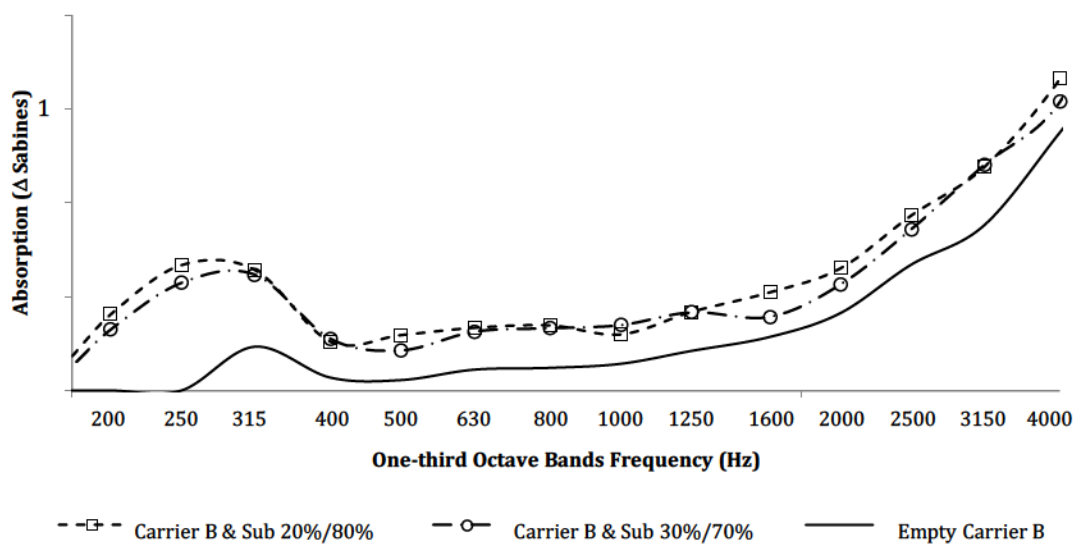


Figure 45. Comparison of absorption (Δ Sabine) of carrier B filled with substrate

The effect of moisture in the substrate

The effect of the amount of water in the substrate was investigated on a single panel which requires substrate represented by Carrier A and Carrier C, which has room for only a small amount of potting soil (Figure 46 and 47). Dry substrate mixture 30%/70% for living wall was taken directly from the bag in which the mixture was stored. There is a nominal amount of moisture (unquantified) in this "dry" substrate compared to the living wall carrier with substrate in "field capacity". Field capacity is established by saturating the substrate and allowing the substrate to drain for 24 hours.

Figure 46 shows the absorption (Sabine) for Carrier A filled with dry substrate and with substrate at field capacity. The trends look very similar before 630 Hz. The absorptivity increases with frequencies for both cases. After 630 Hz, the drier substrate mix absorbs significantly (about 0.5 Sabine) more sound than the substrate in field capacity: This difference is 0.3 Sabine at 1000 Hz and increases to about 0.6 around 2000 Hz and increases to 1 Sabine at 400 Hz.

Figure 47 illustrates that the empty Carrier C has comparable; and even higher absorption than the carrier with substrate. after 800 Hz the trends are similar (increasing with frequency). And the drier Carrier C is about 0.2 Sabine more absorptive than carrier C in field capacity.

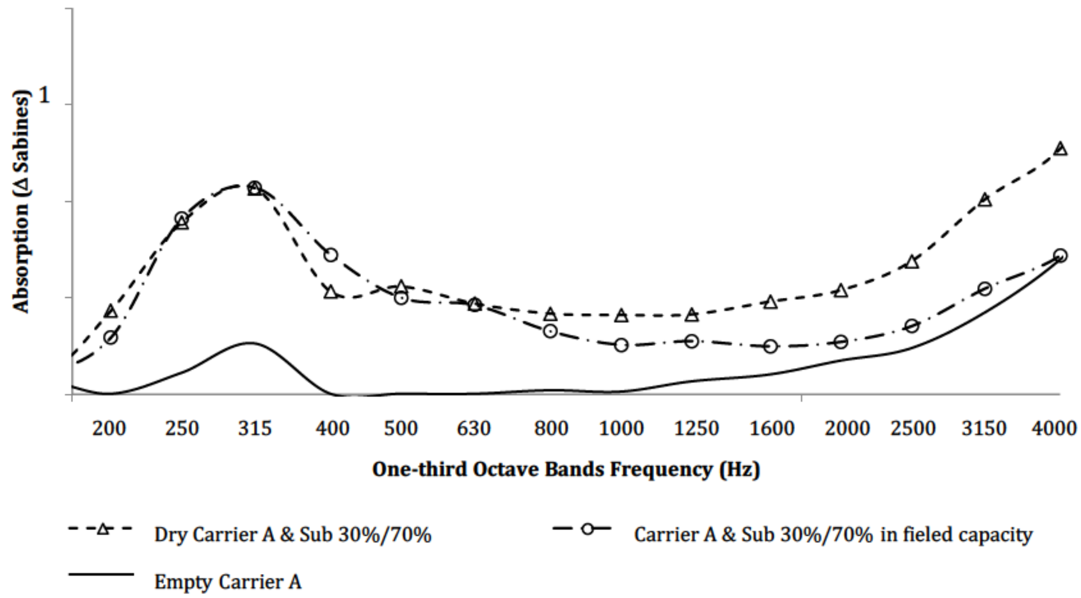


Figure 46. Comparison of absorption (Δ Sabine) of Carrier A filled with substrate (30%/70% mix); dry and in field capacity

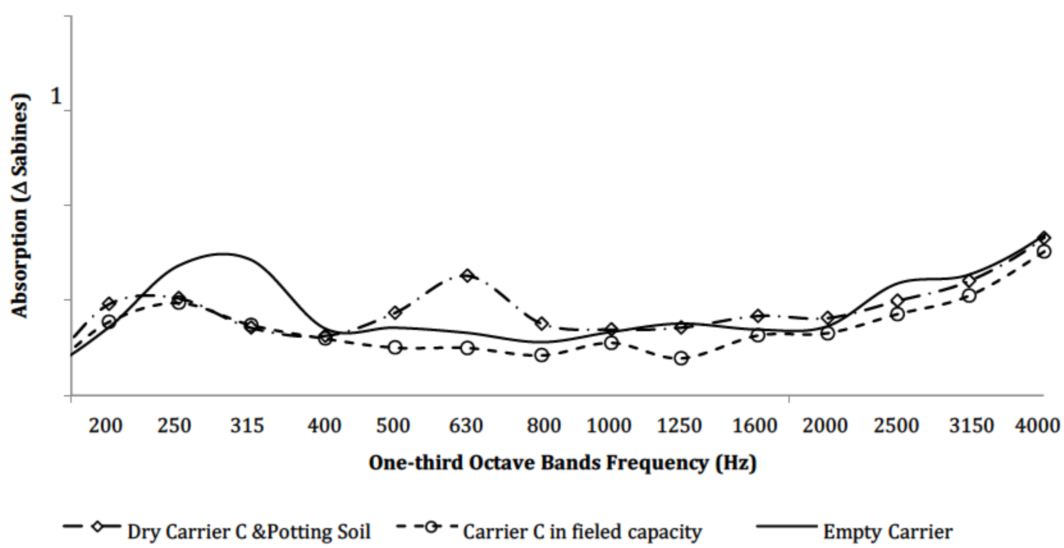
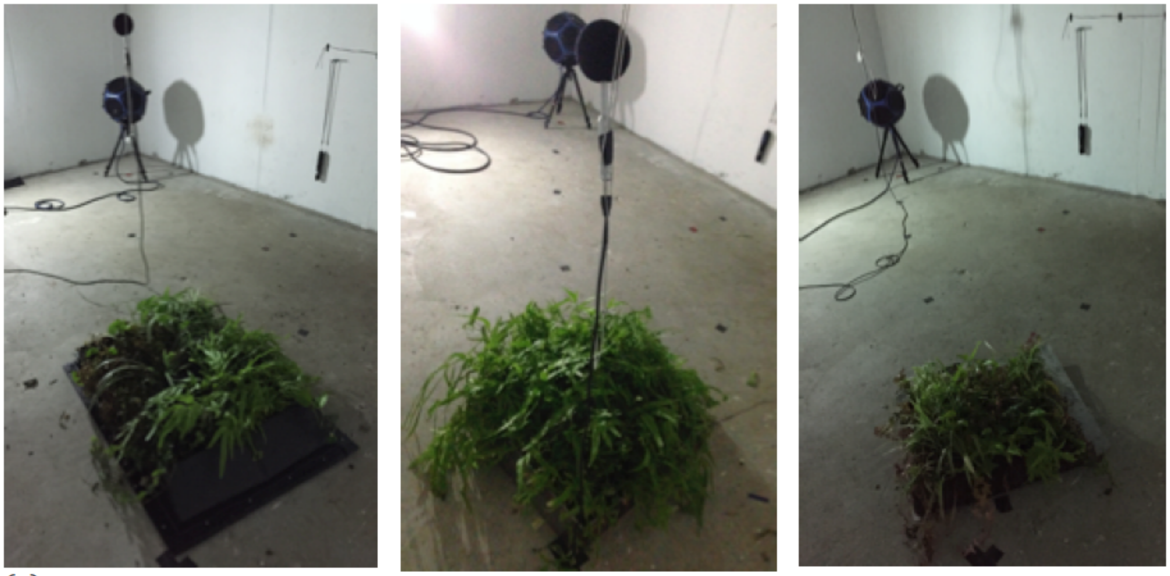


Figure 47. Comparison of absorption (Δ Sabine) of carrier C filled with substrate (30%/70% mix); dry and in field capacity

Vegetated living wall panels

The graphs in this section show absorption patterns of the three living wall systems planted with a mixture of six species Ivy, Creeping Fig, Spider Plant, Pilea, Fern and Golden Pothos. Figure 48 illustrates the single panel vegetated living walls in the reverberation chamber. A mixture of the three plant specimens is grown in each of the carrier systems A, B and C.

Figure 49 illustrates the difference between the absorption of the Carrier A filled with substrate and planted Carrier A. Plants added to the substrate do not increase the absorption of the living wall system above substrate only panels. Moreover, absorption decreases with vegetation above 1000 Hz, but it is still higher than the empty panel used as a reference. Above 1000 Hz the plants diminish the absorption of the panel provided by the substrate. The diminishing absorption increases with frequency. Figure 50 illustrates result similar to Figure 49, the absorption of the carrier B with and without the vegetation is very close below 1600 Hz frequency. Above 1600 Hz panel the carrier filled with substrate is more absorptive than the vegetated panel, above 2500 Hz the absorption of the vegetated panel is even less than the empty carrier panel itself. Below 1600 Hz the net effect of plants on absorption of Carrier C is not clear. Figure 51 indicates that the absorptivity above 1000 Hz of Carrier C does not change by added potting soil and vegetation. The vegetated Carrier C is as absorptive as the empty panel, especially at high frequencies where all trends are the same.



(a) (b) (c)

Figure 48. The measurement condition of random-incident Absorption of the planted living three different living wall systems; (a) Carrier A, (b) Carrier B, (c) Carrier C. (40 plant each panel)

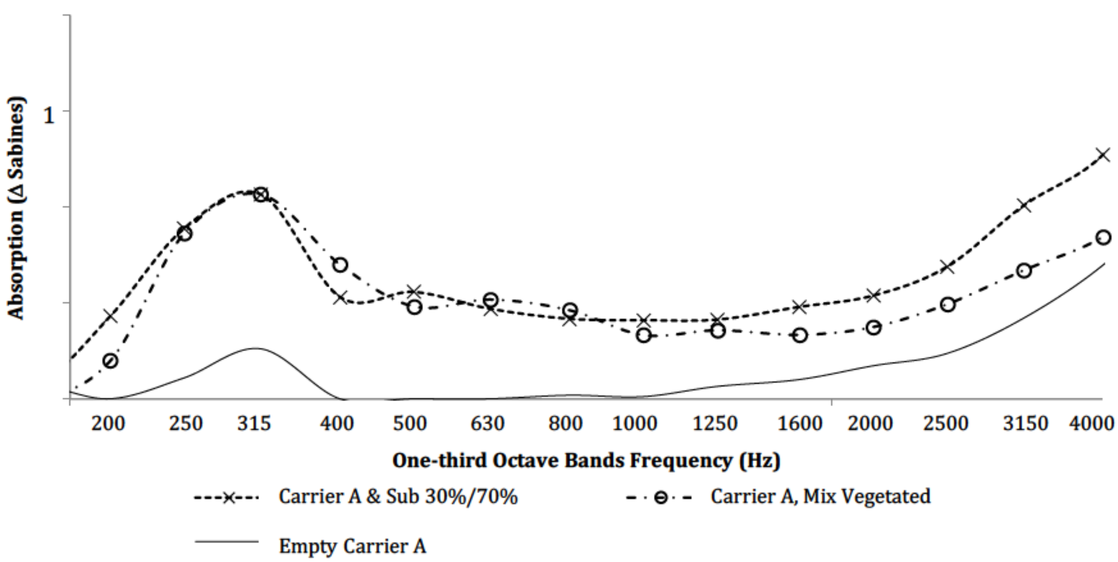


Figure 49. Comparison of absorption (Δ Sabine) of Carrier An empty, with substrate and vegetated.

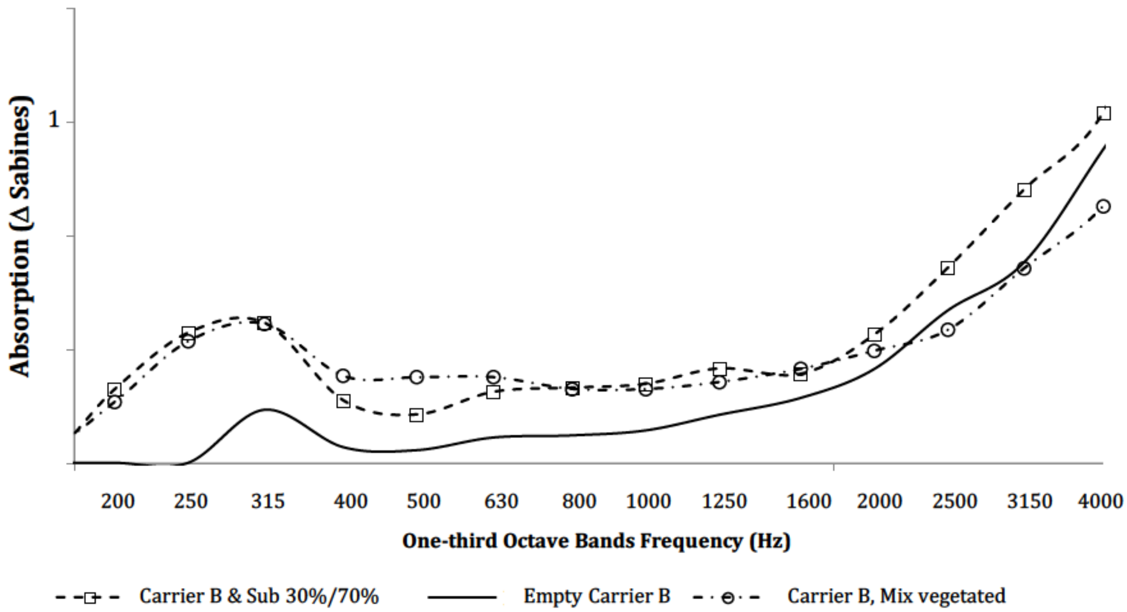


Figure 50. Comparison of absorption (Δ Sabine) of Carrier B empty, with substrate and vegetated.

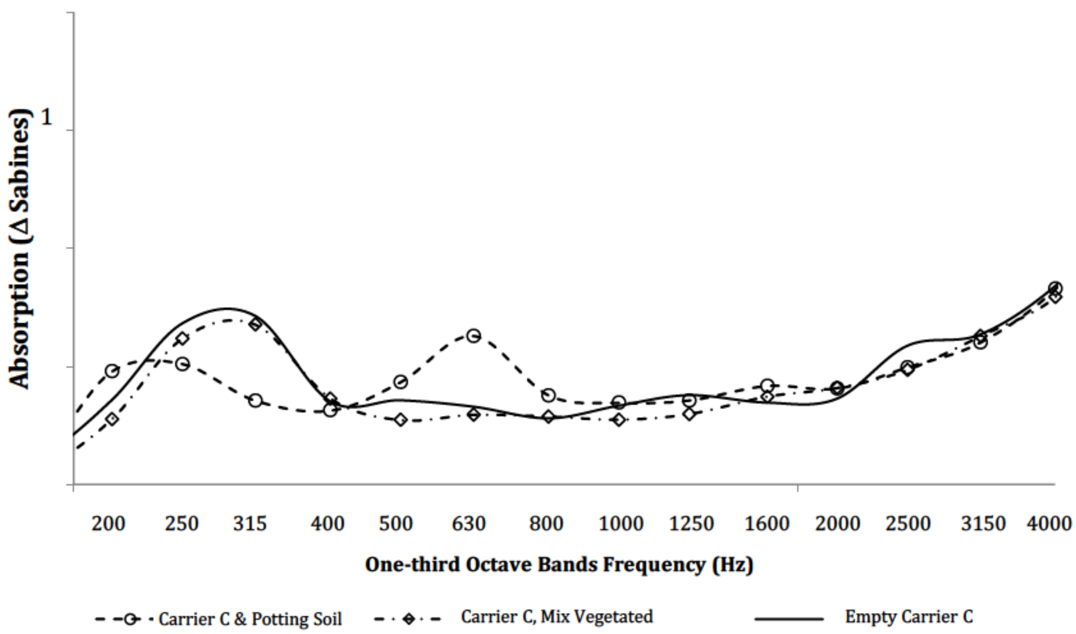


Figure 51. Comparison of absorption (Δ Sabine) of Carrier C empty, with substrate and vegetated.

Figure 52 compares the absorptivity of each living wall system. The average of measurement of the results from 3 planted single living wall panels with the mix of species was used for each system (Carrier A, B & C). Above 1000 Hz the absorption of all three systems are minimal different in trend. Below 1000 Hz system A has about 0.5 Sabine higher absorption than systems B and C.

Checking for the consistency of the results

As discussed in section 4.5.1.1 measurement are conducted to verify the consistency of the results. Three of each carrier systems are planted with the same mix of species to examine the consistency and repeatability of results. Figure 53 presents that all three mixed vegetated Carrier A samples (in 30%,70% carrier) have the same absorption at lower and mid frequency. This shows consistency of measurements for the Carrier A that was planted with the same mixture of species. Similarly, Figure 54 shows that the Carrier B trends are very close to each other but one panel (Mix 1) is less absorptive after 1600 Hz (0.6 Sabine less than the other two.). According to Figure 55, results show minor absorption differences between the carrier C panels. The high frequency difference in absorption of the three samples of the same system is nominally the same as the difference of the average measurement of the three system.

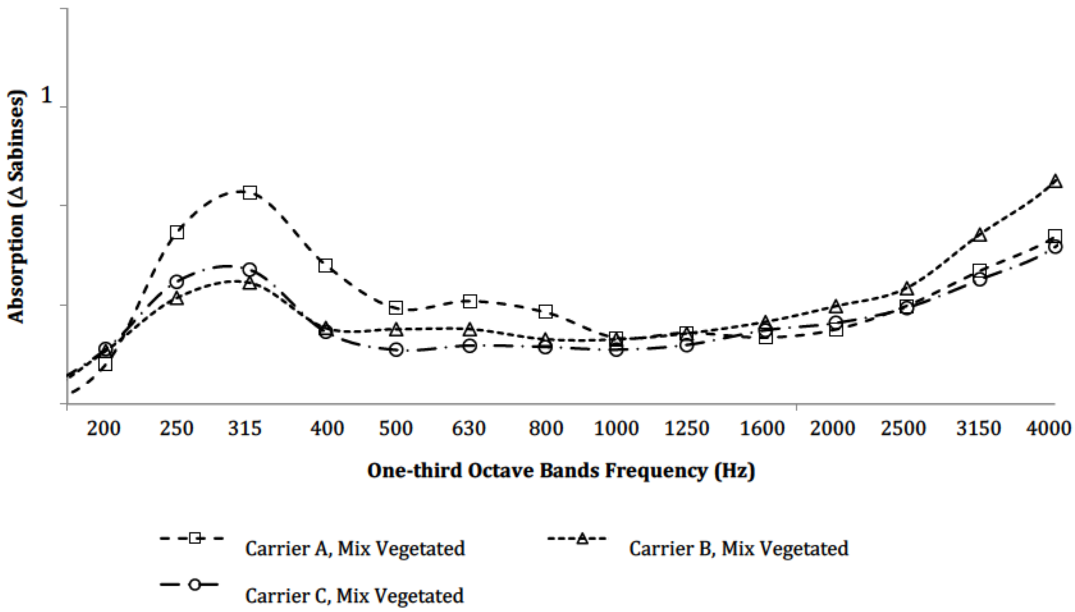


Figure 52. Comparison of absorption (Δ Sabine) of three vegetated (mix species) living wall panels

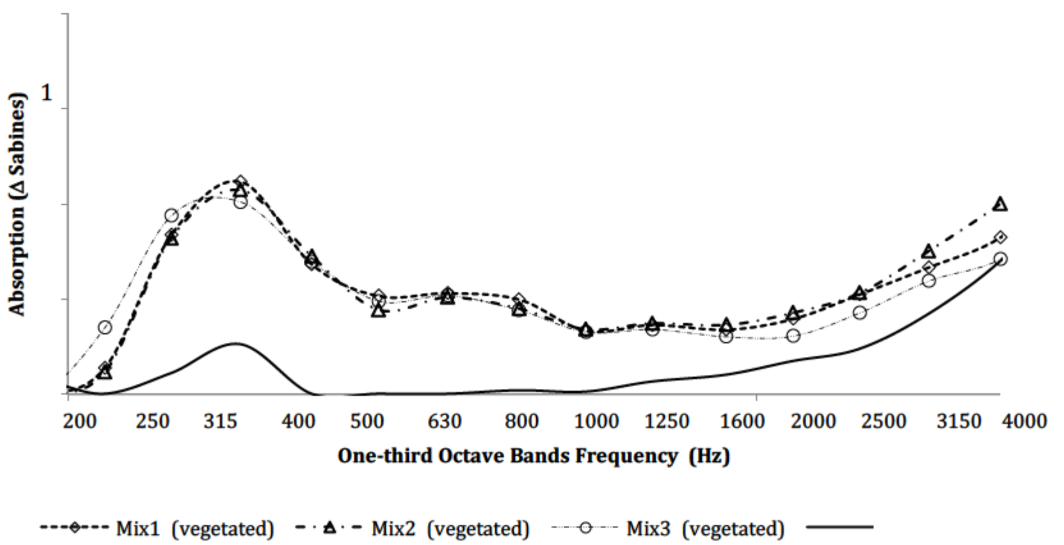


Figure 53. Comparison of absorption (Δ Sabine) of Carrier an empty and planted panels (Mix 1, 2 &3). The test specimens that were studied for checking the consistency of the measurements in carrier A (Section 4.5.1.1).

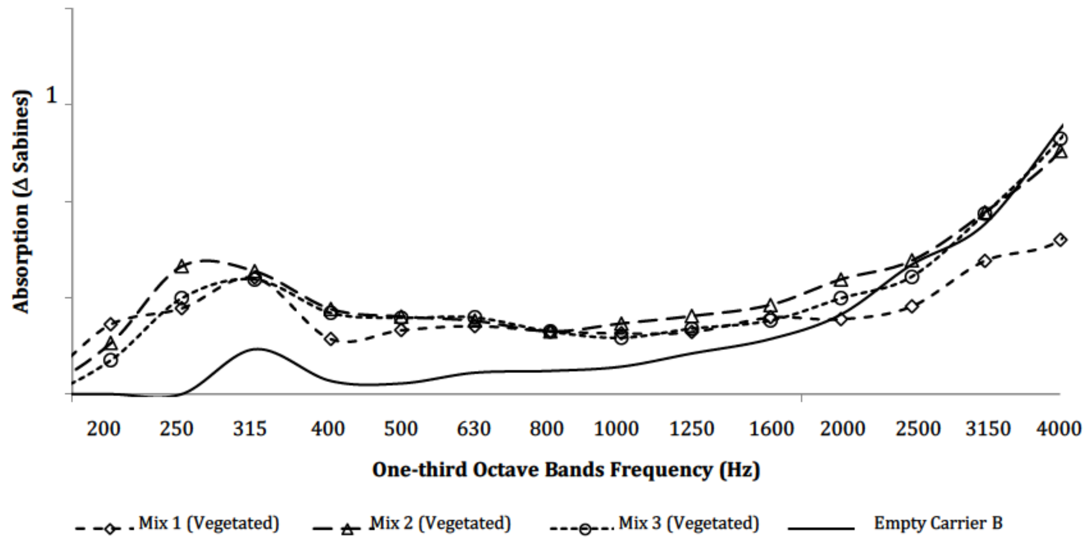


Figure 54. Comparison of absorption (Δ Sabine) of Carrier B *empty and planted panels (Mix 1, 2 &3). The test specimens that were studied for checking the consistency of the measurements in carrier A (Section 4.5.1.1).*

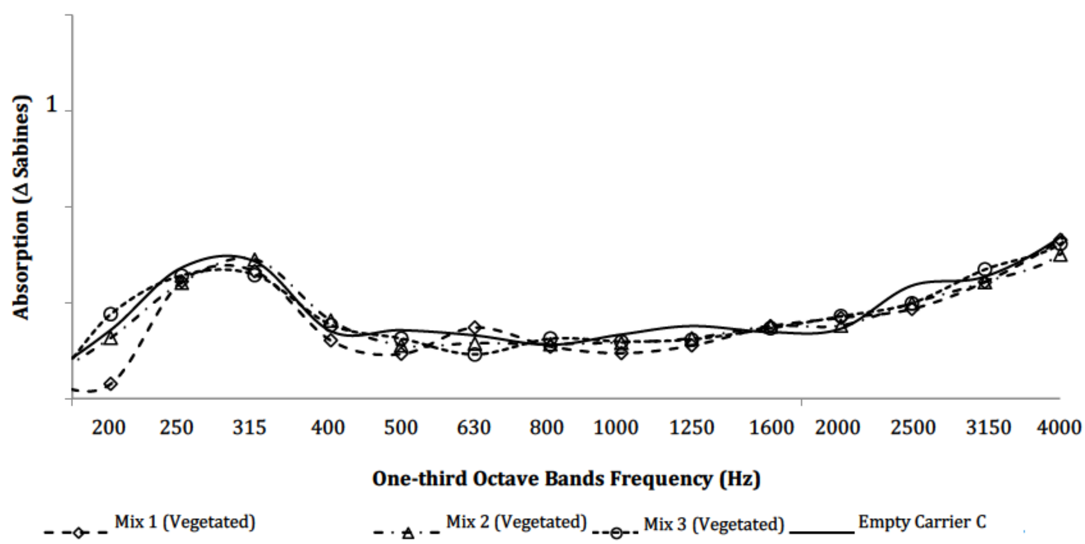


Figure 55. Comparison of absorption (Δ Sabine) of Carrier C *empty and planted panels (Mix 1, 2 &3). The test specimens that were studied for checking the consistency of the measurements in carrier A (Section 4.5.1.1).*

Investigation of Carrier B with 6 individual species (evaluation of single Panel)

Sufficient number of Carrier type B panels were six for the investigation of the effect of the individual species on absorption.

Figure 56 shows that the type of plants affects absorptivity. The trends are almost the same. Golden Pothos has the highest absorptivity overall. The next most absorptive is Pilea with a slightly lower absorption coefficient than Golden Pothos through the frequency band. Creeping Fig, Spider Plant, mix planted panel and Fern are similar in terms of absorption at mid frequencies (630-1000 Hz). After 1000 Hz, the difference in the absorptivity of Creeping Fig, Spider Plant, mix vegetated is more significant and increases with frequency. The trend for Fern does not increase with frequency between 6300 and 2500 Hz. The mix planted panel is a panel using a combination of six species (Spider Plant, Ivy, Pilea, Creeping Fig, Golden Pothos and Fern) in the Figure 56, and its absorptivity is somewhere between the other 6 species.

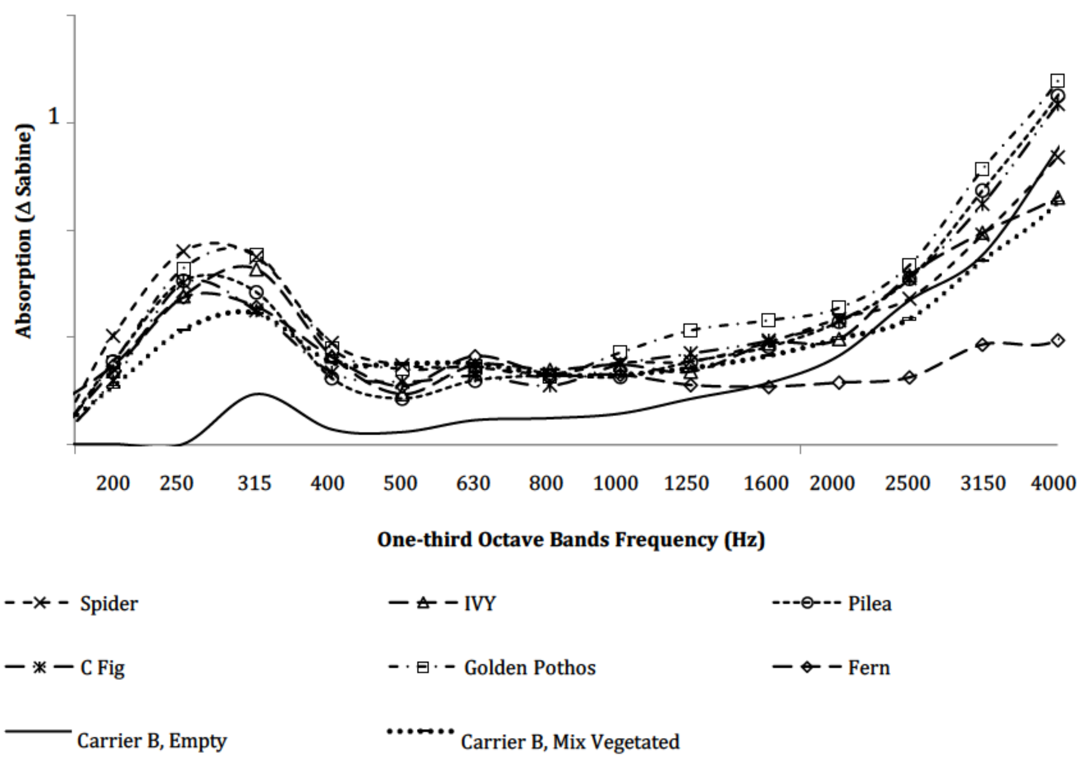


Figure 56. Comparison of absorption (Δ Sabine) of vegetated Carrier B panel

5.2.3. Absorption evaluation of a multiple of panels

Carrier B was again used for this series of measurement taken to investigate the effect of multiple panels as it was not expected to be linear.

Figure 58 shows the random-incident absorption (Sabine) results for 1 vegetated Carrier A panel and 3 vegetated Carrier A panels. The absorption is consistently greater at all frequencies. At low frequencies below 500 Hz, the absorption increases by more than two, with the addition of two more panels. On the other hand, at frequencies above 500 Hz, 3 carriers provide about one fold more absorption than a single carrier.

The 4-panel sample is a combination of 3 mixed planted panels and 1 homogenous panel. 8 panels are a combination of 3 mixed panels and 5 homogeneous planted panels excluding the Fern species (Figure 57).

Illustrated in Figure 59, increasing the number of Carrier B panels significantly increases the absorption at low frequencies (below 630 Hz) and the absorption result almost doubled with a doubling of the panels. The increased number of panels has a greater effect at low frequencies. Above 800 Hz, there a two- fold increase in absorption from 1 panel to 4 panels (about 1 Sabine) and from 4 panels to 8 panels and additional two-fold increase. After 800 Hz there is an approximate one-fold increase with each doubled the number of panels.

Figure 57. The measurement condition of the living wall made of 8 vegetated Carrier B panels

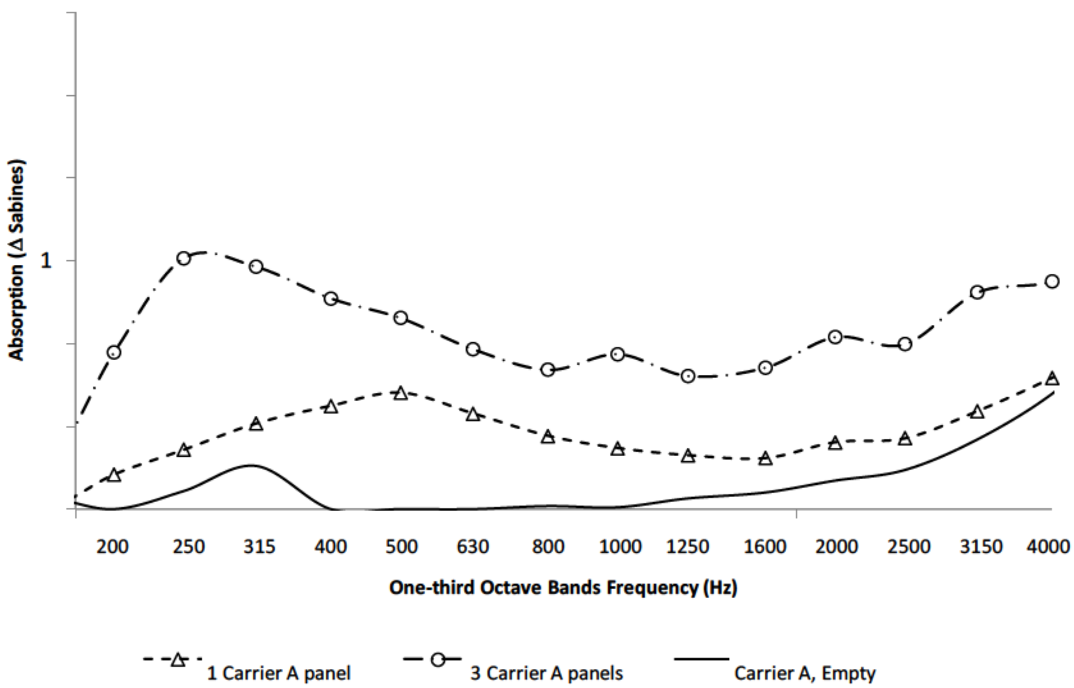


Figure 58. Comparison of absorption (Δ Sabine) of multiple, Carrier A

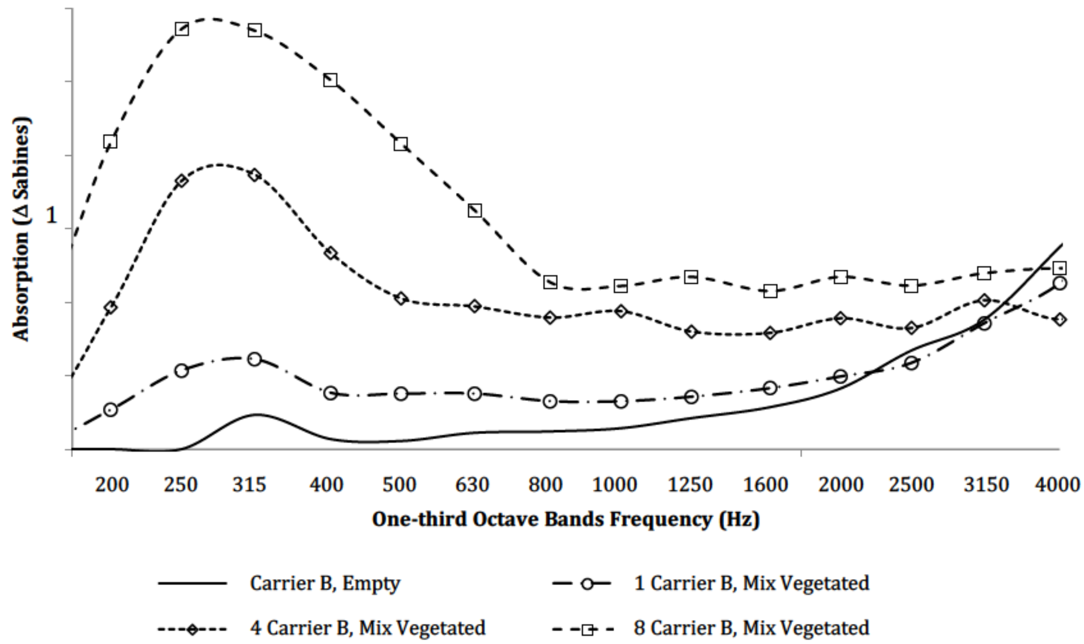


Figure 59. Comparison of absorption (Δ Sabine) of multiple, Carrier B

5.3. 1/3 Scale Measurements; Absorption and Scattering

This series of test illustrate the effect of percentage coverage on sound absorption and sound scattering. Recall that measurement method at a one-third scale was developed, due to the capacity and size of the reverberation chamber. Additionally, (see section 4.5.3) the 1/3-scale of the plants is reviewed in section 5.1.

(a) (Base Plate) Turning Table

(b) Turning table covered with substrate

Figure 60. The measurement condition of (a) Base plate and (b) substrate 100 mm top soil

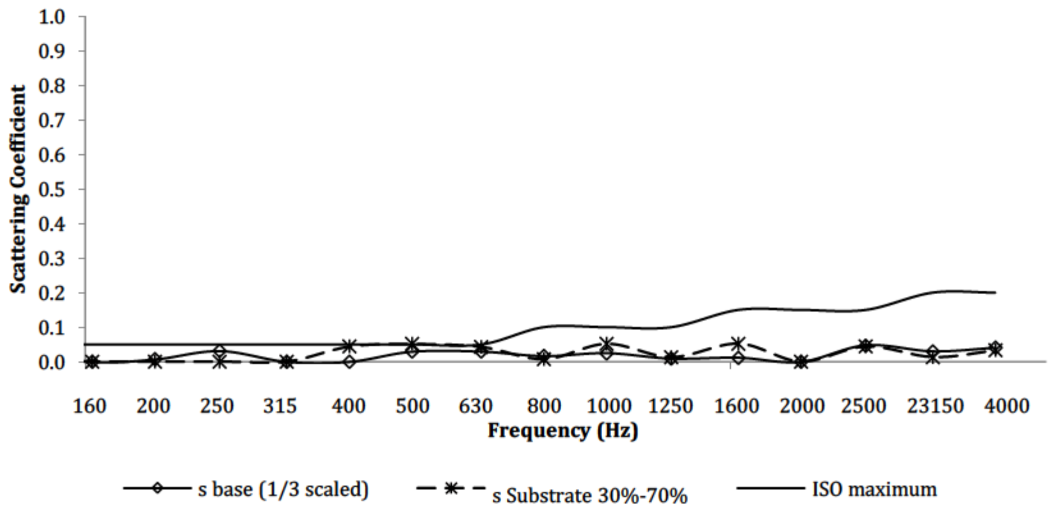


Figure 61. Scattering coefficient of base plate and substrate (30% pumice, 70% potting soil)

Absorption coefficient of different species

This section discusses the investigation of the absorption coefficient of different species as a function of percent coverage. The evaluation method is to be discussed in section 6.3.2.

Figure 62 illustrates the Golden Pothos with different percentage coverage, 25,50 and 100% on the turning table. The sample with 100% coverage has the highest absorption through all frequencies. SAA is 0.31, 0.31 and 0.37 for 25% coverage, 50% coverage and 100% coverage respectively. The absorption coefficient curve for Golden Pothos at mid frequencies between 1000 and 2500 Hz; 0.4 for 25% and 50% and 0.45 for 100% coverage respectively (Figure 63). [2]

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[2] Golden Pothos; NRC(25%)=0.30, NRC(50%)=0.31, NRC(100%)= 0.37

(a) (b) (c)

Figure 62. The measurement condition of 100 mm substrate with Golden Pothos. (a) 25% vegetation coverage), (b) 50% vegetation coverage, (c) 100% vegetation coverage

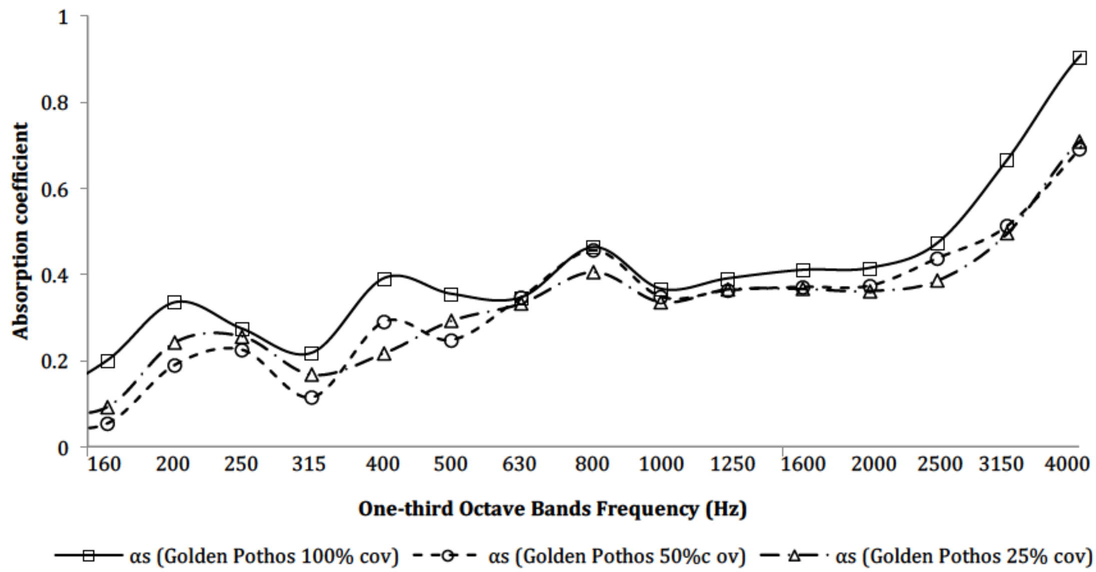

Figure 63. Absorption coefficient of Golden Pothos, different vegetation coverage (25%, 50% & 100%)

Figure 64 illustrates Ivy with different coverage 25,50, 100% on the turning table. As shown in Figure 65, at mid frequencies the absorption coefficient of Ivy with 100% coverage is about 0.07 higher than the absorption of the Ivy with 50% coverage and 25% (SAA = 0.34, 0.27 and 0.25 respectively). The difference between the 50% and 25% coverage, is around 0.02.[3]

[3] Ivy; NRC(25%)=0.25, NRC(50%)=0.27 , NRC(100%)=0.34

(a) (b) (c)

Figure 64. The measurement condition of 100 mm substrate with Ivy. (a) 25% vegetation coverage, (b) 50% vegetation coverage, (c) 100% vegetation coverage

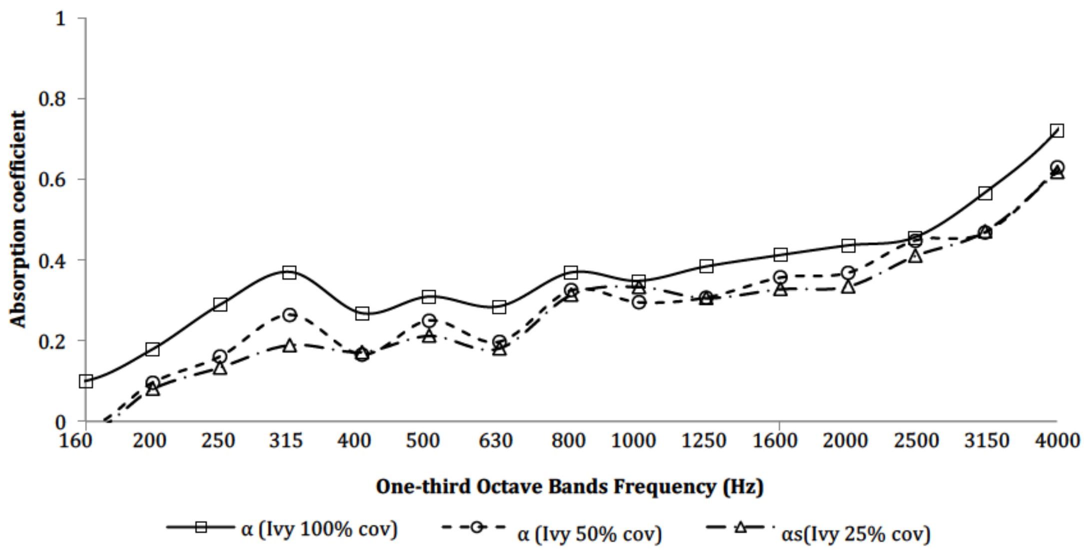

Figure 65. Absorption coefficient of Ivy, different vegetation coverage (25%, 50% & 100%)

Figure 66 shows the set-up for the absorption coefficient measurements with Pilea. By comparing the 3 sets of measurements in Figure 67, the difference in absorption coefficient of Pilea at low frequencies is more significant than the difference at frequencies above 630 Hz. The high frequency absorption coefficient about 800 Hz for Pilea is almost the same for all the measured coverage percentages. The absorption coefficients for different coverages are within the same range at mid frequencies with the SAA values being 0.34, 0.34 and 0.4 for 25%, 50% and 100% coverage respectively.[4]

(a) (b) (c)

Figure 66. The measurement condition of 100 substrate with Pilea. (a) 25% vegetation coverage, (b) 50% vegetation coverage, (c) 100% vegetation coverage

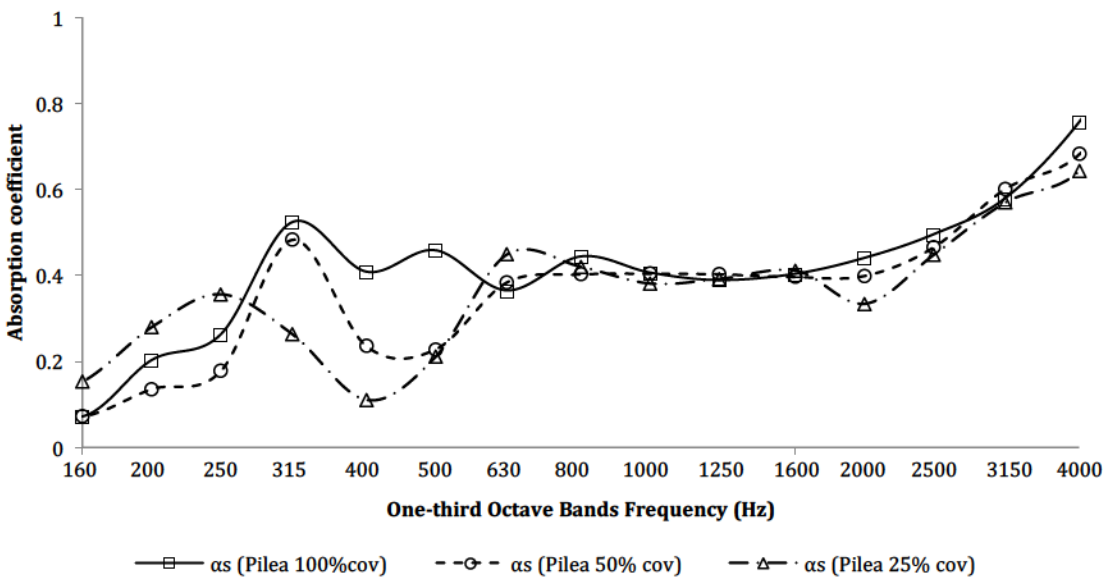

Figure 67. Absorption coefficient of Pilea, different vegetation coverage (25%, 50% & 100%)

Figure 68 shows the set-up for the absorption coefficient measurements with Creeping Fig. Results (Figure 69) display a slight difference in absorptivity of Creeping Fig with increase in plant coverage. As shown at higher frequencies (above 1600 Hz), the absorptivity of Creeping Fig is more dependent on the density of the

[4] Pilea; NRC(25%)=0.32,NRC(50%)=0.34, NRC(100%)=0.4

coverage. The absorption gradually increases with increasing coverage. The SAA of the Creeping Fig is0.30 for 25%, 0.32 for 50% and 0.34 for 100% plant coverage at 4000 Hz.[5]

(a) (b) (c)

Figure 68. The measurement condition of 100 mm substrate with Creeping Fig. (a) 25% vegetation coverage, (b) 50% vegetation coverage, (c) 100% vegetation coverage

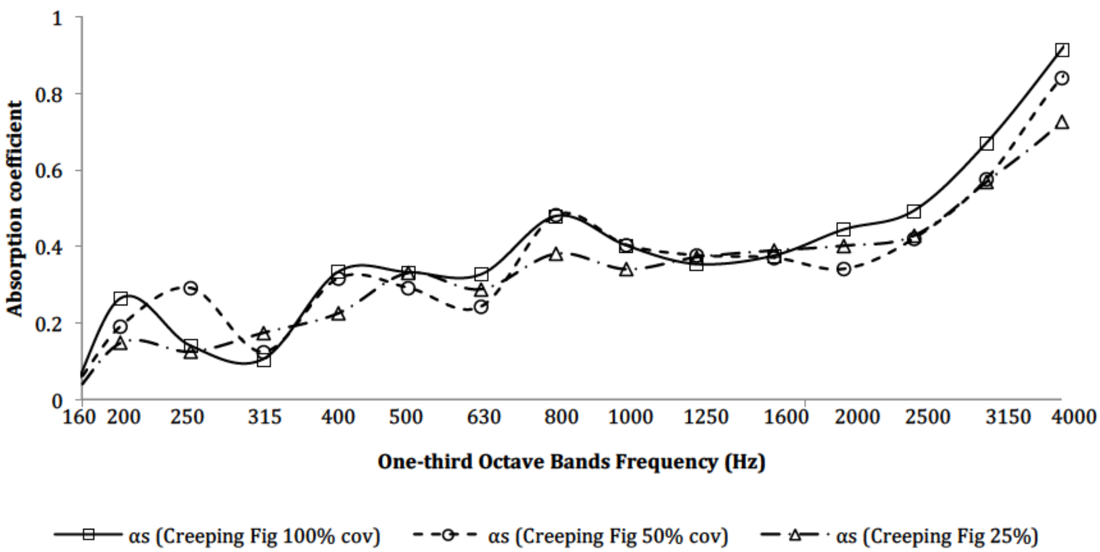

Figure 69. Absorption coefficient of Creeping Fig, different vegetation coverage (25%, 50% & 100%)

The measurement set-up for absorption coefficient measurements of Spider Plant are illustrated in Figure 70. As illustrated in Figure 71 absorptions for the three sets of coverage are fluctuating between 0.4 and 0.6 at frequencies between 630 and

---

[5] Creeping Fig; NRC(25%)=0.3, NRC(50%)=0.32 , NRC(100%)=0.34

1000 Hz. The sound absorption average (SAA) of Spider Plant is 0.48, 0.38 and 0.31 for 25% , 50% and 100% coverage. And unique to the six plants species evaluated the SAA of the Spider Plant decreases with increasing coverage, this anomaly is not understood .[6]

(a) (b) (c)

Figure 70. The measurement condition of 100 mm substrate with Spider Plant. (a) 25% vegetation coverage, (b) 50% vegetation coverage, (c) 100% vegetation coverage

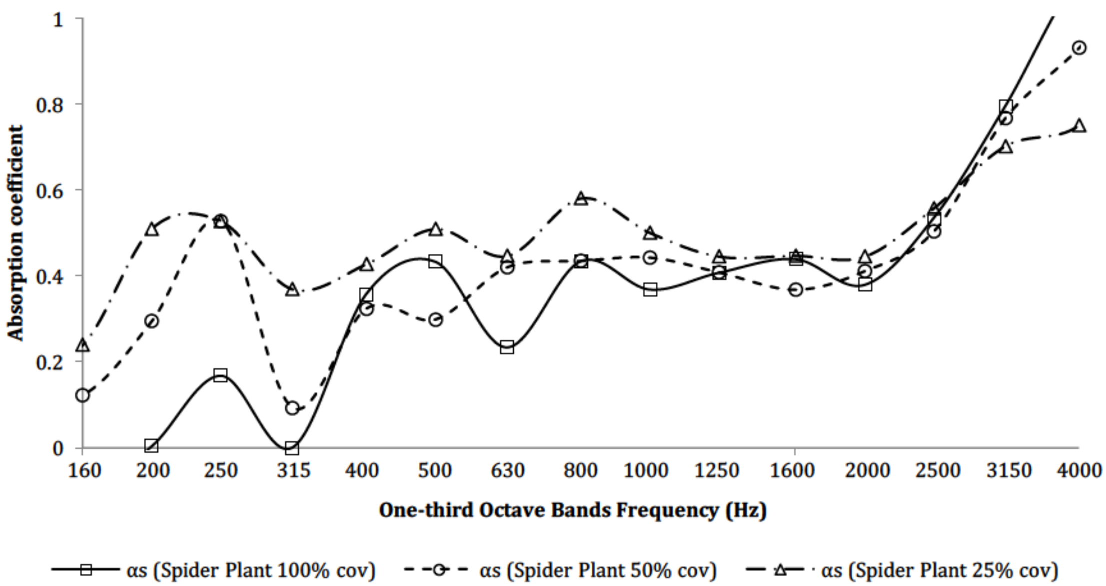

Figure 71. Absorption coefficient of Spider Plant, different vegetation coverage (25%, 50% & 100%)

The measurement set-up for the absorption coefficient measurement of the Fern plant is illustrated in Figure 72. Figure 73 illustrates a significant difference about 0.2 between the absorptivity of Fern with 25% coverage and 50% coverage at all

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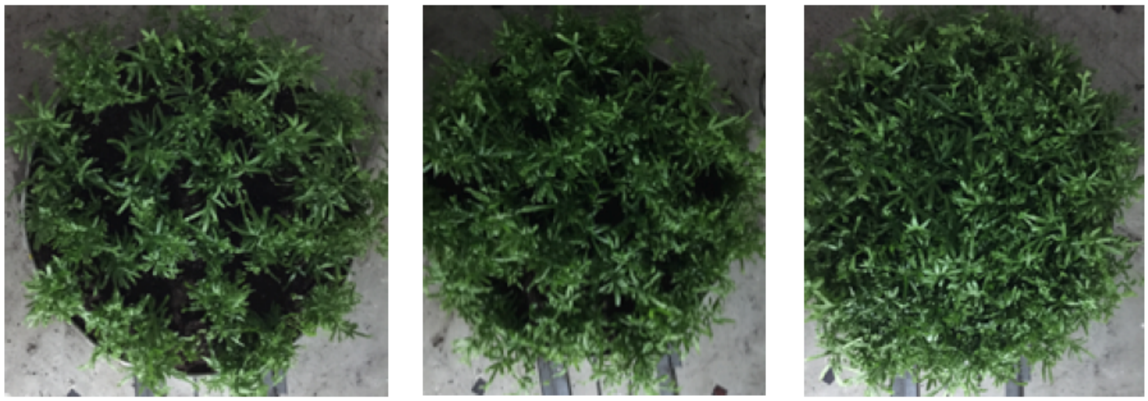
[6] Spider Plant; NRC(25%)=0.4, NRC(50%)=0.37 , NRC(100%)=0.31

frequencies, relative to the difference between 50% coverage and 100% coverage. The sound absorption average increases with density of the plants. It is 0.11, 0.31 and 0.33 for 25%, 50% and 100% respectively.[7]



(a) (b) (c)

Figure 72. The measurement condition of 100 mm substrate with Fern. (a) 25% vegetation coverage, (b) 50% vegetation coverage, (c) 100% vegetation coverage

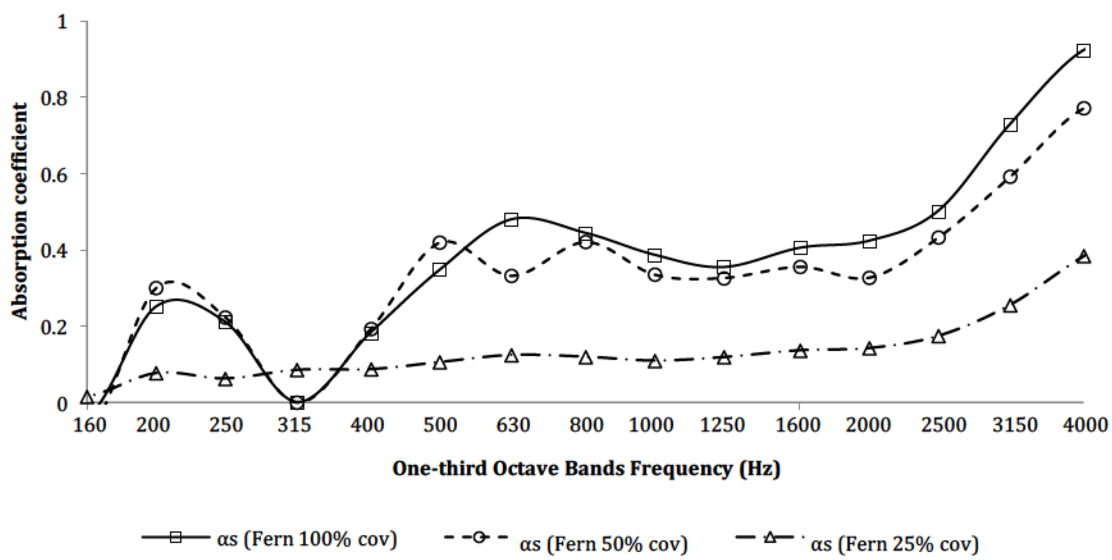


Figure 73. Absorption coefficient of Fern, different vegetation coverage (25%, 50% & 100%)

[7] Fern; NRC(25%)=0.1, NRC(50%)=0.3 , NRC(100%)=0.33

5.3.1. The scattering coefficient of plant species changes with different percentage coverage of vegetation

This series of the tests in this section investigates scattering pattern of the six available species and investigates the impact of the percentage coverage of vegetation on sound scattering. The evaluation method is discussed in section 4.5.3.

In Figure 74 scattering coefficient of Golden Pothos with three different levels of vegetation coverage is shown. It can be seen that, in general, scattering coefficient increases with frequency and percentage of coverage. Golden Pothos's average scattering coefficient at mid frequencies (200-2500 Hz) with 25%, 50% and 100% coverage is 0.05, 0.13 and 0.14 respectively. Scattering coefficient of Golden Pothos with 50% coverage is around 0.14 higher than 25%, while there is not much difference between the scattering coefficient at 50% and 100% coverage, which is about 0.04.

As shown in Figure 75, average scattering coefficient of Ivy (200-2500 Hz) is 0.005 at 25%, and it is 0.01 with 50% coverage and 0.05 with 100% coverage. The scattering coefficient of Ivy increases with increasing frequency and vegetation coverage. 25% and 50% coverage of Ivy, is almost same in terms of scattering sound, 100% coverage scatters more at frequencies above 800 Hz.

Figure 76 shows the scattering coefficient of Pilea with different vegetation coverage. It can be seen that scattering coefficient is almost the same at frequencies below 500 Hz. At 100% coverage scattering increases above 2000 Hz. And the average sound scattering for Pilea is 0.015, 0.04 and 0.014 for 25%, 50% and 100% coverage respectively.

In the case of Creeping Fig, it can be seen that the overall trend is upward and the scattering coefficient gradually increases with frequency above 800 Hz, especially at

100% coverage (Figure 77). The average scattering coefficient is 0.10, 0.11 and 0.19 at 25%, 50% and 100% coverage respectively between 200 and 2500 Hz.

Figure 78 suggests that the scattering coefficient of Fern with different coverage percentages fluctuates around 0.05 at frequencies below 630 Hz. Above that, it gradually increases and the average sound scattering of Fern is 0.05, 0.06 and 0.17 for 25%, 50% and 100% coverage respectively.

Figure 79 shows a variation of the scattering coefficient curves of Spider Plant over different frequencies. The differences between the scattering coefficient of the different percent coverages is more pronounced than the other plant species. In the lower frequencies, as well as the average sound scattering of Spider Plant is 0.07, 0.05, and 0.1 for 25%, 50% and 100% coverage respectively.

Clearly above 630 Hz scattering is increasing with coverage and it is interesting to see increase consistency at a 100% coverage.

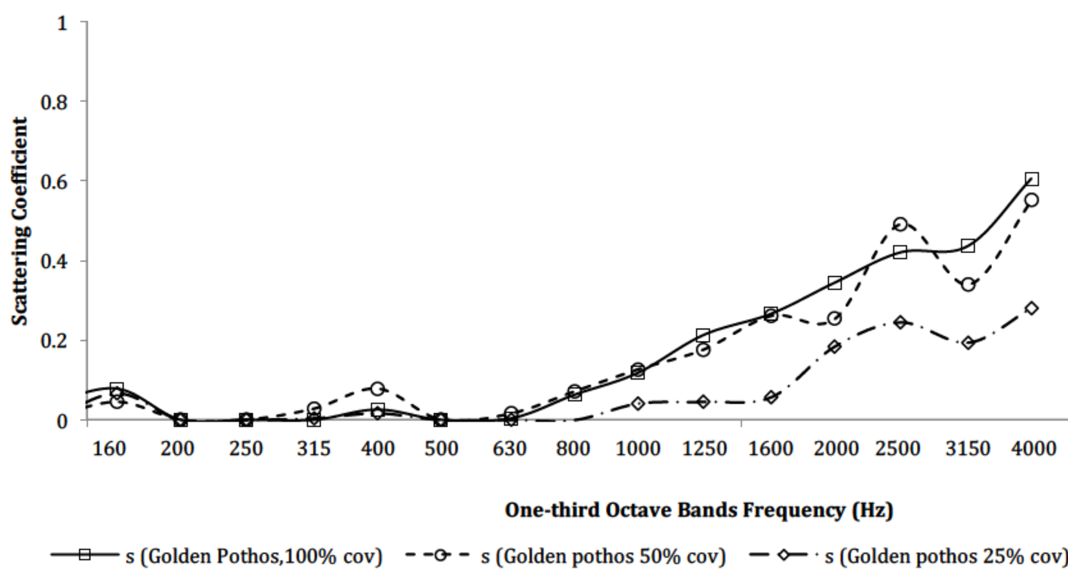


Figure 74. Scattering coefficient of Golden Pothos, different vegetation coverage (25%, 50% & 100%)

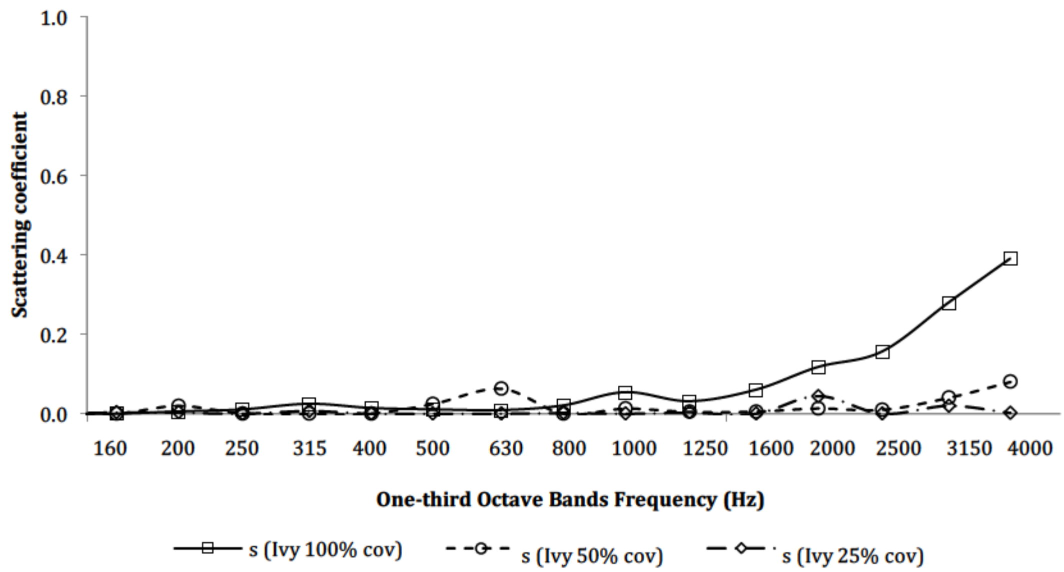


Figure 75. Scattering coefficient of Ivy, different vegetation coverage (25%, 50% & 100%)

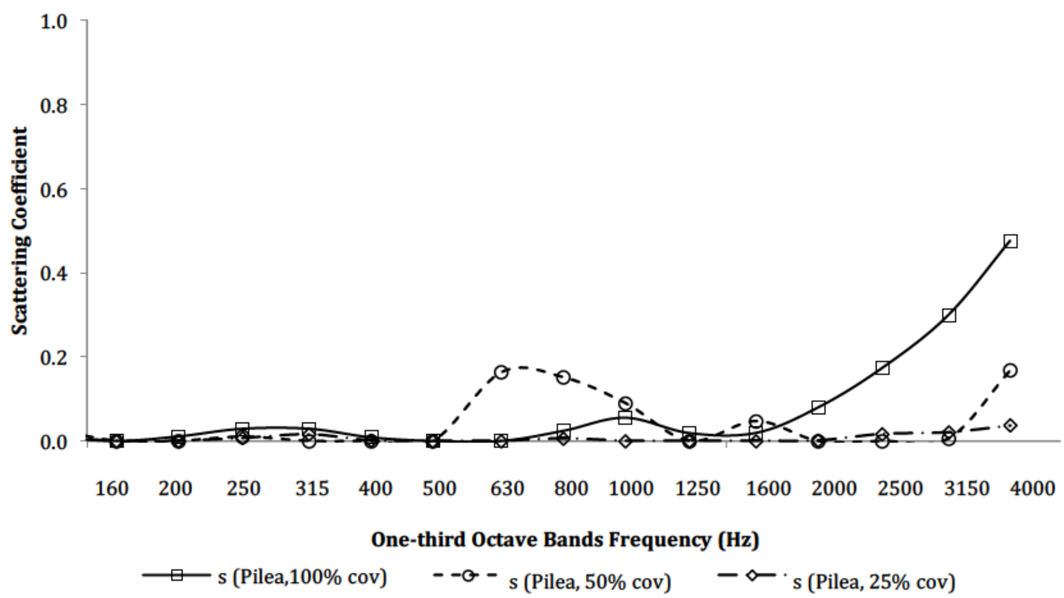


Figure 76. Scattering coefficient of Pilea, different vegetation coverage (25%, 50% & 100%)

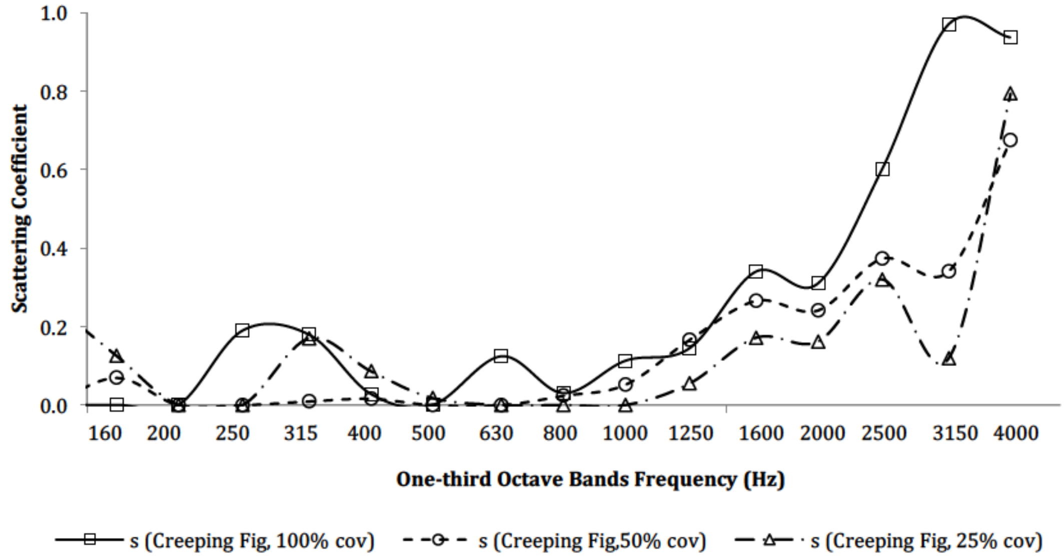


Figure 77. Scattering coefficient of Creeping Fig, different vegetation coverage (25%, 50% & 100%)

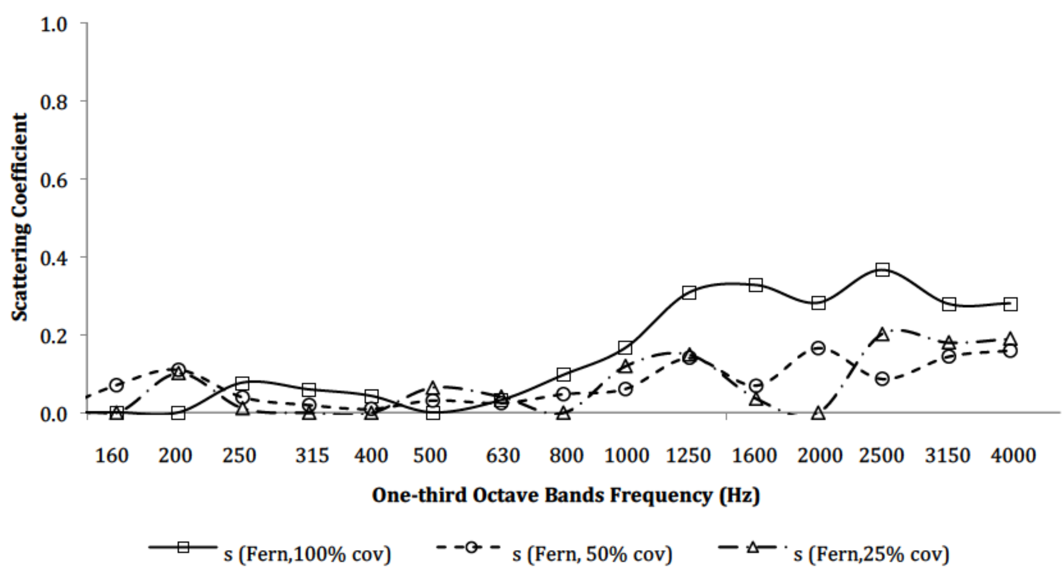


Figure 78. Scattering coefficient of Fern, different vegetation coverage (25%, 50% & 100%)

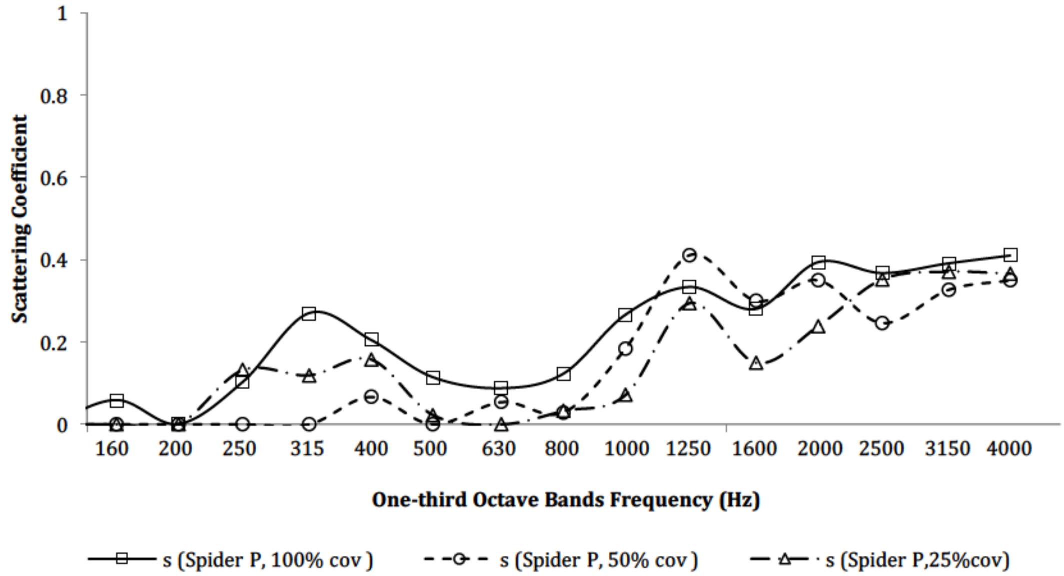


Figure 79. Scattering coefficient of Spider Plant, different vegetation coverage (25%, 50% & 100%)

6. Discussion

The absorption of the living wall panel in Sabine was determined first for the empty carrier which are constructed with significantly different modules. Secondly for the carriers with substrate, the substrate evaluated included a 30/70 mixture of pumice and potting soil and a 20/80 mixture of the same. Additionally, the effect of the water content of the 30/70 mixture was evaluated. Finally, the absorption of the fully vegetated panel was evaluated.

The materials and construction of the carriers do not dominate the absorption performance of the system once the substrate is installed. Although the 2D panel size of the carrier A is twice the area of carrier B. The substrate mass of the two non-hydroponic systems are within 10% of each other. And the two system performed similarly in the mid frequency and within 1 Sabine in low frequency and 0.5 Sabine in high frequencies. The results also show the increase in organic matter of the 20/80 of pumice and potting soil relative to the 30/70 did not affect absorption.

6.1. Absorption of living wall panel measurement

The absorption of the living wall panel in Sabine was determined first for the empty carrier which are constructed with significantly different modules. Secondly for the carriers with substrate, the substrate evaluated included a 30/70 mixture of pumice and potting soil and a 20/80 mixture of the same. Additionally, the effect of the water content of the 30/70 mixture was evaluated. Finally, the absorption of the fully vegetated panel was evaluated.

The materials and construction of the carriers do not dominate the absorption performance of the system once the substrate is installed. Although the 2D panel size of the carrier A is twice the area of carrier B. The substrate mass of the two non-hydroponic systems are within 10% of each other. And the two system performed similarly in the mid frequency and within 1 Sabine in low frequency and 0.5 Sabine

in high frequencies. The results also show the increase in organic matter of the 20/80 of pumice and potting soil relative to the 30/70 did not affect absorption.

6.1.1. Effect of moisture content and vegetation on the carries' absorption

According to Figure 41, the absorption (Sabine) of the empty Carrier A, made from ABS plastic, is lowest, Carrier B, made from stainless steel, is more absorptive and Carrier C, made of insulation material, it exhibits significantly higher absorption.[8]

Results indicated that using a mix of 70% potting soil and 30% pumice the difference in absorption (Sabine) between the panels with dry substrate and the panels with substrate in field capacity in the experiment is considerable in two substrate based systems. In the hydroponic system, which requires irrigation on the hour, absorption decreases relative to its wetness, aligning with the additional of the plants to the carriers and substrate again affects absorption.

Above 400 Hz, the substrate at field capacity is less absorptive than the dry substrate. The result of this study is comparable with the result of the previous experiment [11].

Yang's investigations of the absorption coefficient for a vegetation substrate it was reported that highly porous substrates maintain a high absorption even with high moisture content [11].

The addition of the plants to the carriers and substrate again affects absorption. At mid and high frequencies, the result suggests that the planted panel, carrier A and B is less absorptive than the panel that is filled with substrate only, measured at field capacity. Also, the difference between planted panels and substrate-only panels absorption increases with frequency, especially after 1600 Hz for Carrier A and

[8] Carrier A: recyclable ABS plastic; Carrier B: stainless-steel; Carrier C: isolative rock wool material used as a substrate.

Carrier B. The absorption of Carrier C is the same for the empty panel and the planted panel. The vegetation improves the low frequency absorption of carrier however it inversely influences the mid and high frequency absorption.

The effect of plant type on the absorption of a single panel was evaluated on carrier C. The six plant species and a mix of species affect absorption similarly in the low and mid frequencies. At higher frequencies above 1000 Hz the variance in absorption increases with frequency.

6.2. Absorption and scattering of 1/3 scale model; the species type effect on absorption and scattering coefficient at different coverage density

The measurement results of the absorption and scattering coefficient of the foliage components of six living wall species, with various levels of vegetation coverage, showed that generally, the absorption and scattering coefficients increase with increasing vegetation density.

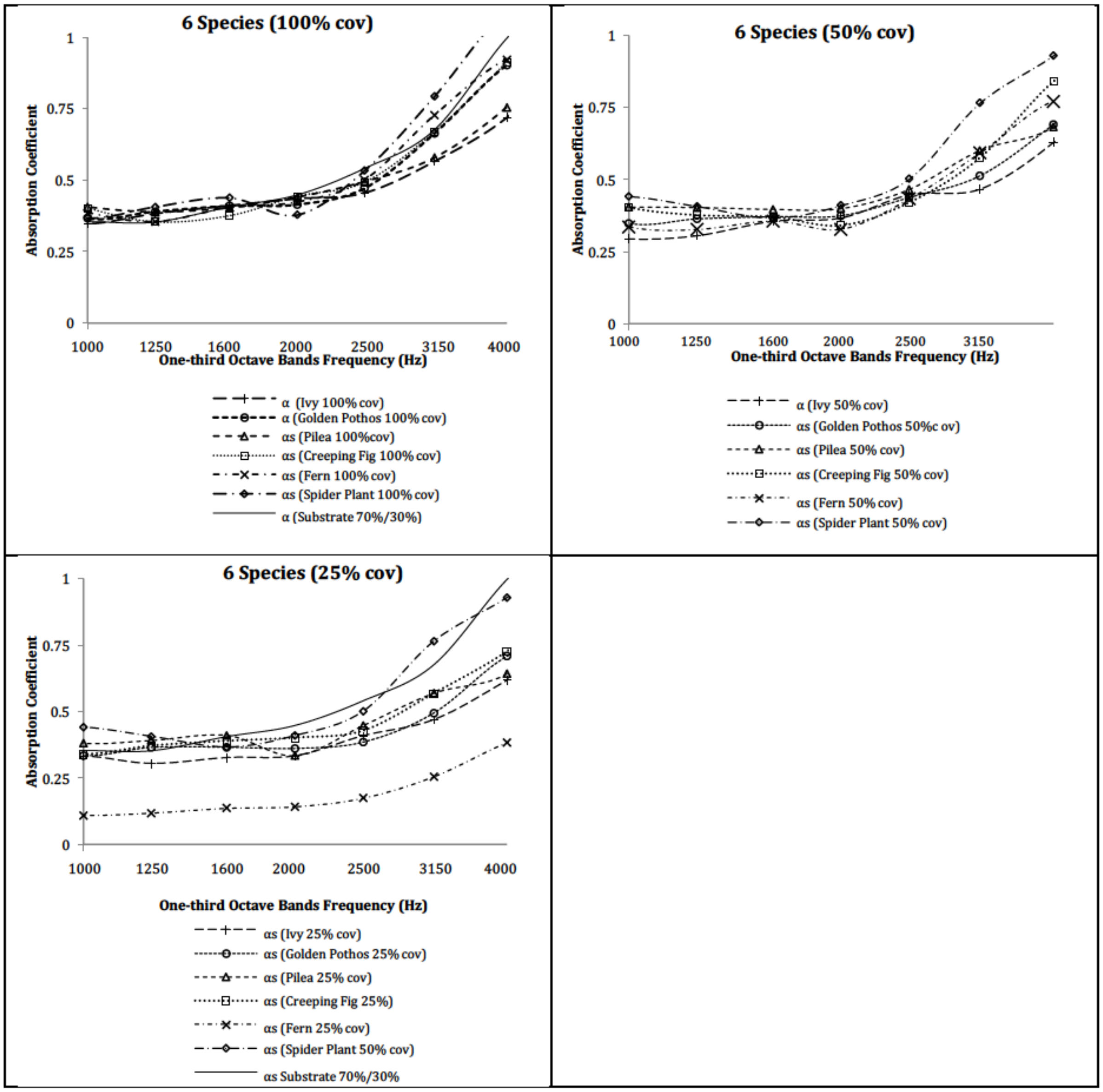
Prior investigations by Navarro et al [38] showed a greater effect of scattering on the reverberation time for materials with lower absorption coefficients.

The results of study by Hurber and Bednar suggested that the low scattering coefficients produce high reverberation times in the simulation. Reverberation time is increased when the absorption coefficient is not uniform [35].

Following is a comparison of the effect of plant species and percentage coverage of the plants on the absorption and scattering properties of vegetation.

Table 7 illustrates the absorption coefficient of 6 different plant species for each vegetation coverage. Table 7 shows that the absorption coefficient trends of different species are more similar as the coverage density increase.

Table 7. Absorption coefficient of all species with 100%,50% &25% vegetation coverage (Frequencies between (1000-4000 Hz)



With the least vegetation coverage (25%), the difference between species on sound absorption is more pronounced. At 50% coverage it is clear that at frequencies above 1000 Hz, the trends are more similar. At 1600 Hz frequency all species with 50% coverage have about the same absorption. At frequencies higher than 1600 and with 50% vegetation coverage, Spider Plant is the most absorptive and Pilea, Creeping Fig, Fern, Golden Pothos and Ivy are the next absorptive ones respectively. At 100% coverage, the type of species is significant only at high frequencies. Between 1000 Hz and 2000 Hz, the type of the plant does not make any difference in terms of absorption. The results also indicate that the plant properties are more significant higher frequencies the variance in absorption increases with increasing frequency but is dimension as coverage increase. (Table 7)

Table 8 below shows the absorption coefficient result between 200Hz and 2500 Hz. A Sound Absorption Average (SAA) value is a single number rating that indicates the level of sound absorption provided by the product being tested [28].
The SAA value is the average of the sound absorption coefficients at twelve 1/3-octave frequencies ranging from 200 to 2500 Hertz. The results shown in Table 8 indicate that at 100% coverage, different species behave differently in terms of absorptivity at different frequencies.

Table 8. Absorption value for 6 plant species planted on the turning table at three different coverage percentages

Species	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	SAA	NRC
Golden Pothos 25% cov	0.24	0.26	0.17	0.22	0.29	0.33	0.41	0.34	0.37	0.37	0.36	0.39	0.31	0.3
Golden Pothos 50% cov	0.19	0.22	0.11	0.29	0.25	0.35	0.46	0.35	0.36	0.37	0.37	0.44	0.31	0.31
Golden Pothos 100% cov	0.33	0.27	0.22	0.39	0.35	0.35	0.46	0.37	0.39	0.41	0.41	0.47	0.37	0.36
Ivy 25% cov	0.08	0.13	0.19	0.17	0.21	0.18	0.31	0.33	0.30	0.33	0.33	0.41	0.25	0.25
Ivy 50% cov	0.09	0.16	0.26	0.16	0.25	0.20	0.32	0.29	0.31	0.36	0.37	0.45	0.27	0.27
Ivy 100% cov	0.18	0.29	0.37	0.27	0.31	0.28	0.37	0.35	0.38	0.41	0.43	0.45	0.34	0.34
Pilea 25% cov	0.28	0.36	0.26	0.11	0.21	0.45	0.42	0.38	0.39	0.41	0.33	0.45	0.34	0.32
Pilea 50% cov	0.14	0.18	0.48	0.24	0.23	0.38	0.40	0.40	0.40	0.40	0.40	0.47	0.34	0.34
Pilea 100% cov	0.20	0.26	0.52	0.41	0.46	0.36	0.44	0.41	0.39	0.40	0.44	0.49	0.40	0.40
Creeping Fig 25%	0.15	0.13	0.18	0.23	0.33	0.29	0.38	0.34	0.37	0.39	0.40	0.43	0.30	0.30
Creeping Fig 50% cov	0.19	0.29	0.12	0.32	0.29	0.24	0.48	0.40	0.38	0.37	0.34	0.42	0.32	0.32
Creeping Fig 100% cov	0.26	0.14	0.10	0.33	0.33	0.33	0.48	0.40	0.35	0.38	0.44	0.49	0.34	0.33
Spider Plant 25% cov	0.51	0.53	0.37	0.43	0.51	0.45	0.58	0.50	0.44	0.45	0.44	0.56	0.48	0.40
Spider Plant 50% cov	0.29	0.53	0.09	0.32	0.30	0.42	0.43	0.44	0.41	0.37	0.41	0.50	0.38	0.37
Spider Plant 100% cov	0.00	0.17	0.00	0.36	0.43	0.23	0.43	0.37	0.41	0.44	0.38	0.53	0.31	0.31
Fern 25% cov	0.08	0.06	0.09	0.09	0.11	0.12	0.12	0.11	0.12	0.14	0.14	0.17	0.11	0.1
Fern 50% cov	0.30	0.22	0.00	0.19	0.42	0.33	0.42	0.33	0.33	0.36	0.33	0.43	0.31	0.3
Fern 100% cov	0.25	0.21	0.00	0.18	0.35	0.48	0.44	0.39	0.35	0.40	0.42	0.50	0.33	0.33

Averaging the absorption from the six plant species at different level of coverage it is illustrated that, in general, the absorption coefficient increases with increasing the plant species density of coverage (Figure 80).

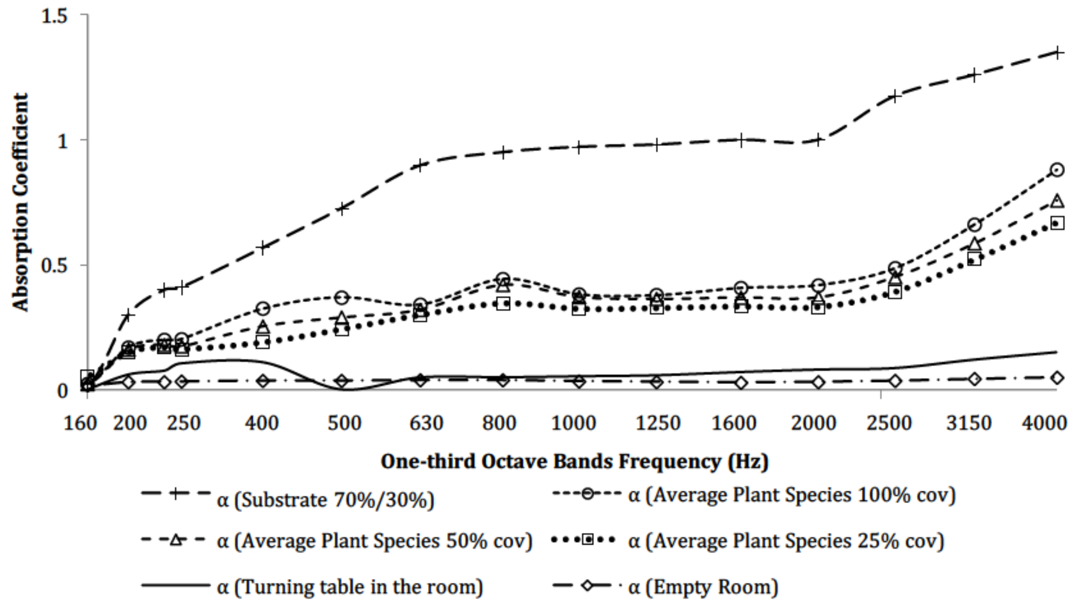


Figure 80. Average absorption coefficient of 6 different species with 3 different vegetation coverage, Empty room and turning table in the room

6.2.1. Scattering

The impact of plant coverage on sound scattering was investigated for each vegetation species. As expected the overall trend is similar to absorption, scattering increases with frequency. However, the variance in scattering between the plant species increase with increasing coverage. Table 10 compares the scattering coefficient of 6 different plant species at the same vegetation coverage for frequencies between 1000 Hz and 4000 Hz.

Table 9 illustrates the NRC (Scattering) of six species under study at 25%, 50% and 100% coverage respectively.

According to Table 10 it is clear that at 100% coverage, Spider Plant, Creeping Fig, Fern and Golden Pothos scatter more sound energy at mid frequencies (between 1000 and 2500 Hz) with the average sound scattering of 0.24, 0.19, 0.187 and 0.14 respectively in comparison with Ivy and Pilea with 0.5 and 0.4 sound scattering average respectively.

Table 10 shows that the scattering coefficient results for 6 species with a density of 50% coverage follows a similar trend to 100% coverage. Sound scattering average for Spider Plant, Golden Pothos, Creeping Fig, Fern, Pilea and Ivy is 0.15, 0.13, 0.11, 0,06, 0.04 and 0.01 respectively at frequencies between 1000 Hz and 2500 Hz. With even less vegetation coverage (25%), the difference between species sound scattering is more pronounced.

Table 9. NRC (Scattering)of different species at 25%, 50% and 100% coverage

NRC(Scattering)	Golden Pothos	Ivy	Pilea	Creeping Fig	Fern	Spider Plant
25% cov	0.07	0.002	0.008	0.18	0.09	0.19
50% cov	0.17	0.02		0.13	0.07	0.18
100% cov	0.16	0.05	0.05	0.26	0.2	0.26

Table 10. Scattering coefficient of 6 different species, 100%, 50% & 25% vegetation coverage

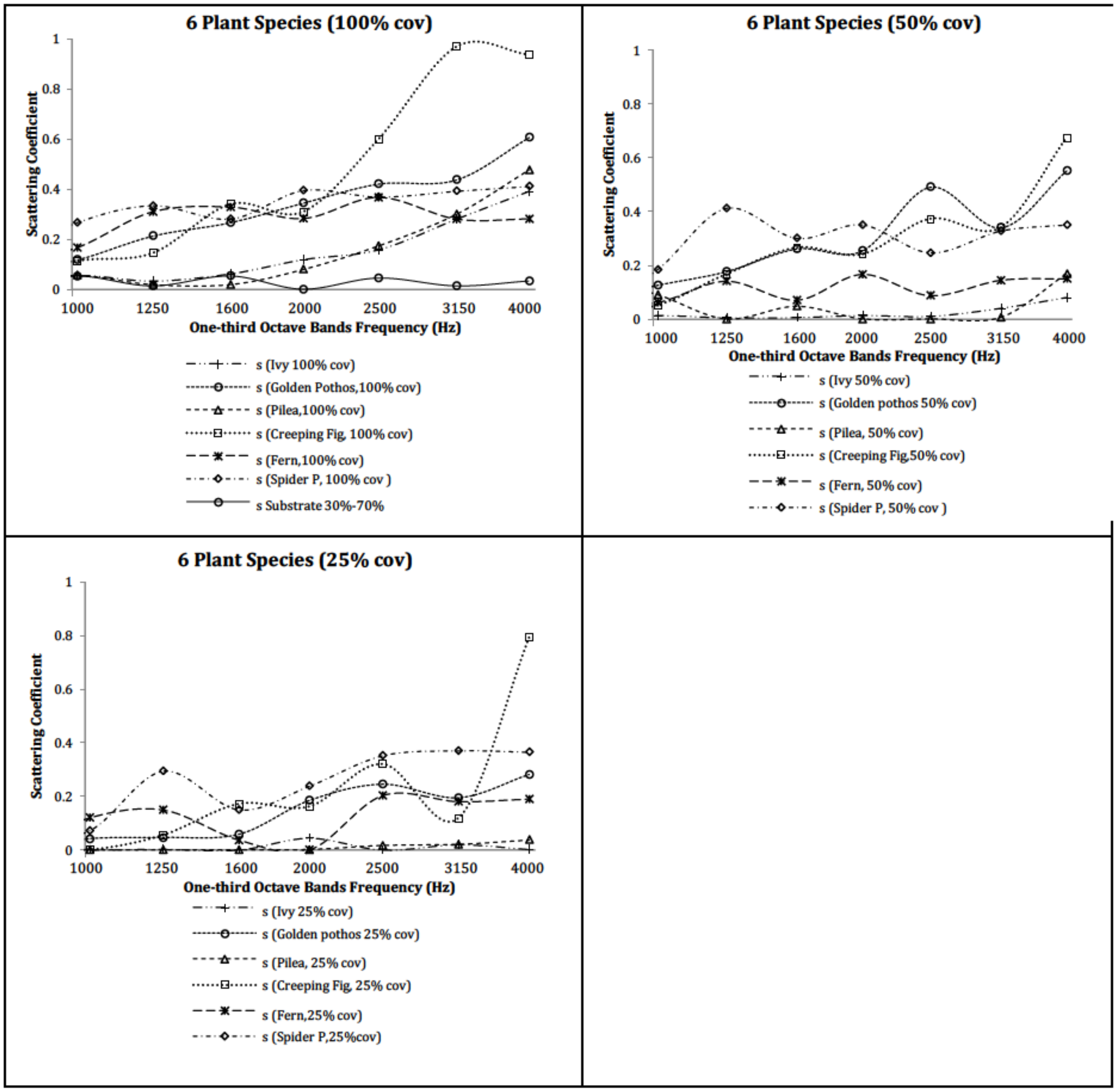


Figure 81 illustrates that scattering coefficient (averaged between all species) increases with vegetation coverage above 500 Hz. It can be concluded that the vegetation density, evaluated as coverage percentage is important in increasing the scattering coefficient.

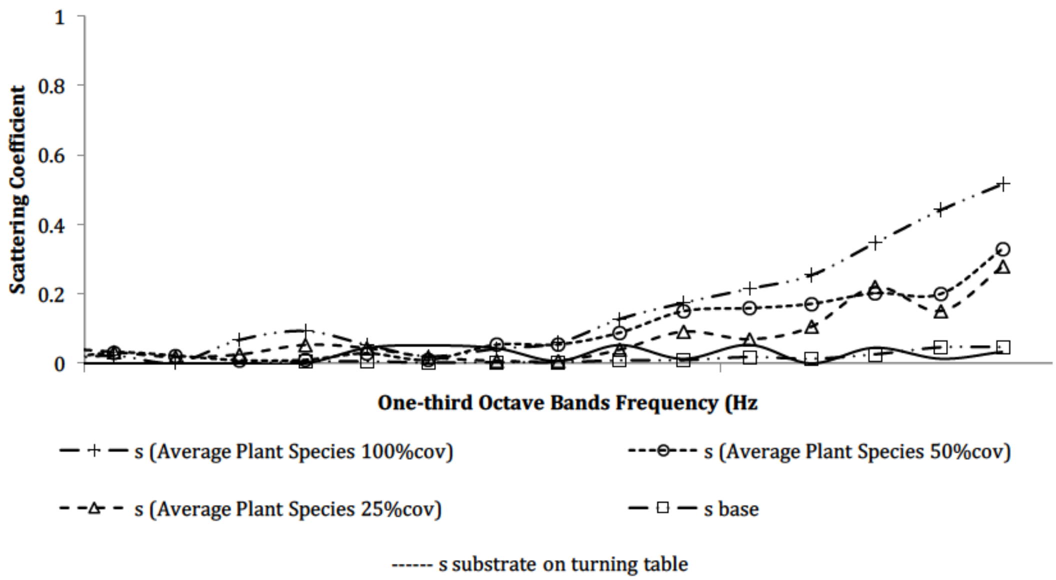


Figure 81. Average scattering coefficient of 6 different species with 3 different vegetation coverage, and turning table in the room

6.2.2. The relationship between the absorption & scattering coefficient and the properties of six available species

Absorption and scattering and plant properties measurements were completed on plant species at 1/3-scale. From the measurements, it was investigated how significantly plant characteristics (section 5.3) can affect absorption and scattering coefficients.

The relationship between the acoustical characteristics of absorption and scattering) and the properties of the six plant species was examined using simple scattering plots to identify possible correlations.

The relationships between the absorption coefficients and scattering coefficients to properties of the plants are presented in Appendix 6. The plants characteristics Height, leaf thickness, stem diameter, leaf length, dry mass, wet mass and leaf area are independent variables. Additionally, compounded variables were examined including; Leaf Number * Leaf Area, Leaf Number * Leaf Area * Leaf Thickness, Leaf Number * Leaf Area * Stem Diameter, Leaf Number * Leaf Area * Stem Diameter * Height, Leaf Number * Leaf Area * Wet Mass, Leaf Number * Leaf Area * Dry Mass. Recall that Leaf Number * Leaf Area is the total leaf area which is not equal to LAI.

In general, the correlation suggests that, LAI*Mass (dry and wet) predicts scattering coefficients at mid-frequencies (200 - 2500 Hz) and absorption coefficient at high frequencies (2500-5000).

There is a weak indication that total leaf area and mass in the range of 200 and 2500 Hz have an impact on the absorption coefficient of the vegetation (Appendix 6-Table A). At high frequency, the correlate of total leaf area and absorption is slightly stronger (Appendix 6-Table B). At the specific frequency of 1333 Hz (Appendix 6-Table C), there is clearer indication of relation between absorption coefficient and

total leaf area and with the compound variables of LN * LA Mass and also LN * LA * Leaf thickness. Those appear strongly related to scattering at 1333 Hz though (Appendix 6-Table E).
With respect to the correlation of plant properties, total leaf area * mass may relate to the average scattering coefficient (Appendix 6-Table D-F). There is a weak indication, which asks for further investigation.

In order to have results from multiple regressions modelling, more samples are required. This is a further exploration of the study by Attenborough [3], that found the absorption by leaves to be important at high frequencies above 1kHz, whereas below 1 kHz there is little sound absorption by leaves.

6.3. Solving for the acoustical coefficient

Living wall panels are usually used in a combination of geometric arrangements and because there is a diversity of application of Living Wall Systems, it is desirable to have an absorption coefficient for predictive modelling. Therefore converting the measured Sabine to an absorption coefficient value is required.

Result indicates that for both Carrier A and Carrier B the absorption (Sabine) does not increase linearly with the number of panels (Figure 59). The panels are in a 3-dimensional shape with complex surfaces. The unusual shape of the panels and the fact that the effective area changes with an assembly of multiple panels must be taken into account. Two methods were attempted to derive the absorption coefficient of the living wall systems. The first method calculates the absorption coefficient by dividing the area of the test specimen into the measured Sabine (Equation 7).

The second method involved developing frequency dependent linear regression equations to resolve the coefficient.

It was considered that the acoustical effective area, may be different from the architectural area of the living wall unit and that the acoustical effective area could be determined.

6.3.1. Attempted method one

The ratio of absorption (Sabine) over area should be the same regardless of the number of panels. However, using architectural area (defined as 2D area) of the panels in the ratio resulted in a mismatch between 3 and 1 Carrier A as shown in Figure 82. To address this problem, an effective acoustical area was derived.

The first approach simply summed the total exposed surface areas of the panels in a living wall geometric configuration.

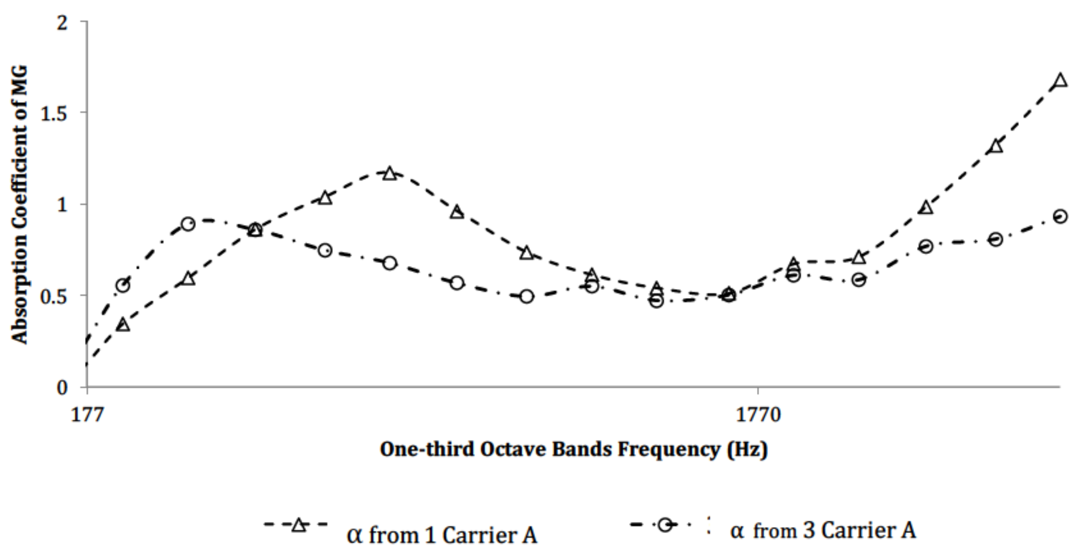


Figure 82. measured absorption coefficient of 1 Carrier A

Simple geometrical approach

The effective acoustical area (Equation 10) for multiple panels (1, 2, 3, …, n) each living wall system is:

Effective Area = n1(ab)+n2(bc)+n3(ca) *Equation 11*

Where n= number of exposed surfaces of a geometric and configuration

And a, b, c= the dimension of the panel

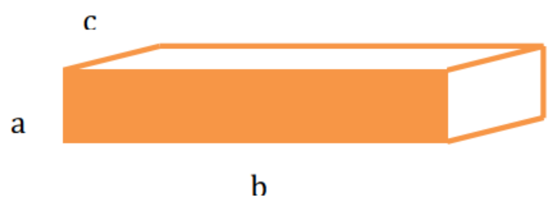


Figure 83.Sample box

Using this simple geometric approach to did not result in a consistent absorption coefficient.

Complex geometric approach

The second approach used complex geometry to describe the carrier and leaf area index to describe the expose surfaces of the plants and drive the acoustical effective area. This area is calculated by measuring the sides and the main area of the panel. The substrate and leaf areas are both estimated using the Leaf Area Index (LAI) of 40 pots for every panel. But even with this calculation, the acoustical effective area did not result in a consistent absorption coefficient (Sabine over area ratio) for 3 and 1 Carrier A panels.

Neither geometrical approach provides valid method to derive the absorption coefficient over the frequency spectrum (125 Hz to 4000 Hz). Further according to

Figure 58 and 59 (section 5.2.3), the ratio between the absorption of different number of carriers varies with frequency. This suggests that the effective acoustical area is frequency-dependent.

6.3.2. Resolving equation

The goal here is to derive total absorption for a specific number of panels. Figure 84 illustrates the plotted average Sabine absorption (range from 200 to 2500 1/3 octave data) from all three types of living wall system. Using a linear approximation, Equation 12, can be derived for calculating for the average SABINE panel. The number of panels used in total there were 15 measurement of a single panel, 6 measurements of three panels, 3 measurements of four panels and 3 measurement of eight panels. Repeating the same procedure for NRC range (one-octave band 250 and 2000 Hz leads to finding Equations 14-19.

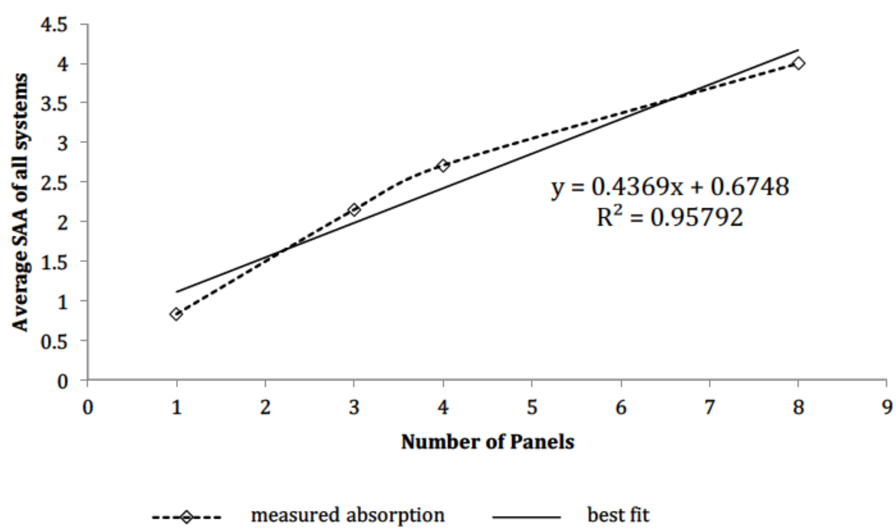


Figure 84.relationship between the average Sabine and quantity of panels

* The R^2= 0.95792 indicates that the linear regression model has a high level of fit with the measured data. Although there is a limited statistical power due to the number of samples.

$Sabine_{(200\text{-}2500\,Hz)} = 0.4369\,N + 0.6748$ *Equation 12*

$Sabine_{(200\text{-}2500\,Hz)} = 0.4577\,N + 0.7167$ *Equation 13.*

N= Number of panels

However, the absorption of the panels are frequency-dependent. Therefore, using the same methods mentioned above (Figure 86), the following equations were derived for each frequency.

These equations are based on panel size between 0.36 and 0.72 where N is number of panel.

$Sabine_{125} = (0.1054\,N + 0.1435)$ *Equation 14.*

$Sabine_{250} = (0.6485\,N + 0.7537)$ *Equation 15.*

$Sabine_{500} = (0.4346\,N + 0.744)$ *Equation 16.*

$Sabine_{1000} = (0.2665\,N + 0.79063)$ *Equation 17.*

$Sabine_{2000} = (0.4358\,N + 0.8144)$ *Equation 18.*

$Sabine_{4000} = (0.6896\,N + 0.8515)$ *Equation 19.*

Equation 14 to 19 were used for the room sensitivity analysis (section 6.4)

6.3.3. Scattering coefficient for application in Odeon

Surface scattering functions used in Odeon are derived from Rindal theory. In Odeon the scattering coefficient for the middle frequency of 707 Hz, is required as an input for the materials list, Odeon expands this coefficient into values for each octave-band [43].

In order to find the 707 Hz scattering coefficient value for each species the scattering coefficient results from lab measurement for each species was plotted in a graph along with the values generated by Rindal algorithm (figure 87).

Odeon results vs. lab measurements

Scattering coefficient of 6 different species is measured at different frequencies as shown in Figure 85.

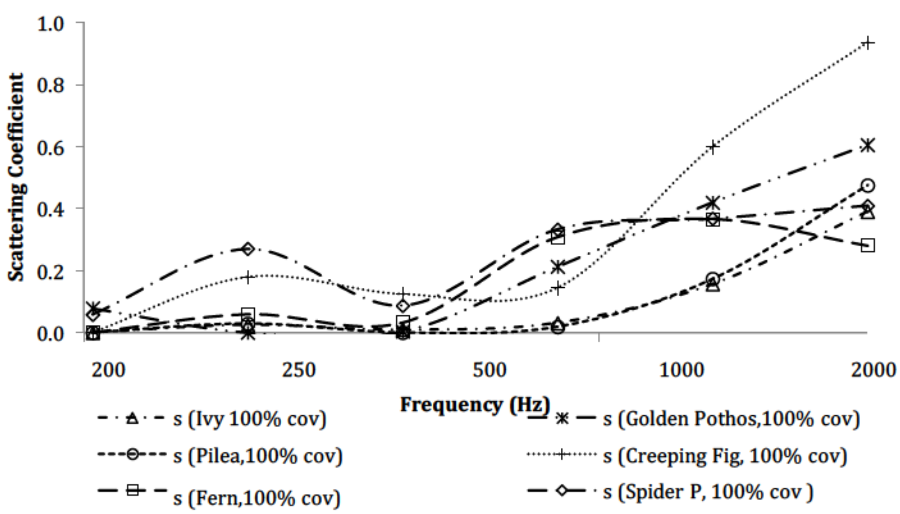


Figure 85. Scattering coefficient of six species results from Lab measurements

Figure 86 below illustrates the average scattering coefficient of the same species excluding the Creeping Fig. The average scattering coefficient is 0.11 for the middle frequency of 707 Hz (average of 500-1000 Hz). As Odeon, the coefficient is expanded into scattering coefficients values for each octave band – by interpolation or extrapolation. The graph labeled 0.11 in Figure 87b shows the result.

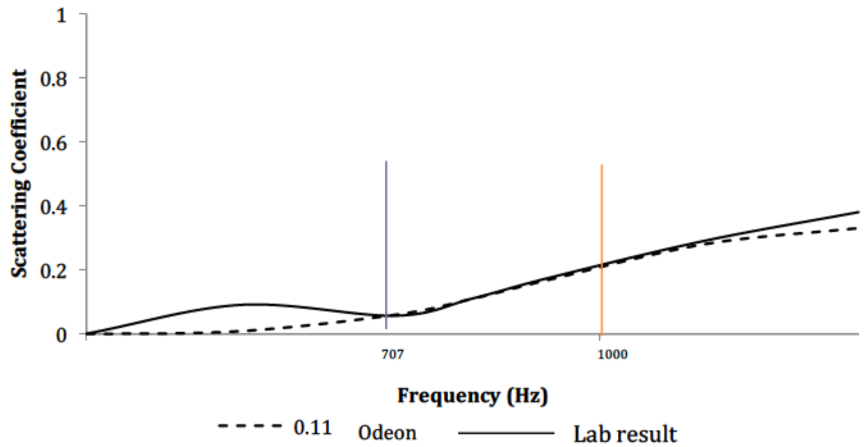


Figure 86. Scattering results from Lab measurements & Odeon suggested scattering coefficients (Frequency functions for Plants at 707 Hz) [43])

Comparing the average scattering coefficient from the lab measurements with Odeon software's expanded scattering coefficients, it was determined that graphs align well in the mid and high frequencies. Although the lab results suggests some more scattering in the low and high frequencies than the Odeon model.

6.4. Room sensitivity analysis

Odeon was used to estimate the reverberation time of a 56 m^2 room size space, with and without the living walls. The effect of different configurations of living wall systems in the room were modeled. In addition, the sensitivity of using the empirically measured scattering coefficient value to the living wall surfaces was analyzed.

6.4.1. Room definition

The case study could be a typical office or small classroom size space. The room dimensions were set at 7.5m * 7.5 m and height 3.5 with the base drywall condition developed was on all wall surfaces and concrete for the floor and ceiling surfaces. The point source was located in the middle of the room at 1-meter height. One source in the room and five-receiver locations were randomly located.

First, the base condition was modeled. Second, the room was modeled with one wall covered with living wall systems (21 1-m^2 panels). Third, the room was modeled with 2 walls covered with living wall systems parallel and perpendicular to check the effect of different configurations of living walls. Finally, the case study was also modeled with all 4 walls covered with the living wall system. The models were repeated with and without considering scattering coefficient. The Odeon model default for scattering was not used. The scenarios modeled included scattering coefficient of 0 for all surfaces, scattering coefficient of 0 for wall, floor, and ceiling surfaces, and scattering coefficient value derived from lab data for living walls surfaces.

For the first series of Odeon models, the assigned absorption was derived from equations 13 to 18. The assigned scattering coefficient was taken from Section 5.3.3. For the second series, both absorption and scattering coefficient of the living wall surfaces were taken from 1/3-scale measurements on a turning table (Section 5.3).

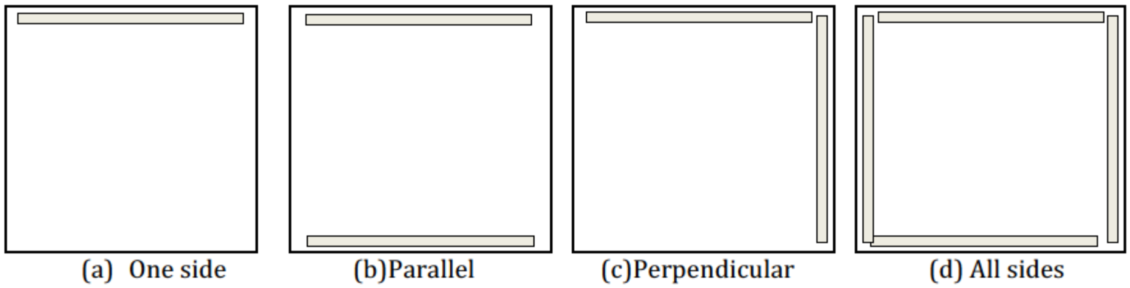


Figure 87. Living walls different configurations in room.

6.4.2. Model the room effect of living walls

The vegetated living wall systems in the room were modeled in Odeon using absorption values and scattering coefficient found from lab measurements (5.3.3)

Figures 88, 89 and 90 illustrate that the difference between the result of reverberation time living walls with and without the scattering coefficient, is more dramatic for the room with 1 living wall, 21 panel with 2 living walls, 42 panels or 4 living walls, 84 panels.

As seen in Figure 88, Odeon result shows the significant difference in reverberation time between the model that includes the scattering coefficient of the living wall area and the model with scattering coefficient set to 0 for all surfaces. Reverberation time values increase by about 0.25 through all frequencies when scattering is considered. This emphasizes the importance of considering the scattering coefficient when using Odeon software modelling for the acoustical evaluation of the space.

Figure 90 illustrates that when all the four walls of the room are covered with living walls, applying the scattering coefficient to the living walls surfaces does not make a significant difference in terms of reverberation time in the room.

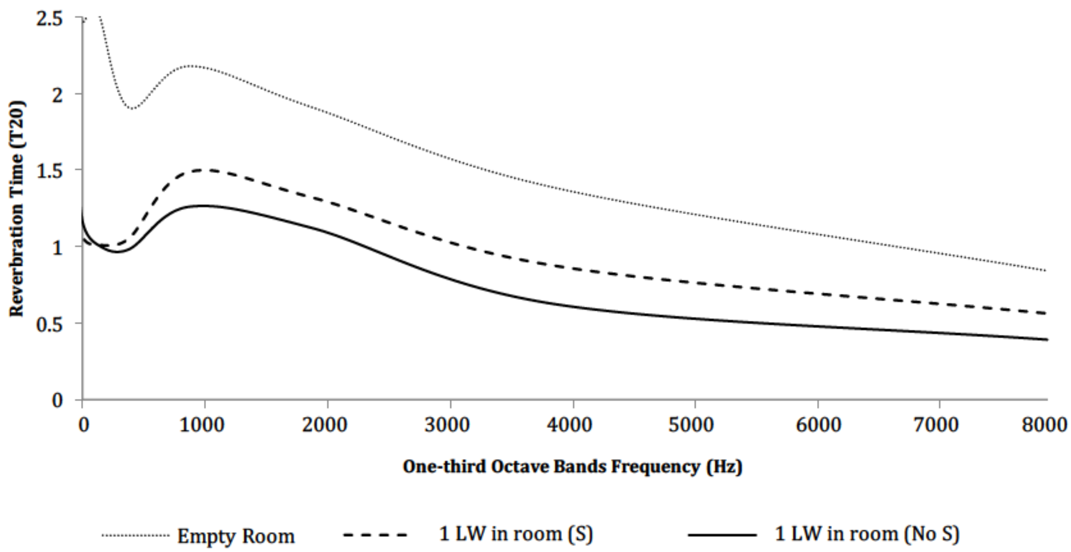


Figure 88. Reverberation time of the room with living wall on one side; sc=0 vs. sc value

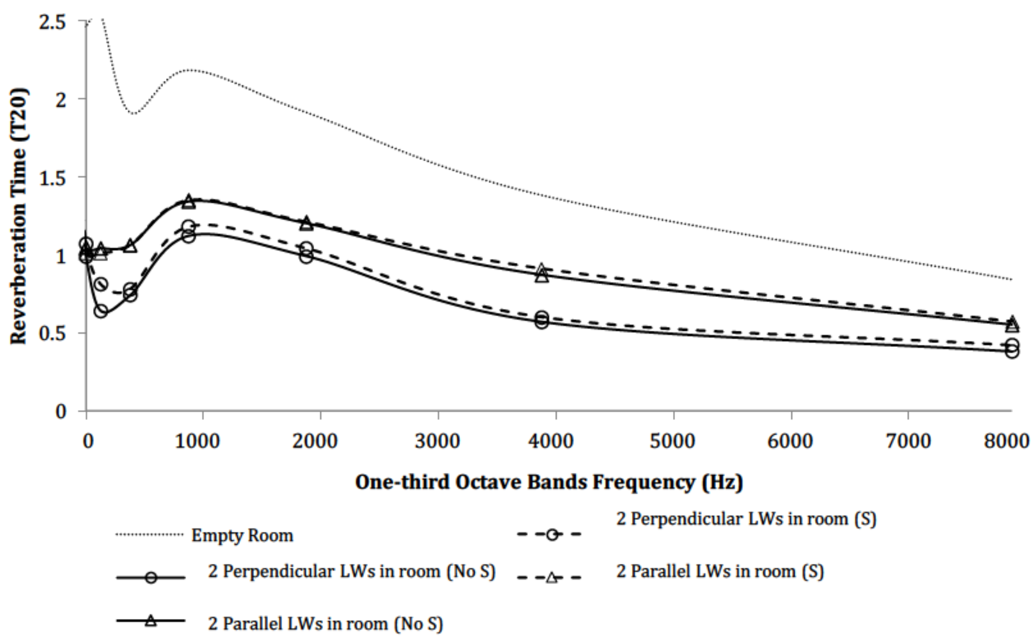


Figure 89. Reverberation time of the room with living walls on two sides; sc=0 vs. sc value

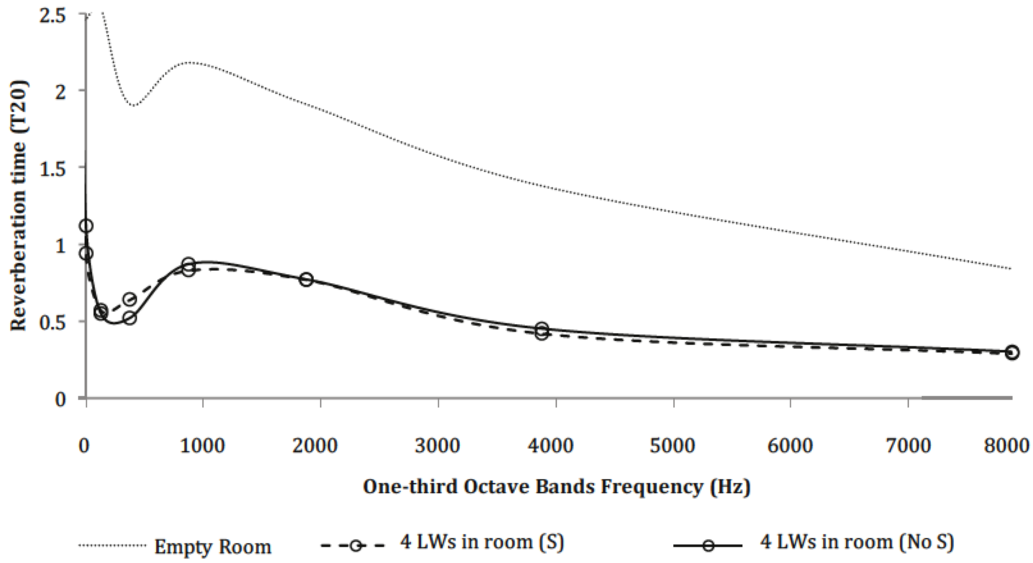


Figure 90. Reverberation time of the room with living walls on all sides; sc=0 vs. sc value

No S: Scattering coefficient wasn't applied to any surface of the model

S: Scattering coefficient was applied to the surfaces covered with living wall

LW: Living wall

In the second series of model of the absorption coefficients and the scattering coefficients obtain in the laboratory measurements by the ISO method were used. Similar to the first series of modelling the use of the scattering coefficient increases the overall room reverberation time by a fraction 0.2 seconds.

Figure 91 shows the effect of number of living walls and their different configurations in-room on reverberation time. At 1000 Hz, the reverberation is 1.5, 1.4, 1.2 and 0.8 for 1, 2 parallel, 2 perpendicular and 4 living walls, respectively. It can be seen that the perpendicular installation is more effective than parallel installation in terms of reverberation time of the room. Above 4000 Hz, the reverberation time with 1 wall covered with living wall and 2 parallel walls covered with living walls are equal. 2 perpendicular living walls and 4 living walls in the room follow the same trend, while adding 2 more perpendicular walls for a total of 4 walls reduces reverberation time by about 0.3 at low frequencies and 0.2 at frequencies after 4000 Hz. The graph shows that, in general, increasing the number of living walls decrease the reverberation time of the room and keeping the walls perpendicular is more efficient than having them in parallel. These model is include the absorption values derived from equation 12-19 and to lab measured scattering coefficient.

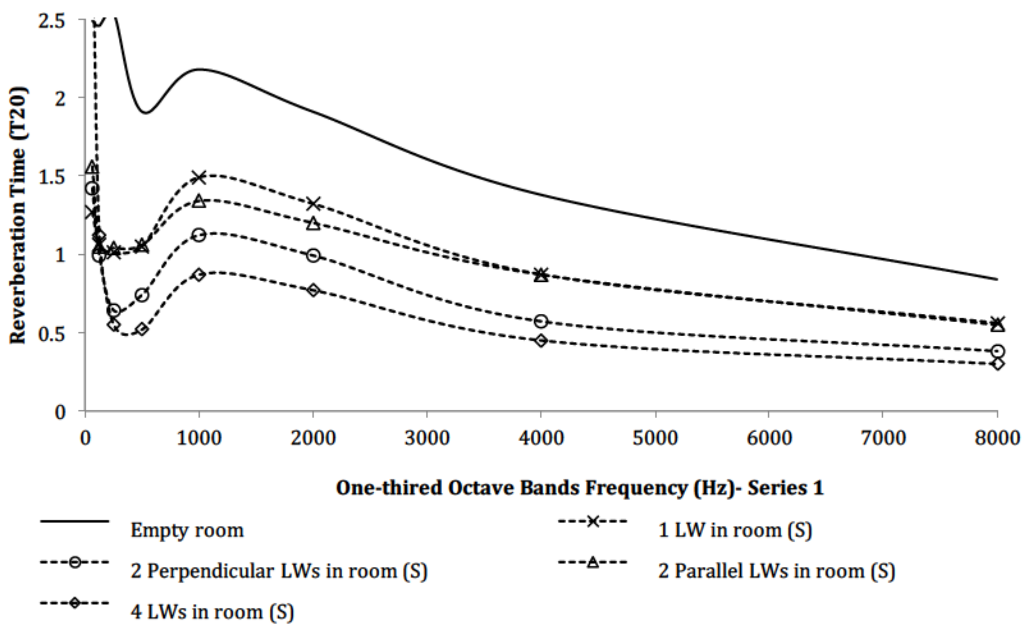


Figure 91. Reverberation time of the room with different configurations (Empty room is base line)

Figure 92 shows reverberation time of plant species with two different absorption coefficients. The Odeon model is implemented for species on turning table and the ones on living wall panels.

The graphs labeled "S" shows the result of reverberation time with scattering coefficient applied to the living walls. Reverberation time increases by applying scattering coefficient in both cases.

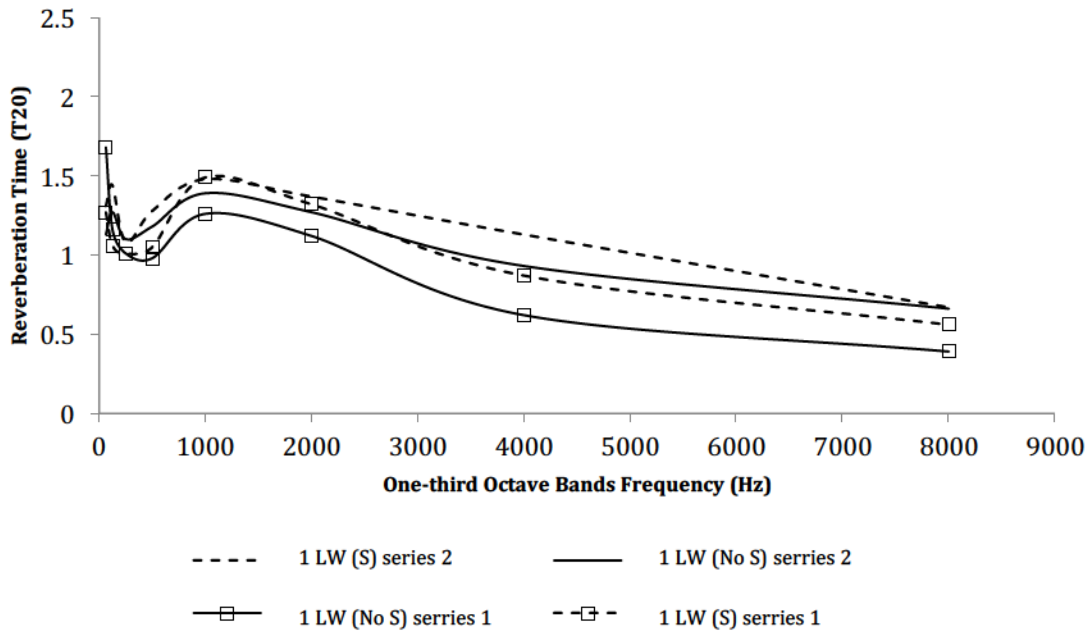


Figure 92.Reverberation of the room with different absorption coefficient values for living walls.

7. CONCLUSIONS AND OUTCOMES

In this interdisciplinary research the basis of the data analysis was to find optimal carrier properties for efficient sound absorption in interior living walls.

Experimental data for sound absorption properties of materials is an essential tool for noise control specialists. In this research, acoustical characterizations of interior living walls are measured. The evaluation goal is to quantify the impact of the interior living walls on indoor acoustical quality. A series of measurements were carried out in a reverberation chamber to examine random-incidence absorption coefficients of full living wall system, also random-incidence absorption and scattering coefficient of a variety of vegetation, considering various factors such as vegetation types and vegetation coverage. The final step was modelling the case study by using the data from the lab measurements to investigate the model sensitivity to the data.

Two methods were established for obtaining data on the acoustical characteristic of living walls in reverberation chamber. First one is the absorption measurement of living wall system at full scale and second one is the 1/3 scale absorption and scattering measurements of living wall plant species.

When comparing absorption (Sabine) of empty, vegetated and carriers filled with substrate to one another, it is clear that the absorption of all living wall panels have the same trend with variation in absorption due to different materials and geometry of the panel. Adding substrate and plant to carriers changes their relative performance and for the substrate base system negates the differences of panel construction. The research confirmed that drier substrate mix absorbs significantly more sound than the substrate in field capacity. At mid and high frequencies, the result showed that the planted panel is less absorptive than the panel that is filled with substrate. The vegetation improves the low frequency absorption however it inversely influences the mid and high frequency absorption.

The impact of the three different levels of plant coverage in sound absorption and sound scattering was investigated for each plant species. From the results it can be concluded that the absorption coefficient and scattering coefficient increases with increasing the plant species density of coverage. With less vegetation coverage, the difference between species sound scattering is more pronounced. While the absorption coefficient trends of different species are more similar as the coverage density decreases

In this study the relationship between the absorption coefficient and scattering coefficient and the properties of the plants was presented.
There is an indication that at mid frequencies total leaf area and mass have an impact on the absorption coefficient of the vegetation. It can be concluded that LAI*Mass (dry and wet) predicts scattering coefficients at mid-frequencies (200 - 2500 Hz) and absorption coefficient at high frequencies (2500-5000).

Two series of Odeon models with considering different method of assigning absorption and scattering values for living wall surfaces was used to estimate the reverberation time of a room, with and without the living walls. The result using data from the measurement of fully establish, rather than plant species data is most plausible. Results show that vegetation decreases the reverberation time and increasing the number of living walls decrease the reverberation time of the modeled room. Results also illustrate the importance of considering the scattering coefficient when using Odeon software modelling and scattering coefficient data is more essential for smaller living wall installations. Also different configurations of living wall systems were modeled.

Some differences with previous studies were found in terms of the sound absorption coefficient, most likely due to the differences in the tested constructive. However, despite these differences, the potential of the green wall sound absorption tool for buildings can be confirmed. It could be concluded that green walls can be used as a sound absorptive materials inside the buildings. We also concluded that the effect of the type of the plant on absorption and scattering of the living walls is not noticeable in practice.

The practical consideration for designers of soil-based living wall systems is that the primary determining factors in absorption and scattering is the amount of soil and plant coverage for a given living wall system's surface area. This is true even when empty carriers have different absorption and scattering characteristic. It should also be noted that type of the plant species has limited impact on absorption and scattering of the living wall system.

The main contribution of this research is to characterize and introduce interior living walls as a sustainable and acoustically beneficial material to the designer team and to provide the designers with practical means to evaluate an installation of the living wall systems. Absorption and scattering coefficients are now available for room prediction.

8. FUTURE WORK

This interdisciplinary research goal is to look at the potential of the interior living wall and enable more sophisticated and mature use of it. The results of these evaluations provide us with enough information to explain the acoustical benefits of using interior living walls. Eventually**,** with an understanding of all the mentioned factors and parameters, the efficiency of living walls can be optimized to improve the acoustical environment of a room.

To determine the exact influence of the scattering coefficient on the reverberation time, further statistical analysis is necessary. To determine the validity of the measured data a cross examination of room prediction modelling and field measurements are required.

GLOSSARY AND ABBREVIATIONS

Absorption coefficient: A value that shows how efficient a material absorbs incident sound.

Diffuse sound field: Sound field in which the incident sound intensity on a plane surface is equally distributed over all solid angles covering a hemisphere [17].

Hydroponic: The technology of growing plants without soil.

Interrupted noise method: Method of obtaining decay curves by direct recording of the decay of the sound pressure level after exciting a room with broadband or band-limited noise [18].

Integrated impulse response method: Method of obtaining decay curves by reverse-time integration of the squared impulse response [18].

Impulse response: Temporal evolution of the sound pressure observed at a point in a room as a result of the emission of a Dirac impulse at another point in the room [18].

Moisture Content (MC): The amount of water in a material like soil [42].

Noise Reduction (NR): Noise level measured at source position minus noise level measured at receiver position.

NRC or NRCC: National Research Council of Canada.

Real Time Analyzer (RTA): Instrument for measuring an acoustic property.

Reverberation Time (RT): The time it takes for sound levels to attenuate by 60dB within a space, important acoustically for calculation of room sound absorption [41].

SAA: The SAA value is the average of the sound absorption coefficients at twelve 1/3-octave frequencies ranging from 200 to 2500 hertz. [62]
sound absorption average, SAA—a single number rating, the average, rounded off to the nearest 0.01, of the sound absorption coefficients of a material for the twelve one-third octave bands from 200 through 2500 Hz, inclusive, measured according to this test method.

Sound Attenuation: Decrease in sound level.

Sound pressure level (SPL): is the ratio of the absolute, **Sound Pressure** and a reference **level** which is the threshold of hearing. **SPL** is presented in a logarithmic value of decibels (dB) [41].

Specular reflection: reflection that obeys Snell`s law, i.e. the angle of reflection is equal to the angle of incidence [17].

Speech Transmission Index (STI): A value to evaluate the speech transmission quality. Measuring some physical characteristics of a transmission channel, for instance a room, telephone line, etc. can determine the effect of transmission channel characteristics on speech intelligibility.

Speech intelligibility: A measure to predict how clearly speech can be understood in a room. (Vorland, Michael, Eckard)

Scattering: The difference between the total reflected energy and the specular reflected energy

AKNOWLEDGEMENTS

Special thanks to Dr. Maureen Connelly and to my fellow graduate student Rosa Lin and Ivan Cheung and to the committee members, Dr. Karen Bartlett and Michel Labrie MAIBC and everyone who has helped me along the way to make this thesis project possible.

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APPENDICES

Appendix 1: The considered acoustical standards and criteria in this research

Table 11. Standards

Acoustical Measurement Standards	
Primary Measurement Standards	- ANSI S_{12} :Measurement of sound pressure(indoors)
Laboratory Measurement Standards	- ASTM C-423: Sound absorption of materials
Field Measurement Standards	- ANSI S12.2: Criteria for evaluating room noise - ASTM E-1574: Sound pressure level in residential spaces - ASTM E-1130: Speech privacy in open offices - ASTM E-336: Airborne sound attenuation in buildings

Table 12. Criteria

Noise Level Criteria	
Lw, LwA	Sound power levels of a source
dB, dBA, dBC	Sound pressure levels at a receiver
NC	Indoor noise criteria, in octave bands
RC	Indoor room criteria, in octave bands
RC Mark II	Indoor room criteria in octave bands
NCB	Indoor balanced noise criteria, in octave bands
RNC	Indoor room noise criterion, in octave bands
ISO226	One of available criteria for evaluating low frequency noise

Appendix 2: Irrigation system

Table 13. System`s water flow (Irrigation system)

Wall (everything in kg)	Water (kg) in 5 min	Water Flow (Lit/Day)	Lit of water in 1 min
Modulo green - All	2.604	3.1248	0.5208
Modulo green - Top left	0.942	1.1304	0.1884
Modulo green - Bottom right	0.894	1.0728	0.1788
Plant connection - Top row	2.844	3.4128	0.5688
Plant connection - Middle row	3.047	3.6564	0.6094
Plant connection - Bottom row	2.195	2.634	0.439
Evergreen - All		2.748	

Appendix 3: 1/3 scaled turning table parameters

Table 14. Parameters and dimensions of turning table [45]

Parameters & Dimension of Turntable	ISO 17497-1 Standard	1/3 scale model	
		Actual	Represents
Diameter of Turntable	3.0 m	1.2 m	3.75 m
Area of Turntable	7.065 m²	1.23 m²	3.7 m²
Thickness of Turntable	-	1.5 cm	4.5 cm
Air gap below the table	As small as possible	9 cm	27 cm
Volume of chamber	Min 197 m³	88.78 m³	2397.06 m³
Frequency Range	40-5000 Hz	53-2333 Hz	160-5000 Hz

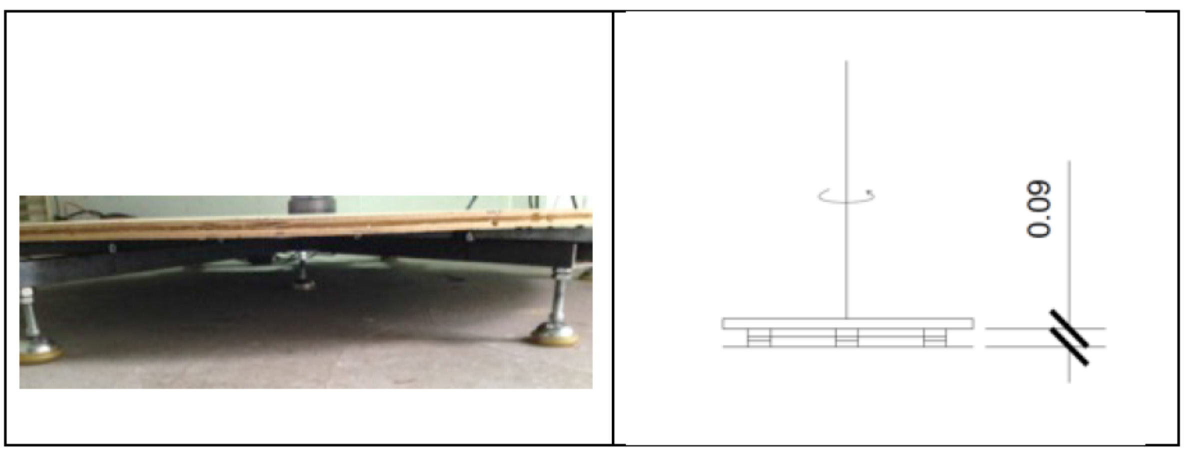


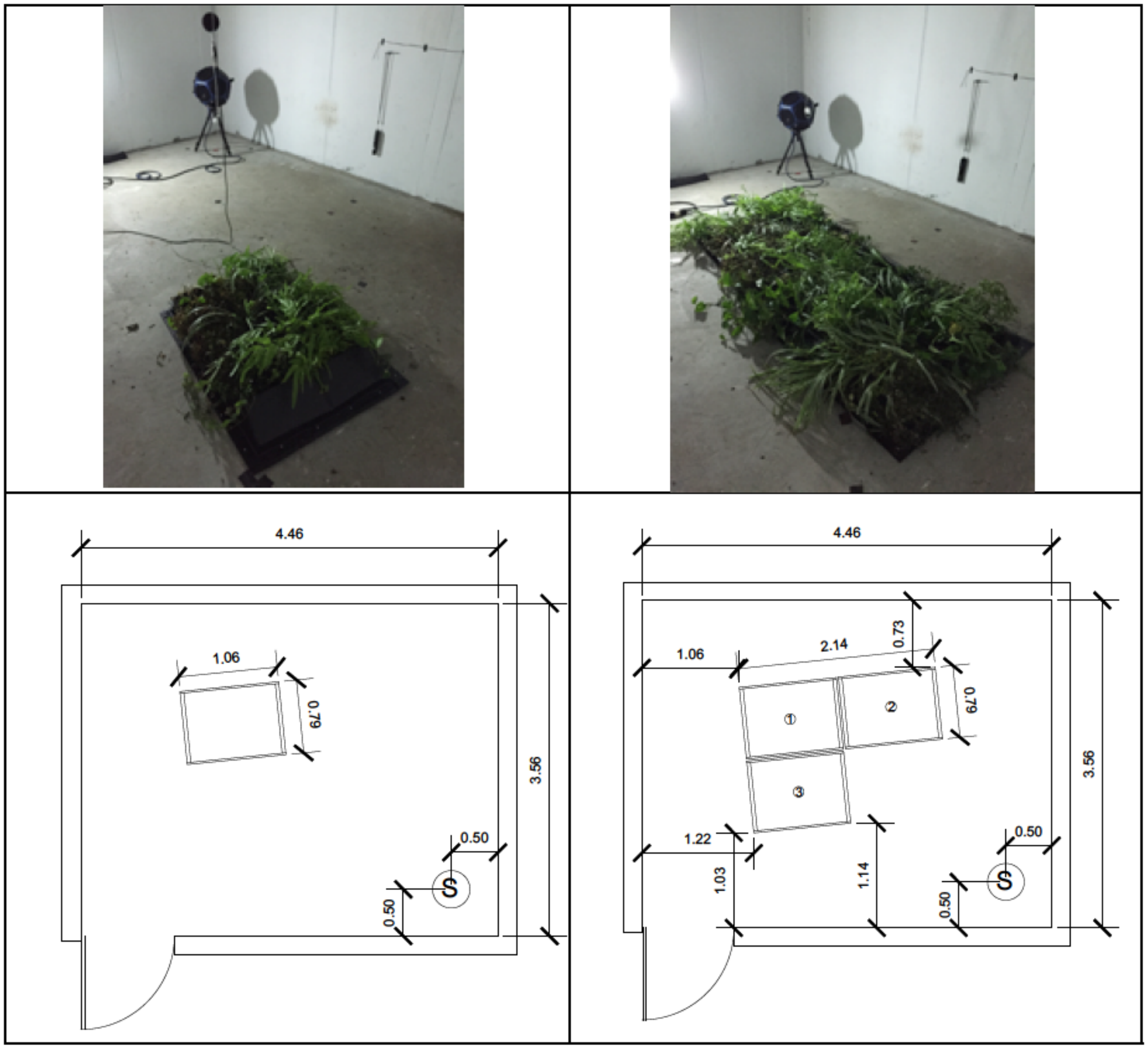
Figure 93. Section of turning table

Appendix 4: Equipment and facilities

The acoustic chamber used for absorption and scattering evaluation. The equipment required includes:

- Omni-directional speaker (must be implemented to achieve an excited, uniform, measured space.),
- RTA (real time analyzer),
- Test signal noise generator,
- Power supply and power,
- Pressure microphone,
- Computer to analyze the data,
- Scattering table
- Odeon software to be used for analyses.

Appendix 5: The measurement condition of Carrier A & B



(a)1 Panel (b) 3 Panels

Figure 94. The measurement condition of (a) 1 Modulo green panel and (b) 3 Modulo green Panels

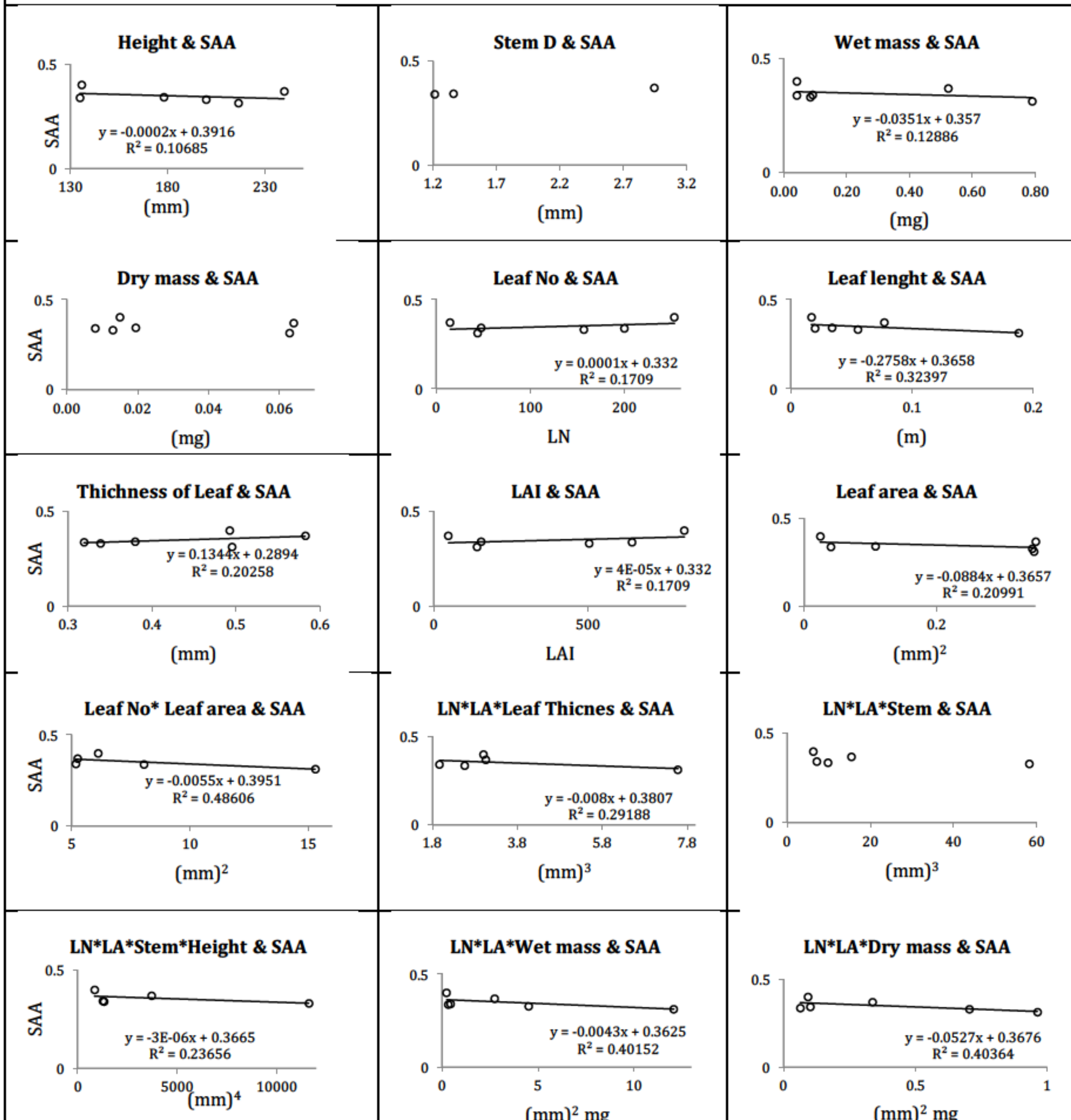
1 Panel	8 Panels

Figure 95. The measurement condition of Multiple plant connection panels

Appendix 6:

Table A. SAA Sound Absorption Coefficient (Average of 200 to 2500 Hz) & Plant Properties

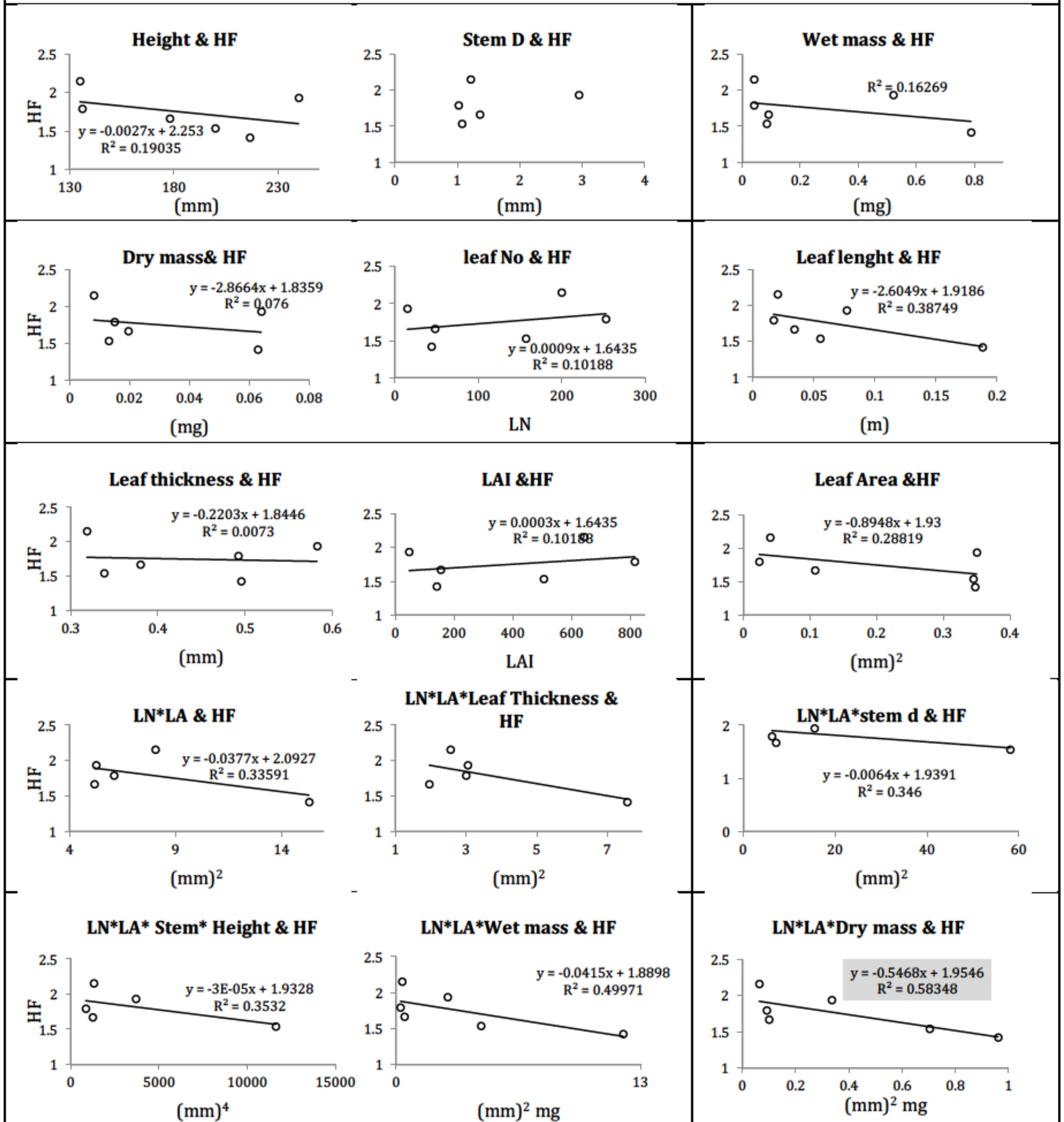
Plant Properties



LN: Leaf Number of plants under measurements on scattering table. **LA**: Leaf Area (mm^2). **SD**: Stem Diameter

Table B. Sound Absorption Coefficient, High Frequencies, (Average of 2500 to 5000) & Plant Properties

Plant Properties



HF: Sound Absorption Coefficient Average of High frequencies (2500-5000)

Table C. Sound Absorption Coefficient (At 1333 Hz) & Plant Properties

Plant Properties

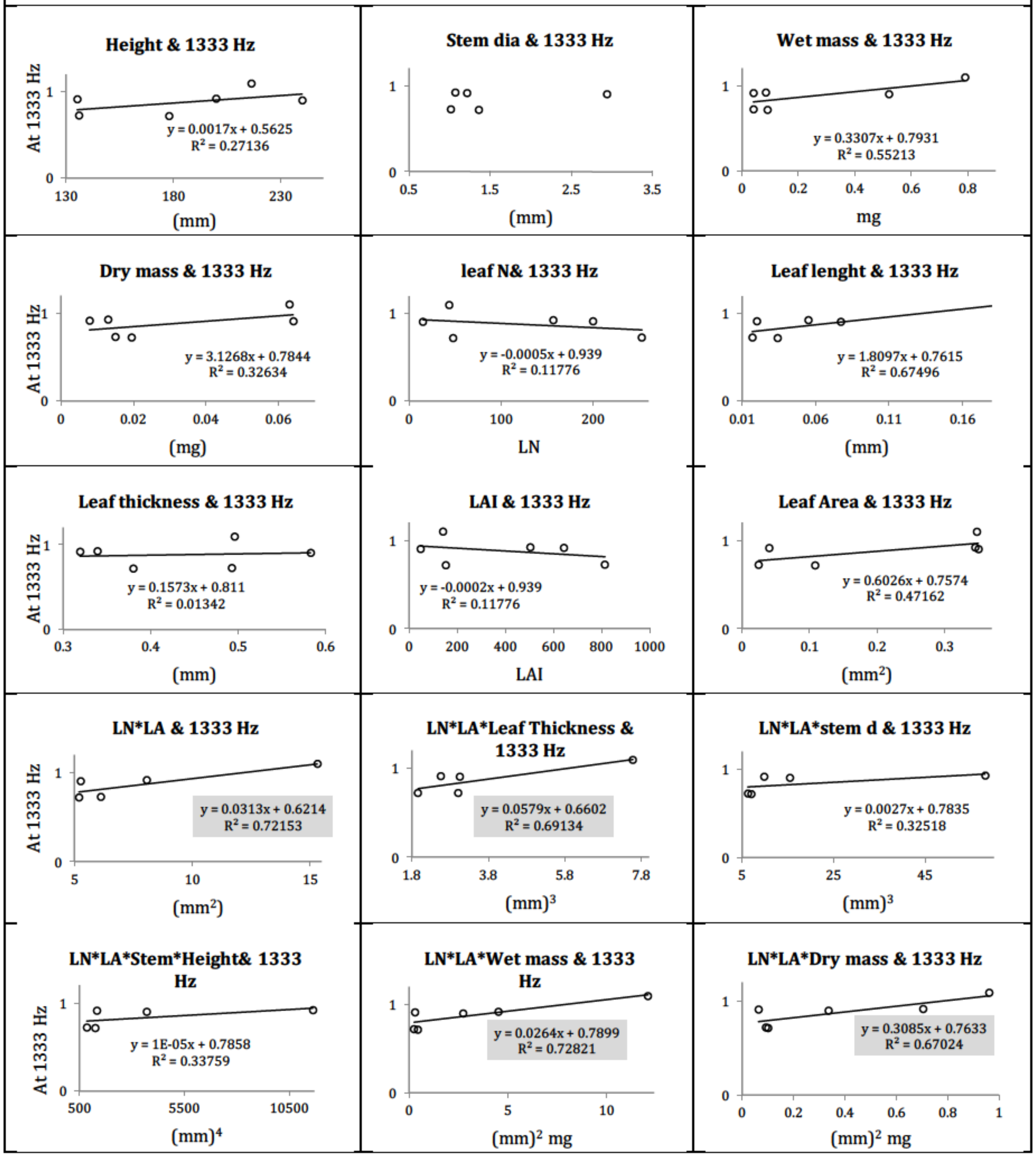


Table D. Sound Scattering Coefficient (Average of 200 to 2500 Hz) & Plant Properties

Plant Properties

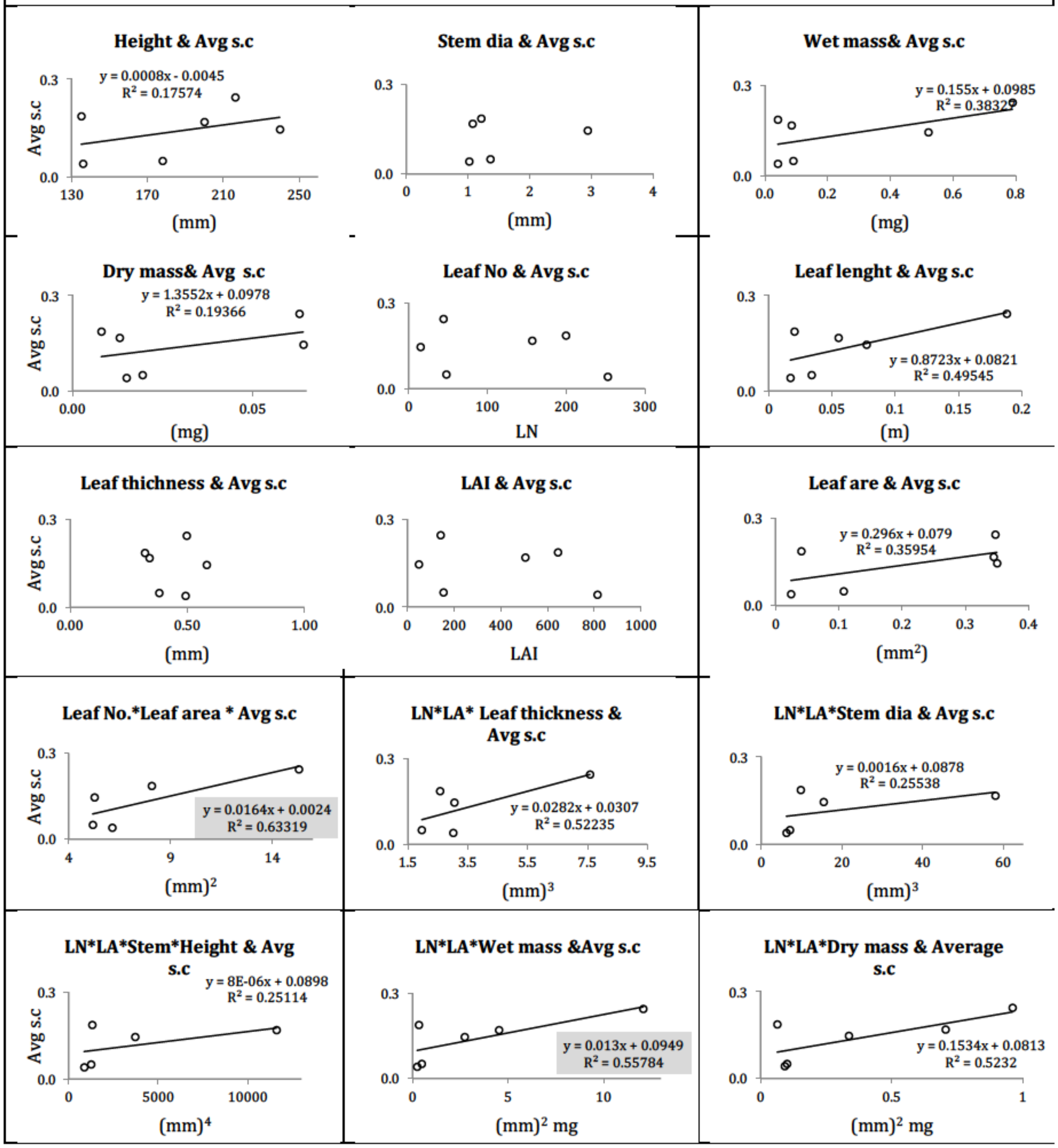


Table E. Sound Scattering Coefficient, High Frequencies, (Average of 2500 to 5000) & Plant Properties

Plant Properties

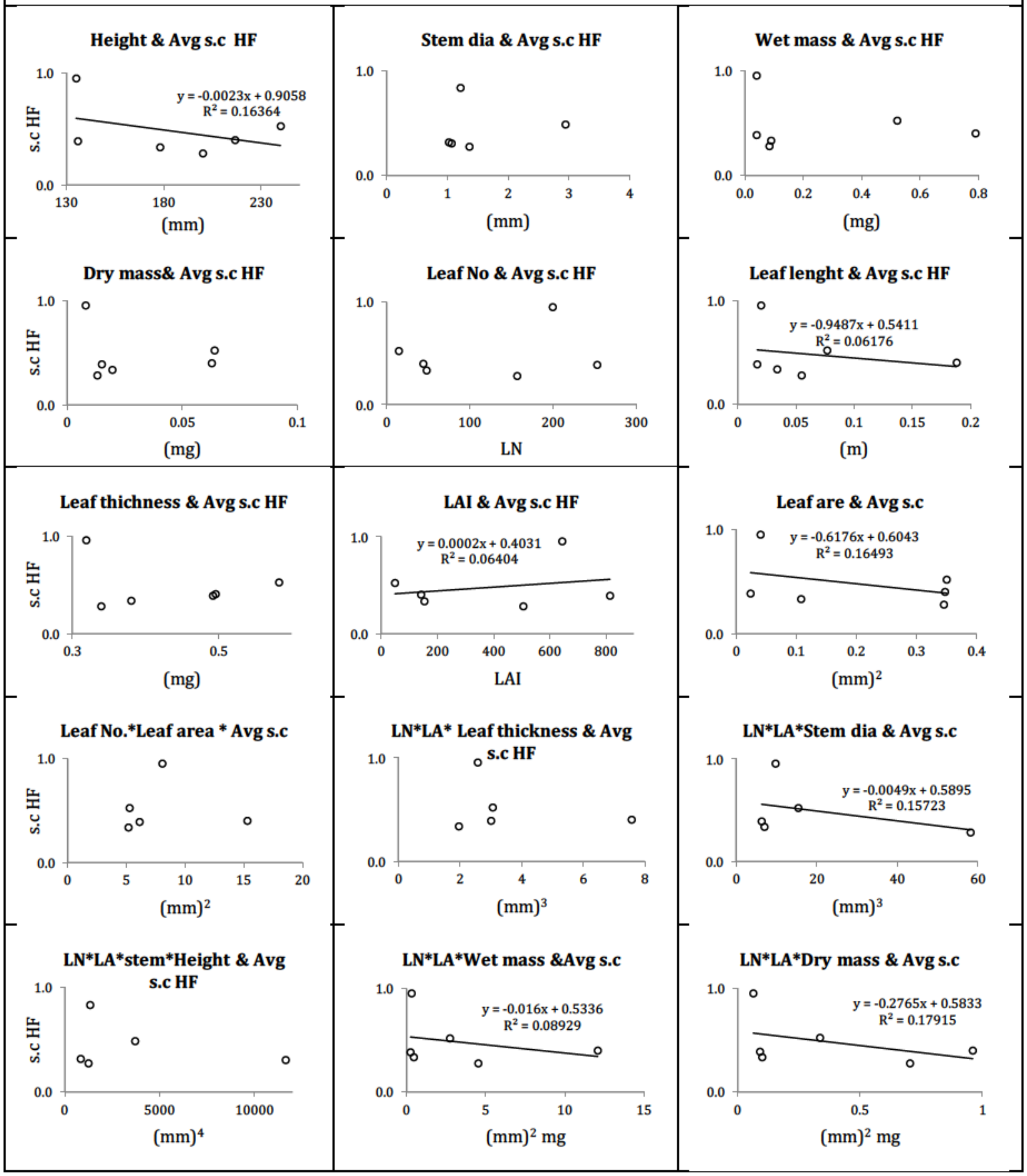


Table F. Sound Scattering Coefficient (At 1333 Hz) & Plant Properties

Plant Properties