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Experimental investigation of the sound absorption characteristics of vegetated roofs

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ABSTRACT

An experimental investigation of the sound absorption characteristics of vegetated roof substrates and plots has been completed. First, an impedance tube was used to measure the normal-incidence absorption coefficients of substrates and their constituents. Substrates provided significant sound absorption, with coefficients varying from 0.03 at 250 Hz to 0.89 at 2000 Hz. Absorption increased with the percentage of organic matter and decreased with moisture content and compaction. A multi-variable regression model was developed for predicting the absorption of substrates. Secondly, the sound absorption of vegetated roof plots was investigated using the spherical-decoupling method. An optimal method, validated in an anechoic chamber, was used to determine the diffuse-field absorption coefficients of unplanted and planted rooftop test plots. Sound absorption increased with increased substrate depth (without vegetation) and decreased with the addition of vegetation and plant establishment. The mean noise reduction coefficient of established vegetated roof plots, with distinctly different plant communities in substrate depths of 50–200 mm, ranged from 0.20 to 0.63 when evaluated over a two-year period. The results confirm that the sound absorption of vegetated roofs is a function of substrate depth, plant community establishment, and moisture content in the plants and substrate.

1. Introduction

Vegetative roofs are increasingly used in sustainable building construction. They have the potential to improve the acoustical environments inside and outside buildings because of beneficial sound absorption and transmission-loss characteristics. A recent research project [1] investigated both aspects of the acoustical performance of vegetated roofs; sound absorption is the topic of this paper.

Mitigating the impact of noise is critical to sustaining our health and wellness [2]. Through surface absorption, vegetated roofs have the potential to reduce noise build-up at the roof level and noise pollution in urban areas [1,3–5]. The sound-absorptive vegetated roof materials placed over typically light-weight acoustically reflective roof membranes will significantly modify the sound path, as energy is primarily dissipated by the vegetation and substrate. Additionally, near grazing incidence, even in the absence of high absorption, phase change of reflected sound further modifies the propagating sound over vegetated roofs – the ground effect [6]. The boundary conditions of the material layers will play a role in the acoustical behaviour of sound depending on substrate depth.

Ultimately, the acoustical characteristics of a system are governed by the properties of the multiple layers of fluids (density), solids (mass and stiffness) and poroelastic (porosity) materials and the fluid-structure interaction [7,8]. Vegetated roofs as engineered systems vary widely in terms of design and implementation. As natural systems, vegetated roofs vary distinctively in terms of the in-situ ecological succession of the plant species [9]. Vegetated roofs can be composed of various material layers such as root barrier, water reservoir/drainage layer, filter fabric, substrates, and plants. The vegetative growing substrate is complex to characterize, varying in terms of the substrate constituents and mix, the depth of the substrate, the vegetation's aerial biomass (foliage above substrate without litter) and root structure, and the in-situ microclimate.

In order to understand the sound absorption characteristics of an established vegetated roof system, it is of interest to first examine the absorption characteristics of the substrate before the effect of the vegetative substrate layer is investigated. There were two parts to this investigation: the first part determined the

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normal-incidence absorption coefficients of six substrates and the second part assessed the sound absorption of vegetative roof plots. The investigation on substrates provides insights into the magnitudes and frequencies of sound energy which vegetated roofs can potentially absorb, and guidance for the specification of the substrate mix to optimize the sound absorption potential of substrates for noise control. The investigation on vegetated roofs identified the conditions which significantly affect sound absorption.

2. Background

2.1. Substrates

Vegetated roof substrates were examined to determine which characteristics contribute most significantly to the absorption of sound energy. Vegetated roof substrates have a granular structure; the aggregates are separated from each other in a loosely-packed arrangement. The substrate must be sufficiently porous to provide internal aeration, and be structurally capable of resisting excessive compaction beyond the mechanical compaction of the substrate on the roof during installation. There is a percentage of sand in most substrates; the void between the sand particles promotes free drainage of water and entry of air into the soil. The percentage of organic matter provides a balance of drainage and water retention. The proportion of minerals to organics varies depending on plant requirements, depth, and the projected maintenance regime. Clay and silts are not as predominant in substrates as in natural soils [10,11].

In acoustical terms, vegetated roof substrates can be defined as an unconsolidated granular, sound-absorbing material. The constituent mix of sand, organic matter, and minerals determines the relative volume of pore space (porosity). Tortuosity and pore structure cause changes in the flow direction; the expansion and contraction of the air flow through the irregular pores results in a loss of momentum of the directional wave propagation of a medium [12]. Several theories of sound propagation within idealized porous materials have been applied to soils [13–15]. However, there is little published literature which hypothesizes or reports the relationship between the properties of vegetated roof substrates and their acoustical characteristics, or the impact of microclimatic and site conditions on the sound absorption of substrates. The following is a summary of the findings of published measurements on and modelling of sand, natural soils, bare grounds, and manufactured porous materials most relevant to vegetated roof substrates.

Laboratory measurements, executed with an impedance tube with one end of the tube submerged in sand, have shown that the absorption coefficient increases incrementally with an increase in the percentage of moisture content up to 6% and then decreases with a greater percentage of moisture content [16].

Absorption coefficients of grounds, measured by the in-situ use of an impedance tube, have shown that absorption decreases immediately after rainfall (relative to pre-rainfall conditions) and increases as the ground drains over the next few days and then decreases as the ground dries [17]. Acoustical attenuation and propagation speed have been determined to be a function of soil moisture [18,19] and level of compaction [20] although a variety of sands and soil textures have been evaluated, none of the samples are in conformance with vegetated roof guidelines for substrates as required for plant viability on rooftops [21,22].

The characteristic impedances and propagation constants of manufactured fibrous absorbent materials have been modelled as a function of frequency and specific flow resistivity, which is predominately a function of the bulk density and the anisotropic fibre size [12]. The models assume the material is a homogenous, unbounded, infinitely extended medium. The application of this model to vegetated roof substrates may not be assumed valid, as the physical characteristics of substrates do not meet the assumptions.

The characteristic impedances and propagation constants of single constituent granular materials have been successfully predicted from porosity, tortuosity, specific density of grain base, and a characteristic particle dimension [23–26]. Standard soils including low-density substratum soil and high-density clay-based soils have been successfully lab-tested and predicted by fluid model [27]. Again, this is not necessarily applicable to the wide variation of vegetated roof substrates, as they have multiple natural constituent components with widely varying particle-size distribution and pore characteristics. A 2013 study showed soil depth of 50 mm providing significant absorption, and greater soil depths show only slight changes [28].

2.2. Vegetation

Vegetation is known to impact the physical characteristics of soil [29]; the vegetation affects porosity and water content through the mechanisms of soil temperature, organic and inorganic composition, and animal life in soil [17]. The mechanism of accessing water from the soil is a function of the root structure and soil interface. Additionally, the aerial biomass affects the microclimate of the soil properties. Vegetation foliage and root structure are known to affect the impedance, and thus the absorption, of grounds [30]. Examined plant communities have shown differences in sound absorption due to differences in height, foliage, and mass [31]. It has been determined that leaf dimension and mass are important properties of plants affecting sound reflection and hence the sound energy incident on soils [30,32,33]. Plant leaf area density and angle of leaf orientation have recently been shown to affect the absorption coefficient of plants [27]. Vertical greenery systems show increasing absorption and scattering with increasing area of greenery coverage in reverberation chamber tests [34,28]. It is not known if the variability of vegetation foliage and root structure, within the limit of the plant species suitable for vegetated roofs, affects the sound absorption of the vegetated roof. Previous work on various grounds suggested that only the first 90-mm depth of vegetated grounds affects absorption [17].

3. Objectives

In the first part of the investigation, laboratory experiments were conducted to determine the relationship of the physical characteristics of vegetated roof substrates due to the constituent mix and two in-situ conditions (moisture content and compaction) to sound absorption. In the second part of the investigation, the goal was to understand the impact of substrate depth and plant community and coverage on the absorption potential of vegetated roofs.

4. Methods

4.1. Laboratory testing of substrates

Impedance tube measurements of six substrates and their constituent parts, with test parameters of moisture content and compaction, were executed to determine which physical properties and characteristics of vegetated roof substrates contribute most significantly to the absorption of sound energy. The substrate characteristics of interest included particle density, bulk density, total porosity, percentage organic matter, and particle-size distribution. The properties of interest that are a function of the microclimate and site conditions include volumetric water content and compaction.

The normal-incidence absorption coefficients of six vegetated roof substrates and their three primary constituents—sand, compost, and pumice—were measured in an impedance tube at three levels of volumetric water content—oven-dry (0%), wilting capacity, and field capacity—and at two states of compaction. The sample depths were 98 mm, as this was the maximum depth achievable in the impedance-tube sample holder, allowing for the analysis of a reasonable range of depths for extensive vegetated roofs. The permanent wilting capacity and the field capacity define the minimum and maximum available water contents required for plant viability and hence defined the limits of volumetric water content. The substrates were evaluated as either non-compacted or compacted at a level which approximates in-situ conditions. The relationship between the absorption coefficient and the properties of the substrate and constituents was examined using multiple linear-regression modelling.

4.1.1. Sound absorption measurement

The most direct method for evaluating the absorption potential of vegetated roof substrates is to measure the complex reflection coefficient in a normally-incident sound field using an impedance tube [35,36]. Using broadband noise, plane waves are generated from one end of the impedance tube normal to the surface of a sample located in a holder at the opposite end of the tube (two microphones, B&K ¼" Type 4135 with B&K ½" Type 2669 pre-amplifiers and SINUS Soundbook). The impedance tube system was calibrated by the two microphone transfer function method, where amplitude and phase are calibration quantities measured with microphones placed in standard and switched configurations, as described in ASTM E1050-98. In total 105 measurement were taken, the specific number of measurements for each sample is described in Section 4.1.2.

On the assumption that the substrate is locally-reacting, the diffuse-field absorption coefficient and a noise reduction coefficient (NRC – the average of the sound absorption coefficients in the 250, 500, 1000, and 2000 Hz octave bands) [37] can be calculated from the complex reflection coefficient (R) derived from the measured transfer function (H) and the geometry of the impedance tube.

Two impedance-tube diameters were available: one of 98-mm diameter for frequencies from 177 to 2050 Hz, and one of 29-mm diameter for frequencies higher than 2050 Hz. This investigation was limited to the lower-frequency range, as the 29-mm tube diameter was too small to accommodate a homogenous sample of the test substrates, due to the granular size of the aggregated components. The upper-frequency limit is inversely proportional to the diameter of the tube and equates to 2050 Hz for the 98-mm tube. The lower-frequency limit is related to the spacing of the microphones and the accuracy of the sound analyzer [38]. The lower frequency cut-off of the apparatus was estimated to be the lower limit of the 250-Hz one-third octave band (i.e., 177 Hz). In this investigation, the impedance tube was used in a vertical orientation so that loose granules and water could be retained in the sample holder.

4.1.2. Substrates and constituents

The specifications and proportions of constituent parts of substrates can vary significantly; the mix is engineered based on the type of vegetated roof (extensive, intensive or rooftop urban agriculture), plant species and micro-climatic conditions. Five of the six substrate samples were selected randomly from products on-site at the British Columbia Institute of Technology (BCIT) Green Roof Research Facility. The samples represented a range of vegetated roof substrates composed of natural materials and currently used for extensive and semi-extensive vegetated roofs in the Pacific Northwest of North America. The sixth substrate had previously been evaluated for conformance to both British Columbia Landscape and Nursery Association [22] and Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau recommendations [21], and had been selected for the subsequent tests on 25 experimental rooftop plots (see Methods, Section B) and subsequent transmission-loss research [1]. The sand, compost, and pumice, common to most of the substrates, were also evaluated as samples.

Vegetated roof substrates for extensive and semi-intensive applications have specified ranges of percentage of organic matter and particle-size distribution of all constituents. The range of volumetric moisture content between wilting point and field capacity represents the range of moisture for plant viability and survival. Compaction is a site condition which may occur at the time of substrate installation and will occur over time due to loading and rain.

The physical characteristics were measured in a commercial lab according to standard soil test methods. Particle density [39,40], available water-storage capacity [39,41], particle-size distribution [21,42], and total porosity are independent of microclimate conditions. The percentage of organic matter [42] changes over time, but not within the time duration of this study, and was measured before acoustic testing. The bulk density and percentage moisture content were measured within 24–36 h of acoustical testing using an oven-dry method [42].

Table 1 shows the physical characteristics of the test samples. The percentage of organic matter (% OM) in the six substrates ranged from 2% OM to 25% OM. The mean value of 14% OM is greater than the 8% OM recommended by the FLL. The maximum water-storage capacity, measured at 10 J/kg, ranged from 24% to 42% by volume and, with one exception, met the FLL recommendation of 35%–45%. Aeration porosity at 10 J/kg ranged from 23% to 34% by volume and, with one exception, met the FLL recommendations of aeration porosity >25%. The particle-size-distribution curves in Fig. 1 correlate the particle-size distribution of the substrate mix with a recommended percentage of three grades each of silt, sand, and aggregate. The curves of three of the substrates fit within the recommended maximum and minimum curves; two had minor deficiencies with either slightly more-or-less coarse and/or fine aggregate. Two substrates contained higher than recommended percentages of aggregate particles >2 mm. The constituent as a single component cannot comply with distribution recommendations.

Large samples of the six substrates and the constituents (sand, pumice, and compost) were oven-dried to 0% volumetric water content (%VWC). From a large container, the first random sample was ladled into the impedance-tube sample holder and levelled to the rim. In order to maintain a representative and random granular distribution of the mix, the substrate was ladled into the sample holder rather than poured. After the first impedance tube measurement was completed, the sample was weighed, and then two repeat measurements were done with equal masses of substrate measured from the large container and placed into the sample holder.

The same process was followed to measure three samples of substrate or constituent at wilting and/or field capacity. The substrate was mixed using a mass approximation of water volume to a predetermined %VWC representing the substrate's specific wilting or field capacity. The air, water, and substrate were maintained at the same temperature (±1 °C). After the sample was tested in the non-compacted condition, the sample was tested in a compacted state. During installation of vegetated roofs the compaction rate for the soil component is taken into consideration; the substrate is installed and compacted to the finished height and then offset with

Table 1
Test sample characteristics.

Samples	% OM[a]	Particle density kg/m^3	Total porosity % vol.	Field capacity[b] % vol.	Wilting capacity[b] % vol.	PSD[c]	Particles >6.3 mm % by mass
Sand	<1	2704.3	36.6	7.5	3.6	0.43	0.10
Compost	32	1755.9	72.6	46.7	36.7	0.28	1.10
Pumice	<1	1996.5	74.7	31.3	27.1	0.28	20.1
Substrate 1	15	1980.9	72.4	33.0	23.7	1.00	7.60
Substrate 2	14	1909.9	74.9	30.6	29.4	0.70	4.40
Substrate 3	15	2196.0	63.0	31.1	25.0	1.00	6.30
Substrate 4	14	2447.2	57.6	18.7	12.5	0.57	50.6
Substrate 5	2	2361.6	61.5	30.5	23.3	1.00	7.00
Substrate 6	25	2205.0	57.7	17.9	15.5	0.86	1.70

[a] Percentage of organic matter.
[b] Field capacity measured at 33 J/kg, Wilting Capacity at 1500 J/kg.
[c] Particle size distribution (See Fig. 1).

the addition of substrate based on a specified substrate-specific compaction rate. The 18% compaction rate by volume is representative of on-site compaction rates [43]. At wilting and field capacities, a compaction rate of 18% was feasible within the impedance-tube sample holder. The sample was compacted in layers while being placed in the sample holder, to avoid excessive surface compaction.

If the percentage difference between wilting and field capacities was less than 5%, then only the oven-dried substrate was tested, at wilting capacity. The bulk density, volumetric water content, air porosity, and total compaction are parameters which are functions of the volumetric water content, and were determined within 24–36 h of the acoustical measurement using an oven-drying method.

4.2. Field testing of small-dimensioned vegetated roof plots

This section discusses field measurement of the absorption coefficients of small-dimensioned (1.68 m × 1.68 m) vegetated roof test plots. It first investigates the implementation and application of the spherical-decoupling method for optimal in-situ absorption measurement. It then discusses the use of the optimal method to perform in-situ measurements of the absorption coefficients of 25 vegetated and non-vegetated test plots representing a range of substrate depths and plant communities commonly used for extensive vegetated roofs.

The first investigation on one test plot was completed inside the controlled environment of an anechoic chamber. Within the chamber, a dimensionally-representative test plot was built on a plywood floor, creating a hemi-anechoic condition to approximate a rooftop context.

Next, the in-situ measurement of 24 of the 25 rooftop test plots was completed on a 1400-m^2 roof top. These test plots were constructed with material layers representative of the common vegetated roof systems of the Pacific Northwest of North America. The test plots ranged in substrate depth in 25-mm increments from 50 to 200 mm; seven test plots contained the substrate only. The varying atmospheric conditions were accommodated at the field site. Based on real-time data from the on-site weather station, acoustical measurements were taken only when wind was less than 5 m/sec; and measurements were not taken during measurable precipitation. The impact of variable pre-test rain fall was eliminated by the use of an irrigation system to provide a common condition of volumetric water content.

4.2.1. Experimental method background

The spherical-decoupling method is a two-microphone technique which measures the reflection coefficient at any incident angle, from which the diffuse-field absorption coefficient can be derived [44]. A more general version of this method has been used to measure sound reflection properties and deduce the sound absorption of locally-reactive surfaces and grounds, such as playing

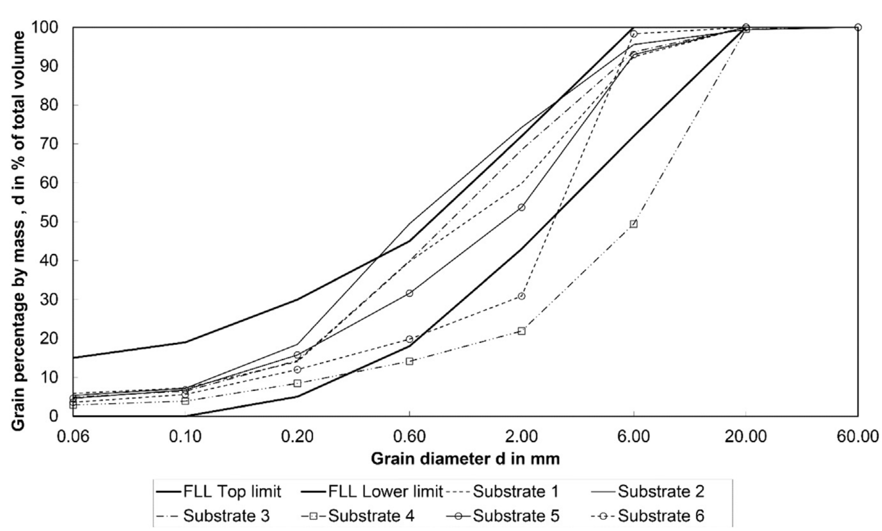

Fig. 1. Particle-size distributions of the sample substrates.

fields and forest floors [45,46]. However, the substrate surface particles and the plants of the vegetated roof do not provide a homogeneous and specularly-reflecting surface, assumed by the theory supporting the spherical decoupling method. Less than ideal surface conditions have previously been accommodated in measurement methods through the determination of an appropriate geometric configuration of the sound source, the microphones, and the surface plane, and through repeated measurements at multiple surface locations.

The experimental setup and the geometry of the measurement setup for the spherical-decoupling method are illustrated in Fig. 2 [47]. For locally-reacting surfaces, as we assume grounds and vegetated roofs to be, the impedance does not change with the angle of incidence. The diffuse-field absorption coefficient can be calculated from the impedance [48].

Considerable work has been done to define the optimal geometry to use in the measurement of the frequency response, to calculate the impedance of grounds. The frequency limits of validity of the spherical-decoupling method are functions of the distance between the two microphones and the angle of incidence of the sound source [46].

4.2.2. Experimental method optimization and validation

The experimental set-up addressed the effect on sound absorption of substrate depth and of the differences in plant community. In order to investigate these factors, small-dimensioned (1.67 m × 1.67 m) vegetated test plots (see Fig. 3) bounded by plastic wood composite borders were constructed on the rooftop. In preparation for using the spherical-decoupling method to measure absorption coefficients of small-dimensioned vegetated roof test plots in the rooftop environment, measurements were made in controlled laboratory conditions to optimize and validate the experimental methods. Given that the application of the test method was on small-dimension plots, not large expanses of ground or vegetated roofs, the objectives of the investigation were as follows: a) to determine the optimal geometric configuration of the sound source and microphones relative to the surface; b) to investigate potential compromises on a rooftop to the ideal hemi-free-field test environment and how they affect measurement accuracy; and c) to determine the required number of repetitions of measurements.

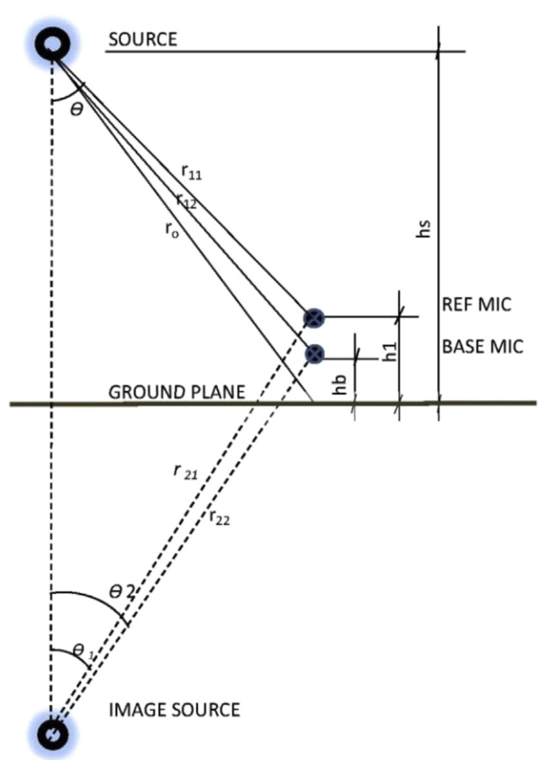

Fig. 2. Geometric configuration of spherical decoupling method experimental setup [47].

Fig. 3. Rooftop test plots of substrates with P3 community (cultivated grasses) in foreground and P1 community (sedums) in mid-ground.

To achieve these objectives, measurements in various test configurations were made in a fully anechoic chamber with usable dimensions 4.7 m × 4.1 m × 2.6 m high. A 1.68-m × 1.68-m test plot was constructed using the same materials and details as the rooftop plots; the perimeter frame, which separated plots from each other on the roof, was wooden and the subsurface was the plywood floor (Fig. 4). The substrate was from the same batch mix as in the rooftop test plots – a blend of white pumice, sand, 15% organic matter, and a non-significant percentage of proprietary amendments. The substrate was evaluated in previous lab tests; the percent organic matter, percent porosity, particle size distribution, and available water content met the regional guidelines [22] and standards, and the international guidelines [21] for extensive vegetated roof substrates.

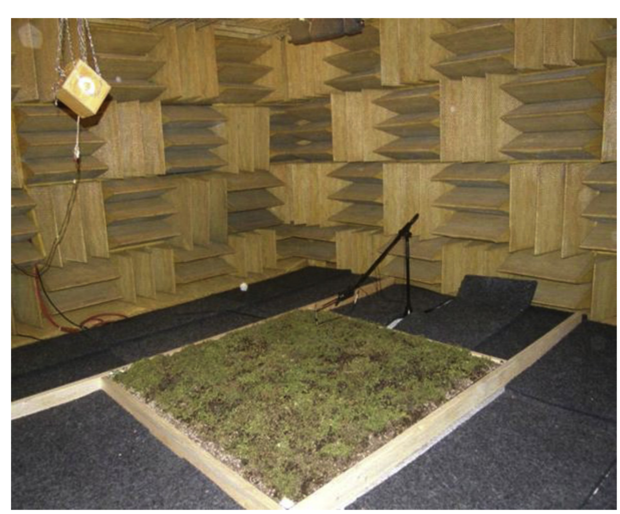

Fig. 4. Planted vegetated roof test plot with surrounding baffles in the anechoic chamber.

Three primary setups were used: the plywood subfloor covered with 50-mm cotton baffles; a non-vegetated roof test plot; and a planted roof test plot. To determine the optimal geometric configurations and investigate disruptions to the theoretical hemi-free-field condition, variations were made to the first two primary setups.

In the final of the three primary setups, the vegetated roof test plot was planted with *Sedum album* ("Coral Carpet"); the coverage of the aerial biomass was 70% (Fig. 5). The sedums were planted for the duration of the measurements only; as such, the root growth was not established. The water content was approximated at wilting capacity.

4.2.2.1. . Optimal geometric configuration. To investigate the optimal configuration of the equipment setup, measurements were repeated with dimensional variations to the geometric configuration (the distance between the two microphones; the distance from the test surface to the closest microphone) and the location of the sound source with respect to angle and distance to the microphone probe. Measurements were made on baffles on plywood, substrate only, a vegetated roof test plot, and a sedum-planted vegetated roof test plot.

The optimal geometric configuration derived from the investigation involved the following: loudspeaker 175 cm above and normal to the test surface; microphone probe directly below the loudspeaker; height of the base microphone above the surface (*hb*) equal to 55 mm; and 25-mm microphone spacing.

4.2.2.2. . Non-ideal field test environment. To investigate the significance of sound-field perturbations by rooftop architectural features, measurements were made in the approximate hemi-free-field condition of the anechoic chamber with and without representative perturbations. On the rooftop, known perturbations included the perimeter edge frame of the vegetated roof test plots, a non-continuous surface with variable acoustical characteristics outside the frame (absorptive and/or non-absorptive surface), posts which supported the loudspeaker and architectural apertures.

In the anechoic chamber, measurements were repeated with and without the perimeter edge, at $\theta = 0°$, 45°, and 75°. Only at $\theta = 0°$ was it found that the perimeter frame did not interfere significantly with the planar wave reflecting from the sound source at $\theta = 0°$.

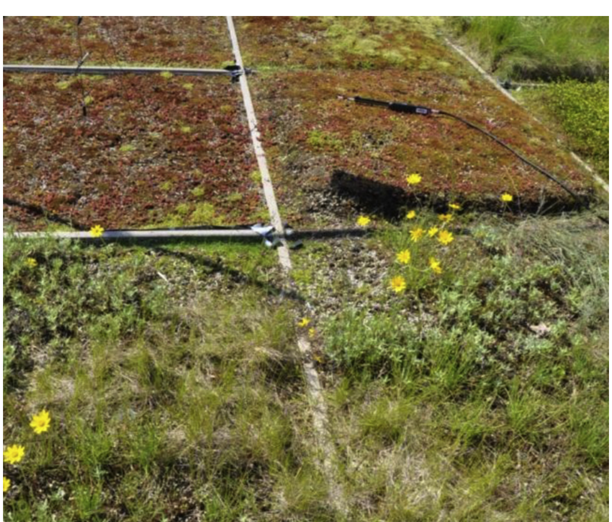

Fig. 5. Rooftop test plots of planted community.

Depending on the location of the plot in the test area, the surrounding surfaces could involve adjacent test plots and/or the highly-reflective roof membrane in varying geometry. To investigate the conditions of the surrounding surface, in the anechoic chamber the cotton baffles were laid on the plywood subfloor to simulate the various surface conditions beyond the perimeter frame. The results indicated that there was no interference by the highly reflective surfaces surrounding the test plot when the sound energy from the source was normally incident; i.e., $\theta = 0°$. As the angle of incidence increased, the agreement between the measurements in the three surface conditions decreased.

4.2.2.3. . Measurement repeatability. Standards recommend averaging four repeat measurements to accommodate the variations in natural grounds [45]. At the location of wave reflection for each measurement the vegetated roof may have various surface properties, variations in foliage (biomass and root structure) and substrate condition (exposed constituents). Measurements were taken at ten different locations on the substrate test plot using a fixed geometric configuration to determine the minimum number of repetitions required. It was concluded that four repeat measurements were sufficient to represent the surface conditions.

For detailed results of the experimental method optimization and validation work, refer to Connelly, 2011.

4.2.3. Vegetated and non-vegetated test plots — methodology and plant selection

The site for the in-situ measurements was on a 1400-m^2 rooftop. The roof is 10 m above grade and has full sun exposure. The annual precipitation is 1885 mm and the average daily temperature is 10.5 °C. Allowable load capacity determined the locations and limits of the test areas on the rooftop. The roof slope is 2% and the test areas are free-draining without any residual rainwater pond below the test plots. The rooftop has a weather station which provides temperature, relative-humidity, wind direction and speed, rainfall, and solar-radiation data.

Two 25-m^2 test areas comprised nine 1.68-m × 1.68-m test plots. One 25-m^2 test area had seven 1.68-m × 1.68-m plots with substrate only. Fig. 6 illustrates the material layers. The range of substrate depth in the Pacific Northwest region of North America is most typically from 75 to 150 mm. The wider range of 25–200 mm depth was selected to confirm the minimum limit of substrate depth for plant viability and to evaluate the extended range of depths acoustically. It was not known if the plants would in fact thrive in the shallowest depth allocated, as viability is a function of the site-specific context and seasonal climatic conditions. The goal was to measure the vegetated plots at two levels of coverage, in the fall and the spring. The compacted substrate was installed adhering to the same mass measurement techniques as the laboratory samples (see Section 4.1.2).

The plant species were selected based on the diversity of the structural characteristics of aerial biomass and root systems. Three communities were selected: P1, a *Sedum album* 'Coral Carpet', which has a dense and evenly-distributed foliage with an extremely shallow root structure of only a few millimetres depth; P2, a coastal community of plants with structural foliage and deep or massive root systems, including *Eriophyllum lanatum*, *Allium cernuum*, *Armeria maritima*, and *Festuca rubra* (in the P2 community the foliage above and the root system below the substrate surface were not homogenous across the test plots); and P3, a mix of cultivated grasses sowed and maintained as required for a playing field. The plants were grown in 100-mm pots in the nursery with the same substrate as in the test plots rather than in a typical peat-based potting soil, to ensure consistency through the substrate

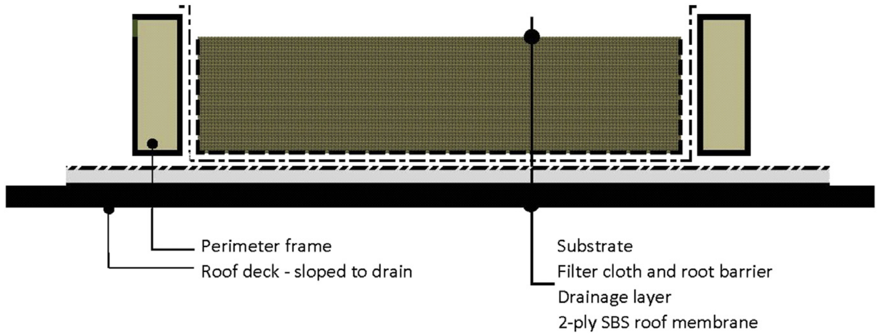

Fig. 6. Rooftop test plot section detail and material layers.

parameter. The test plots were planted in May 2009 with an average of 150-mm plant spacing on-centre.

The method to determine plant coverage was visual assessment using a 25-square matrix array over each 1.65-m × 1.65-m plot. The percent coverage of total plants, the percent coverage of original planted species, and the spontaneous plant coverage were determined. For each matrix, values were assigned on a scale of 1–10, where 1 indicated 0%–10% coverage, 2 indicated 11%–20% coverage, and so on up to 10 which indicated 100% coverage. The values assigned were averaged over the 25-square arrays to determine the percentage coverage. The total plant coverage is a value which describes the surface of the plots in terms of vegetation relative to exposed substrate, inclusive of the original species planted and the spontaneous growth. The spontaneous coverage is a value which describes the surface of the plots in terms of spontaneous plant establishment relative to exposed substrate [49]. The three plant communities selected have significant structural differences in terms of the aerial biomass and root development.

The plant root structure of the test plots was so well-developed that removal of substrate to evaluate the volumetric water content would have been destructive. Nominally, all plots were evaluated at field capacity. The plots were irrigated to full saturation to approximate field capacity 36–48 h after water saturation.

5. Results

5.1. Laboratory testing of substrates

The average normal-incidence absorption coefficients of the substrates are presented in Table 2 in octave bands from 250 to 2000 Hz for each test condition. There was a high level of consistency in the test repetitions of each substrate in each of the five evaluated states: oven-dried, wilting capacity, wilting capacity compacted, field capacity, and field capacity compacted. The significant variation in the substrate characteristics resulted in a wide range of absorption coefficient values. In the oven-dried state the range of the average absorption coefficient was 0.71 across the frequency bands. The average absorption coefficients for wilting capacity, wilting capacity compacted, field capacity, and field capacity compacted were 0.58, 0.48, 0.35, and 0.22, respectively. These results indicate that, in the octave bands from 250 to 2000 Hz, the percentage of organic matter and volumetric water content have the most significant effect on the sound absorption of the substrates. The absorption coefficients of the evaluated substrates correlated positively with the percentage of organic matter and negatively with moisture content and increased compaction, except that the state of compaction had a negligible impact on sound absorption in the lowest (250 Hz) octave band.

Table 2
Average normal incidence absorption coefficients of test substrates.

	Octave band (Hz)				
Oven dried	250	500	1000	2000	AVG.
Mean	0.62	0.76	0.68	0.79	0.71
Min	0.28	0.63	0.53	0.70	
Max	0.77	0.91	0.80	0.91	
Wilting capacity					
Mean	0.28	0.71	0.58	0.75	0.58
Min	0.15	0.36	0.41	0.52	
Max	0.52	0.87	0.81	0.89	
Wilting capacity – compacted					
Mean	0.35	0.50	0.49	0.58	0.48
Min	0.18	0.22	0.32	0.39	
Max	0.53	0.70	0.68	0.79	
Field capacity					
Mean	0.17	0.28	0.42	0.54	0.35
Min	0.13	0.09	0.07	0.08	
Max	0.22	0.70	0.71	0.85	
Field capacity – compacted					
Mean	0.12	0.13	0.23	0.40	0.22
Min	0.03	0.04	0.04	0.06	
Max	0.30	0.34	0.58	0.49	

Fig. 7 shows the absorption coefficients of the compost (organic matter), sand, and pumice (which together formed the majority of the substrate mix), and the average of all test substrates, at 0% moisture content and in a non-compacted state. With the conditions of moisture and compaction removed, the sand (with less than measureable organic content and low pore volume) had the lowest absorption coefficient (0.26–0.40). Absorption increased with frequency in the range of 200–2050 Hz. The pumice, with less than measureable organic content but with a high pore volume, had a higher absorption-coefficient range. The compost, with a high

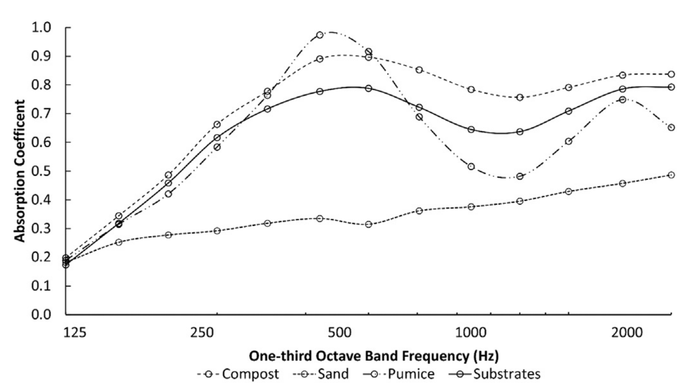

Fig. 7. Measured octave-band absorption coefficients of the average substrate and constituents, at 0% moisture content, at wilting capacity.

percentage of organic matter, had the highest absorption range. The average of the absorption coefficients of the substrate mixes was between those of sand and compost. An increased absorption at around 500 Hz is observed in the higher porosity materials (this excludes sand); similar results have been observed in other impedance tube studies on granular material [50]. The apparent high absorption at about 500 Hz is explained as the first resonance maximum attributed to high level of interference between the direct wave and the reflected wave from the base of the standing wave impedance tube. The pumice with high percentage of coarse particles (see Table 1) exhibits the most noticeable second response.

Fig. 8 shows the relationship between the percentage of organic matter and the absorption coefficient of the compacted substrate at wilting capacity. One substrate had only 2% organic matter, and the absorption coefficient was closer to that of sand than any other substrate. Four of the substrates had 14% or 15% organic matter, which increased the absorption coefficient by 0.15 (1000 Hz); the absorption coefficient of the substrate with the highest organic content (25%) was an additional 0.15 higher (1000 Hz). As organic matter decreased, the nearly non-organic samples exhibited increased erratic spectra behaviour attributed to the increase and volume deviation of inter-granular pore spaces and the deviation from the ideal boundary condition of the sample substrate in the sample holder.

Fig. 9 shows the impact of increased volumetric water content and of compaction on the absorption of the six substrates. In general, absorption decreased with both factors. The moisture content required for plant viability of the substrates evaluated has a range of 12.5%–33% volumetric water content. This range of water content translates to a dynamic range in absorption coefficient of 0.36 (1000 Hz) averaged over all of the evaluated substrates.

5.1.1. Frequency-dependant multi-variable regression models

The relationships between the absorption and the physical properties of the test substrates and constituents (in Table 1) were examined using multi-variable linear-regression modelling. The measured absorption coefficients of the substrates—the dependent variable to be predicted—were normally distributed and did not require transformation prior to analysis. The soil properties and characteristics—the independent variables that are candidate predictors—included percentage organic matter, bulk density, particle density, porosity, available water content, air-filled porosity, volumetric water content, compaction, particle-size distribution, and percentage of particles >2 mm. On bivariate analysis, independent variables that were statistically significant ($p < 0.05$) were considered for inclusion in multiple linear regression models.

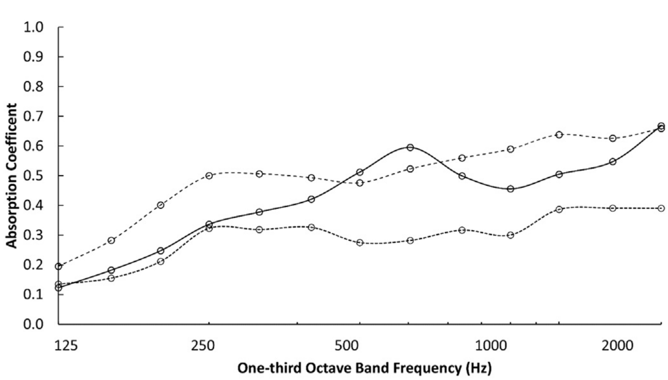

Fig. 8. Variation of measured octave-band normal-incidence absorption coefficients with percentage organic matter and compaction.

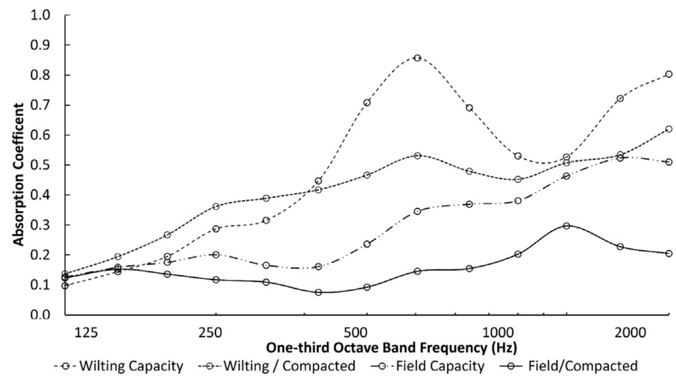

Fig. 9. Variation of measured octave-band absorption coefficients with percentage moisture content.

Co-linearity of the independent variables was evaluated using the Pearson correlation for continuous variable pairs, the Spearman correlation for categorical pairs, and a Chi-squared test for the association of the categorical pair. Highly correlated independent variables ($r_p > 0.4$, $r_s > 0.4$, $p < 0.05$ significance) were evaluated and the variables with the strongest association with the dependent variable on bi-variant analysis were retained in the model. Frequency-dependent models were developed separately to predict the absorption coefficients in octave bands from 250 to 2000 Hz. The final frequency-dependent models were regressed against the determinants by a backward, stepwise linear-regression process, retaining only statistically significant variables ($p < 0.05$).

There were 87 observations for each model. Table 3 reports the coefficients and R^2 values for the final regression models. The R^2 values indicate that the models explain a very satisfactory 66%–78% of the variability in the absorption coefficient. The models for prediction of the absorption coefficient are:

$$\alpha = \beta_0 + \beta_1(\%OM) + \beta_2(P) + \beta_3(VWC = Wilting) + \beta_4(VWC = Field) + \beta_5(COMP) \quad (1)$$

The multi-variable analysis supports the observations made during the measurements. The normal-incidence absorption coefficient is positively associated with the percentage of organic matter and negatively associated with compaction and water content. An increase in water content from wilting to field capacity decreases the absorption coefficient by 0.16; progressing from a state of non-compacted to compact decreases absorption by 0.10 at frequencies above 250 Hz. The effects of these changes in state are of the same magnitude for substrates with 2%–25% organic matter.

Although the unit increase in sound absorption coefficient is similar for the percentage of organic matter and the percentage of porosity, in reality the constitute part of the substrates which is most significantly altered/engineered is the percentage of organic matter which can vary from as low as 2% to as high as 25%, whereas porosity varies within a smaller range (57%–72% in the samples evaluated). Therefore, the greater range in the variability of the percentage of organic matter can affect absorption to a greater extent than porosity. The trends of the four frequency-dependent models are similar, with the exception of the percentage of organic matter and porosity. This is difficult to explain physically. The multi-variable models indicate that there is no effect of compaction in the lowest frequency band of 250 Hz. Fig. 1 illustrates the conformity level of the substrates to FLL guidelines for particle-size distribution (PSD). PSD and Particles >6.3 mm, as independent variables, were candidate predictors of absorption. However, it was determined by modelling that there was no direct

Table 3
Coefficients for multi-variable octave band regression models.

Frequency band Models	Coefficients						Multiple R- squared	n = 87
	Intercept β_0	% OM β_1	Porosity β_2	VWC= wilting β_3	VWC=Field β_4	Compaction β_5		p- value
250 Hz	0.0609	0.7000	0.6259	−0.3388	−0.4218	0.0000	0.7837	0.0000
500 Hz	−0.0423	0.3800	1.0129	−0.1365	−0.4208	−0.1489	0.7887	0.0000
1000 Hz	−0.0503	0.8500	0.8151	−0.1331	−0.2357	−0.0970	0.7471	0.0000
2000 Hz	0.1396	0.7000	0.7195	−0.0439	−0.2263	−0.2016	0.6627	0.0000

relationship between these variables and octave band absorption values.

The models are applicable to a wide range of green roof substrate designs which meet the physical characteristics specified by the FLL design guidelines to support green roof plant viability, however, they would not be applicable to substrate designs which deviate significantly from the design guidelines, substrates with manufactured amendments to alter water holding capacity nor novel hydroponic alternates. A limit of the experimental set-up was the selection of pre-engineered industry products as the test samples; a fabrication of substrate samples, with an incremental gradient of the percentages of constituents, would have benefited the analysis.

5.2. Field testing of vegetated roof plots

The spherical decoupling technique that was used was viable to evaluate the absorption capacity of vegetated roofs in the architectural range from 200 to 5000 Hz. Although frequencies less than 200 Hz are also important in sound propagation over roofs, they were not measured in this experimental set-up. In the controlled environment of an anechoic chamber, the optimal geometric configuration of the spherical decoupling setup for the measurement of vegetated roofs was achieved when the distances of the base microphone above the surface plane and between the two microphones were minimized; however this defined the low-frequency cut-off.

Absorption of the sedum-planted test plot in the anechoic chamber, as quantified by the NRC, was 0.63; the NRC of the in-situ sedum-planted plot of the same depth was 0.37. The results are not directly comparable, as the surface properties of the test plots varied considerably. In addition to variation in plant species coverage and establishment, the significant differences between the two plots included the level of compaction, the level of moisture content, and the surface level particle size distribution. In the anechoic chamber, the plot was planted with an even distribution of 4-inch pots. On the rooftop the coverage was not evenly distributed; the plant viability and mortality varied as the plot established over time. These findings suggest that short-term experimental setups and controlled lab conditions, which do not accurately represent in-situ rooftop properties of a vegetated roof substrate and complex plant ecology, may exaggerate the absorption potential of the vegetated plots. The method developed for this investigation addresses the lack of the generalizability of experimental setups with simulated plantings in controlled environments.

Measurements in third-octave bands from 200 to 5000 Hz were completed on seven substrate plots and seventeen of the eighteen planted rooftop test plots over the course of two seasons. Measurements were completed within a time span of 36–48 h after complete saturation, to represent field capacity. Air temperatures at the time of testing ranged between 15 °C and 23 °C.

Fig. 10 shows the diffuse-field absorption coefficients of the substrates. They increased with frequency from 200 to 1250 Hz and then remained constant to 4000 Hz. The absorption coefficients tended to increase with depth. The mean NRC was 0.62 for depths from 50 to 200 mm (see Table 4). There was no significant

Table 4
10 NRC of substrates – 50–200 mm depths.

Depth (mm)	GWC	NRC
50	48	0.57
75	53	0.56
100	46	0.61
125	50	0.67
150	49	0.65
175	49	0.70
200	52	0.61

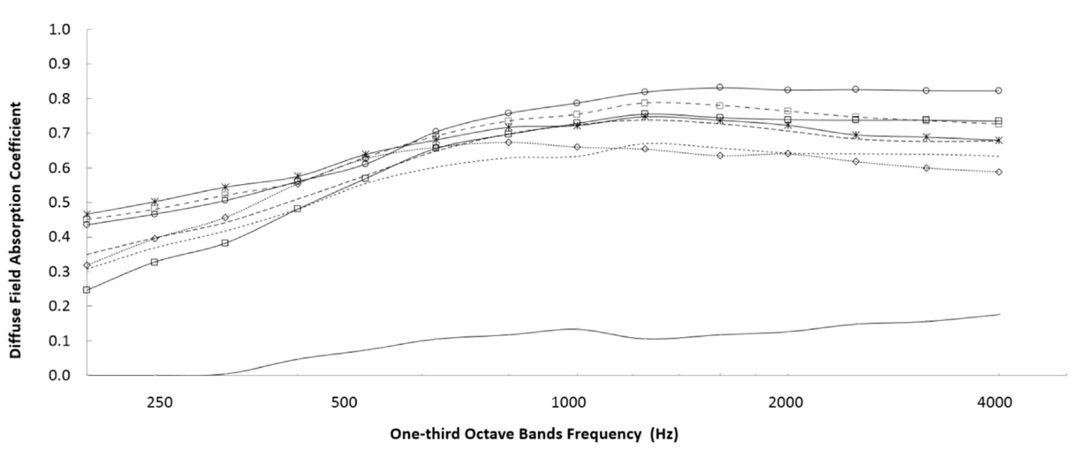

Fig. 10. Measured third-octave diffuse-field absorption coefficients of reference roof and substrates of 50- to 200-mm depth in rooftop test plots.

Table 5
NRC of test plots planted with sedums (P1).

Date	Plant species	Depth (mm)	Coverage (%)		NRC
			Total	Spontaneous	
29-Sep	P1	50	52.6	25.4	0.46
		75	54.2	25.4	–
		100	72.6	27	0.37
		125	56.6	45.4	0.24
		150	82.6	31.8	0.44
		175	75.4	35.4	0.43
		200	43	13.4	0.39

association between the gravimetric water content and the NRC of the substrates. The absorption of the substrate plots, without planting, was significantly greater than that of the exposed roof membrane; e.g., the NRC was 0.62 averaged over depths of 50–200 mm compared to 0.06 on the exposed roof.

The P1 plots, planted with *Sedum album,* were colonized with mosses over the time frame of plant establishment. The total plant coverage in the plots was distributed between the planted species of sedums and the spontaneous establishment of mosses. The plot with a 25-mm substrate depth was not considered sufficiently viable in terms of plant coverage to evaluate. The mosses accounted for 37%–80% of total coverage (Table 5). The trend of increased absorption relative to depth, which was observed in the non-planted plots, was not observed in the plots with the established P1 community (see Fig. 11). However, there was a negative trend between the percentage of spontaneous coverage and the NRC with the range of plots from 50 to 200 mm. In this community, the range of the NRC was 0.39 across substrate depths of 50–200 mm.

Overall, the absorption of the plots planted with community P1 was lower than that of the substrate plots. The variation with frequency was similar for both; however, the mean difference in the absorption coefficient ranged from 0.14 at 200 Hz to 0.35 at 800 Hz in the 1/3 octave band analysis. The mean NRC decreased by 0.24 (see Fig. 12).

The plots were compared between two seasons to illustrate seasonal climatic impacts (Fig. 13). The plots were saturated 36–48 h before evaluation; however, it is reasonable to assume that there was greater evapotranspiration in July when the maximum daily temperature before acoustical evaluation was 27 °C, versus 16 °C in November. The variability in plant coverage, and the climatic difference, affected the absorption at lower frequencies; a greater impact on absorption was observed above 500 Hz. In the P2 (coastal meadow) community, the range of the NRC across substrate depths of 125–200 mm was 0.60 as measured in the fall and 0.13 as measured in the summer. In the P3 (grass) community, the range of the NRC was 0.12 across depths of 125–200 mm in both seasons. The lowest absorption (NRC 0.20) was in the P2

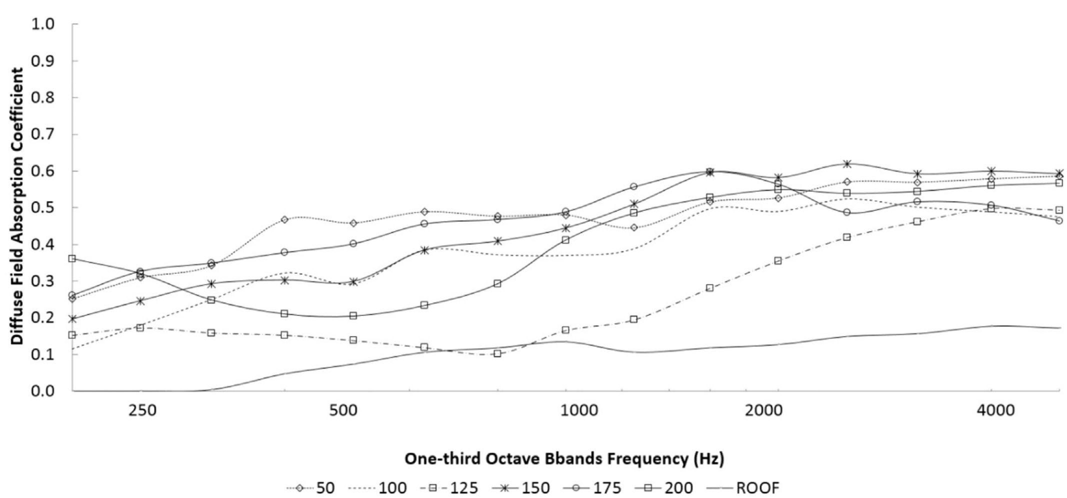

Fig. 11. Measured third-octave-band diffuse-field absorption coefficients of rooftop test plots planted with sedums (P1).

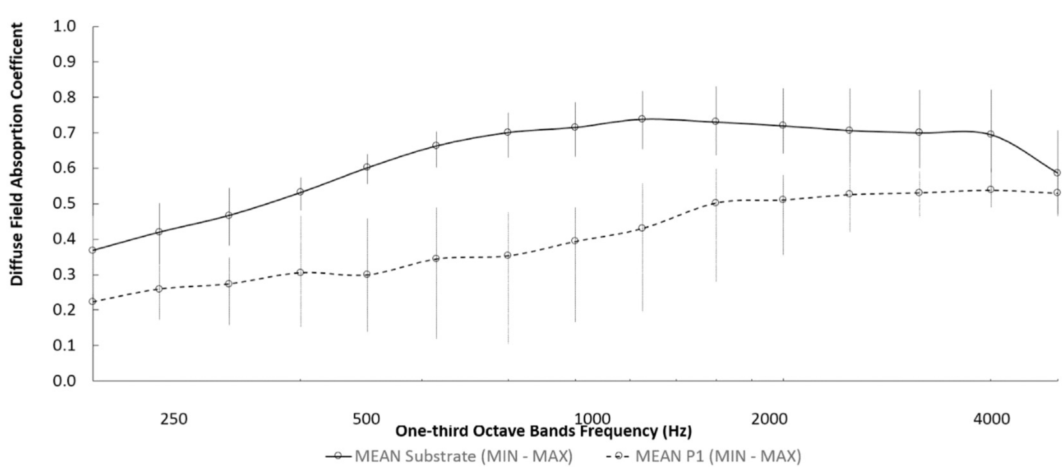

Fig. 12. Measured third-octave-band diffuse-field coefficients of substrate and sedums (P1) in rooftop test plots.

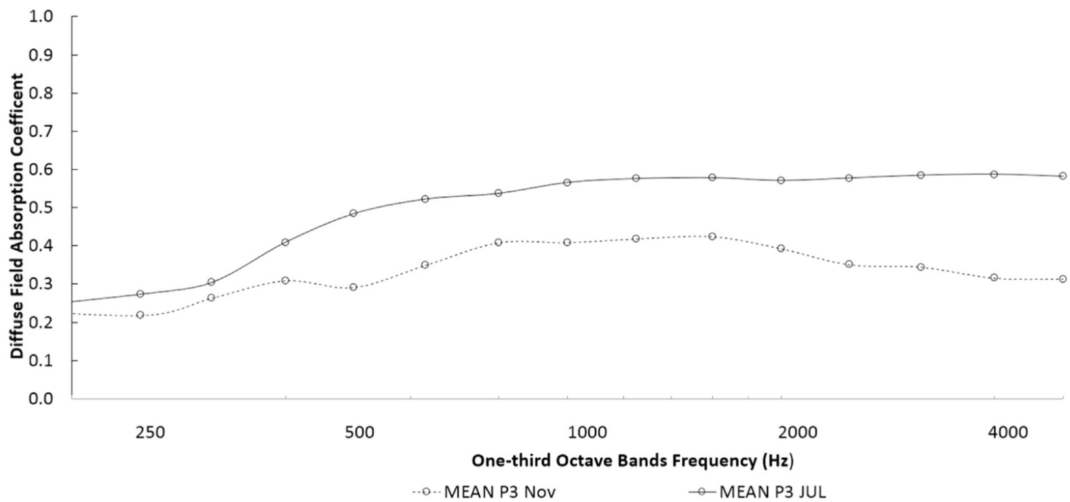

Fig. 13. Measured third-octave-band diffuse-field absorption coefficients of P3 community (cultivated grasses) in rooftop test plots (substrate depths 125–200 mm) in fall and summer seasons.

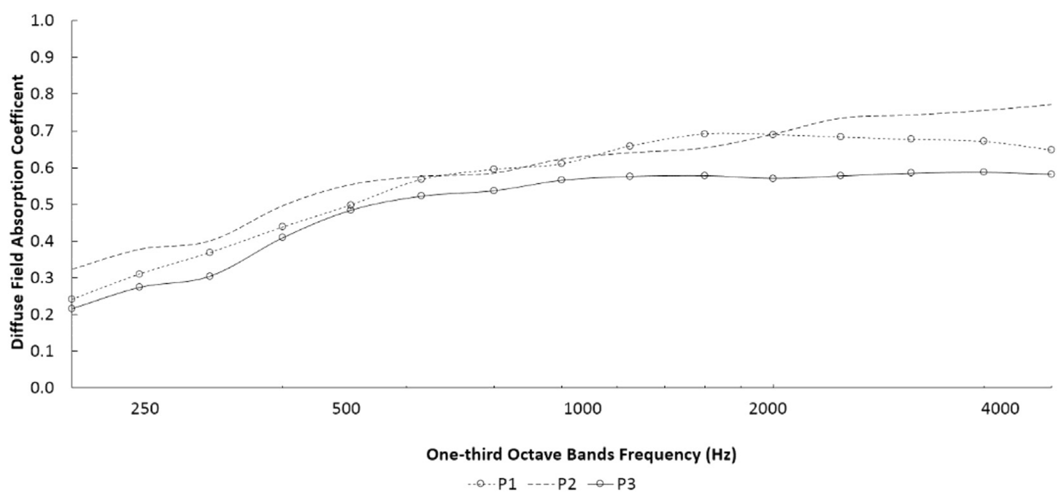

Fig. 14. Measured third-octave-band diffuse-field absorption coefficients of 3 plant communities (substrate depths 125–200 mm) after 2 seasons of establishment.

community planted in a 200-mm substrate depth. This measurement took place in the late fall in conditions of cool temperatures and high levels of moisture in the plants and substrate. The same community measured in summer climatic conditions in a 100-mm substrate depth had the highest absorption (NRC 0.62).

After two years of establishment, a common trend of absorption across the plant communities over the range of depth was observed. However, the ranges of absorption performance between communities overlapped and, therefore, did not allow for differentiation between the three communities (see Fig. 14).

6. Conclusion

In this study, the impedance tube and the spherical decoupling methods have been used to discover the normal- and random-incidence (or diffuse-field) absorption coefficients of a variety of green roof substrates, substrate constituents, and green roof plots. Results showed normal-incidence absorption coefficients of six types of substrates varying from around 0.03 at 250 Hz to 0.89 at 2000 Hz, and that absorption increased with the percentage of organic matter and decreased with moisture content and compaction. Random-incidence or diffuse-field absorption coefficients of green roof plots increased with substrate depth and decreased with the addition of vegetation and an increase in plant establishment. The NRC of seventeen different vegetated roof plots ranged from 0.20 to 0.63.

The investigation confirmed several findings. One, the sound absorption of vegetated roofs is a function of substrate depth, plant community establishment, and moisture content of substrate. Two, vegetated roofs as a building-envelope system has highly sound-absorptive characteristics and some values and conditions for optimal absorption have been quantified. From the observations and results of this work, a multi-variable regression model was developed for predicting the normal-incidence absorption coefficients of substrates, which can be used to assess the sound absorption of substrates in the terms of design specifications, such as proportions of the constituent parts. This is particularly useful as the latest predictive models require input of valid absorption coefficients [51,52]. The use of vegetated roofs as absorptive surfaces to reduce noise build-up and reverberation on rooftop spaces, and the acoustical performance of multilayer building partitions containing green roof systems, can now be investigated and modelled using sound absorption data provided through this work.

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