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Sound insulation of lightweight extensive green roofs

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ABSTRACT

This paper examines factors affecting the sound insulation of lightweight extensive green roofs. The research had three objectives: (1) To examine the extent to which the sound insulation of lightweight extensive green roofs is affected by the variable conditions of their substrate and vegetation layer (soil's distribution, water content and compaction level); (2) To quantify how sound insulation is affected by the main elements making up the roof (substrate and vegetation layer, drainage layer and added cavity); (3) To identify applications for such roofs in relation to their sound insulation performance. For objective 1, it was found that the variable conditions of the substrate and vegetation layer do not significantly affect the sound insulation properties of lightweight extensive green roofs (variations in R_w of no more than 1 dB). For objective 2, results indicated that the addition of a cavity represents the most effective solution for improving sound insulation (+13 dB in R_w for a 50 mm deep cavity with mineral wool), whilst increasing the amount of substrate or using heavier drainage layers tend to provide more limited improvements in R_w (+3 dB for 25 mm of substrate and +2 dB for gravel vs. lightweight drainage membrane). Finally, regarding objective 3, the systems tested were found to provide appropriate sound insulation for both commercial and residential types of constructions. All the results were obtained from tests carried out on small 1 m² samples, so their accuracy and validity will need to be identified through comparisons with large scale tests.

1. Introduction

Green roof systems have become increasingly used in urban spaces, due to their environmental, ecological and visual benefits [1]. They can avoid localised flooding by reducing water runoff [2]; they cool the temperature inside buildings in summer, thanks to evapotranspiration, and act like an additional layer of insulation in winter [3]; they reduce the urban heat island effect compared to traditional buildings [4]; they help remove airborne particles, heavy metals and volatile organic compounds from the local atmosphere and can recreate habitats for enhanced biodiversity in urban areas [5]. They can also provide energy savings, in particular when used to retrofit older buildings [6].

Acoustic benefits of such systems have also been demonstrated within the context of traffic noise mitigation. In particular, acoustic studies have focused on the sound absorption and sound propagation properties of green roofs [7-12], as well as of green walls and vertical greenery systems used on façades [13-15]. These studies have found that green roofs and vertical greenery systems reduce sound propagation compared to rigid roofs/façades, with maximum road traffic noise reductions of approximately 10 dB at mid frequencies around 500 Hz – 1000 Hz, for green systems with a length of 8 m [7,13]. Furthermore, research has shown that positive effects of green roofs are only observed at non-directly exposed parts of façades (i.e. at the opposite side of a building compared to the one where the source is present), and that a sufficient green roof area and flat roof are needed to maximise the traffic noise reductions [8]. The configurations of the systems [11], roof thickness [7,10] and vegetation layer [12], have all been shown to be important factors affecting the sound absorption and sound propagation properties of these systems.

Sound insulation is another feature which can be provided by a green roof system, but previous work on the sound insulation properties of green roofs has been very limited so far. Green roofs are multi-layered systems, and it is known that the use of multiple layers takes advantage of losses in transmission between the layers, increases damping, and can potentially reduce the coincidence effect, all of which contribute to increasing sound insulation [16]. Furthermore, it is known that the acoustic characteristics of porous materials, such as green roofs' substrates, are affected by factors such as porosity, particle size distribution, moisture content and compaction [17]. The soil's texture

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also affects the attenuation of sound as it passes through the depth of the soil, and it has been found that lower attenuation occurs in loose dry soils [18]. Furthermore, the interface between the soil and vegetation layer has been identified as affecting the impedance of the system, and therefore the amount of sound transmitted through it [19].

All these previous studies evaluated specific sound insulation properties of green roofs' elements, rather than their overall sound insulation properties which can be quantified by the sound reduction index (known as the sound transmission loss in North America). The latter has been examined by Connelly and Hodgson [20,21], who measured the sound transmission loss of two different extensive green roofs by using the intensity approach of ISO 15186-1 [22]. The sound transmission loss of a reference roof (Roofing Evaluation Module (REM): 75 mm concrete, steel reinforcing, 318 mm Expanded Polystyrene (EPS) insulation) was compared to that of two green roofs consisting of: (1) the reference roof + 75 mm of substrate; (2) the reference roof + 150 mm of substrate. Results showed that, compared to the reference roof, consistent increases in sound transmission loss could be obtained for the thicker green roof (5-13 dB up to 2000 Hz), whilst the thinner green roof could not provide such improvements between 100 Hz and 600 Hz. These findings suggested that green roofs can be used instead of additional ceilings, especially considering their better performance below 125 Hz, as false ceilings (lightweight with cavity not very large) only increase the transmission loss in the mid and high frequency ranges [23,24]. Connelly and Hodgson also quantified the significant benefits of vegetation used over either a wood frame roof (5-13 dB in the 50-2000 Hz frequency range, and up to 8 dB above 2000 Hz) or a lightweight metal deck (up to 10 dB, 20 dB and > 20 dB in the low, mid and high frequency ranges respectively) [25]. In this study, the moisture content of the substrate did not affect the transmission loss of the systems tested.

Other studies also examined the sound insulation properties of green walls and vertical greenery [13-15]. Wong et al. [13] found that the insertion loss of vertical greenery systems is higher at low to mid frequencies (in the order of 5-10 dB) due to the absorbing effect of the substrate, while it is smaller at high frequencies due to scattering from the greenery. Azkorra et al. [14] tested the sound insulation of a modular-based green wall, a lightweight system for which a weighted sound reduction index (R_w) of 15 dB was measured. Furthermore, Pérez et al. [15] found that a thin layer of vegetation (20-30 cm) used over a masonry construction can provide an increase in sound insulation of 1-3 dB.

The present study focuses on the sound insulation properties of green roofs, and within that context, the work of Connelly and Hodgson [20,21,25] is the most relevant. In refs [20,21] a concrete roof base was used, but lightweight bases are also used in extensive green roofs [25], especially in the retrofitting of existing buildings [6]. These are economical systems typically made of corrugated steel bases or timber joist roofs with plywood or chipboard plates used as the base, and can be found in both residential and commercial buildings. The low mass of such systems can however result in poor sound insulation properties, compared to green roofs constructed over concrete bases. Consequently, a good understanding of the factors affecting the sound insulation properties of lightweight green roofs is critical, in order to be able to provide appropriate design guidance. The present study examined this for a variety of lightweight extensive green roof systems, in view of improving the understanding of how the multi-layered composition of such systems affects their sound insulation. More specifically, the research had three main objectives:

- (1) To examine the extent to which the sound insulation of lightweight extensive green roofs is affected by the variable conditions of their substrate and vegetation layer (soil's distribution, water content and compaction level);
- (2) To quantify how sound insulation performance is affected by the main elements making up the roof (substrate and vegetation layer (which are the main elements affecting the mass of the system), type of drainage layer used, and presence or absence of a cavity);
- (3) To identify applications for the lightweight extensive green roof designs tested, based on their sound insulation performance.

The paper initially illustrates the materials and methods used in the study, followed by the presentation and analysis of the results obtained, and conclusions.

2. Materials and methods

A green roof can be categorized as intensive, semi-intensive, or extensive, depending on the depth of the planting medium and the amount of maintenance needed [5]. Intensive and semi-intensive green roofs have greater depth and can accommodate large as well as small plants, whilst extensive green roof systems typically have shallower system profiles. Due to their minimum maintenance requirements, extensive green roofs tend to be more commonly used [5] and are the only type of green roof considered in this paper. The structure used for tests and the procedures undertaken in this research are illustrated below.

2.1 Test structure

In order to test the sound insulation properties of a typical extensive green roof, the vertical transmission suite located in the acoustic laboratory of Heriot-Watt University was used (Fig. 1). The vertical suite is composed of two rooms: a lower room of 5 m × 4 m × 3 m (60 m³), and an upper room of 5 m × 4 m × 2.7 m (54 m³). The suite comprises a heavy concrete ring beam over which a 12 m² floor can be installed. This design suppresses flanking transmission from the side walls (see [26]), and allows testing direct transmission through the floor.

In the present research, the green roof samples were limited to a 1 m × 1 m section (Figs. 1 and 2), due to funding constraints. This led to reduced size opening tests [27] that required the construction of a highly insulated separating floor around the 1 m² test area, in order to minimise sound transmission from the surfaces surrounding the test area. The highly insulated floor was constructed using deep timber joists (220 mm depth, 45 mm width and 106 kg/m² surface density), with plasterboard plates (12.5 mm thickness and 8.5 kg/m² surface density) screwed under the joists, and chipboard plates (18 mm thickness and 12 kg/m² surface density) screwed over them. The gaps in between the joists were completely filled with mineral wool. Prior to the testing of green roof samples, the 1 m² opening was also filled with mineral wool and covered with chipboard, so that the sound reduction index of this highly insulated floor could be determined ($R_w = 48$ dB and mass-spring-mass resonance of 67 Hz). Although sound transmission from the floor surrounding the samples tested was negligible in most cases, its sound reduction index was required, so that appropriate corrections could be made to calculate the exact sound reduction index of each green roof sample (see section 2.2 for further details).

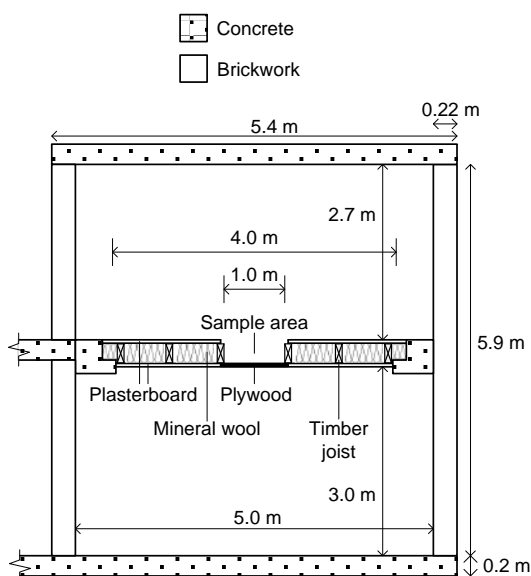


Fig. 1. Section diagram of the vertical transmission suite (not to scale).

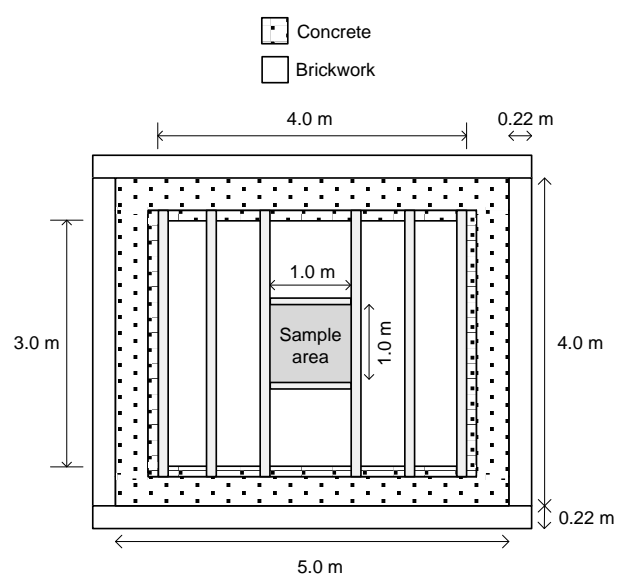

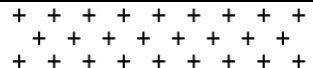




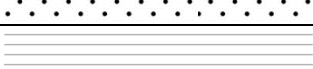


Fig. 2. Plan showing the separating floor and the 1 m² sample area used for green roof samples (not to scale).

Table 1. Materials used for the green roof samples and their physical properties. In addition to the manufactured drainage membrane shown, pebbles and gravel were also used as alternative drainage layers (Fig. 3) and their properties are given in section 2.3. A 50 mm deep cavity placed between the plywood plate and the thermal insulation board was also used in one test. Note: the variable thickness of the vegetation (20-40 mm) did not noticeably affect the surface density across the sedum mat, as the latter was largely dominated by its heavy substrate which had a constant thickness of 20 mm.

	Material	Physical properties
	Vegetation (sedum mat)	Thickness: approx. 20-40 mm Surface density: 18 kg/m ²
	Substrate (top soil)	Varying thickness tested: approx. 8-25 mm Density: 600 kg/m ³
	Filter fleece	Surface density: 0.50 kg/m ²
	Drainage membrane	Thickness: 20 mm Surface density: 0.90 kg/m ²
	Waterproof membrane	Surface density: 0.28 kg/m ²
	Thermal insulation board	Thickness: 50 mm Surface density: 0.50 kg/m ²
	Plywood plate	Thickness: 18 mm Surface density: 9.31 kg/m ²

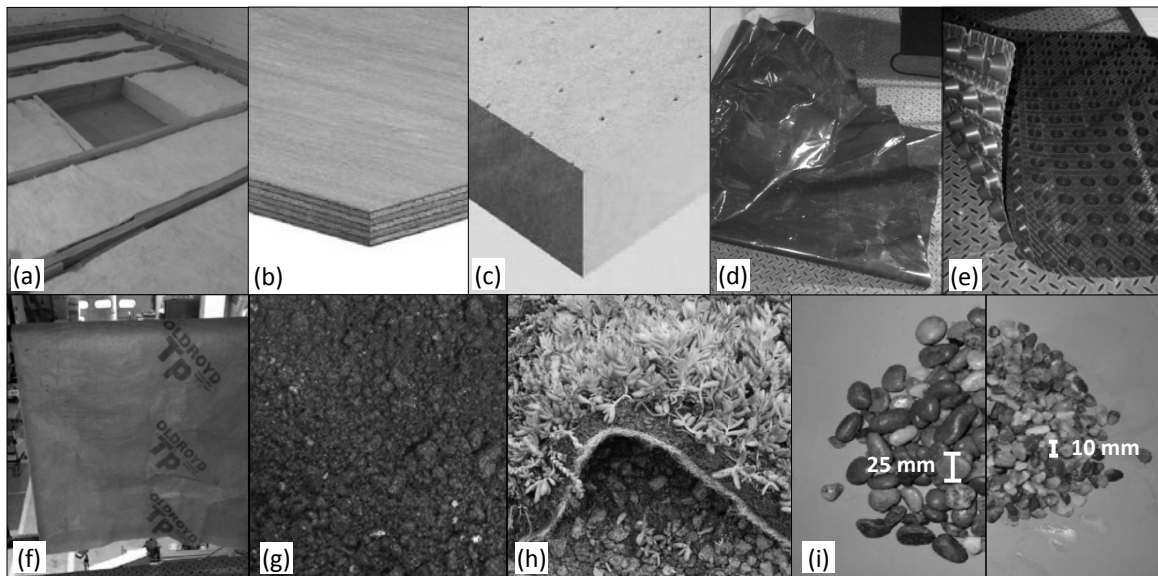


Fig. 3. Materials used for the green roof samples. (a) Timber joist floor with mineral wool insulation (open on top for illustration purposes); (b) Plywood; (c) Insulation board; (d) Waterproof membrane; (e) Drainage membrane; (f) Filter fleece; (g) Top soil; (h) Sedum mat; (i) Pebbles (*left*) and gravel (*right*).

In a lightweight green roof system, joists would normally be present under the roof, but these were not installed here because of the limited depth available in the floor's opening. Joists increase stiffness and therefore tend to improve sound insulation towards low frequencies. However, it is unlikely that stiffness would have been increased noticeably for such a small sample size. Results presented later also indicate that R_w values were only affected by poor insulation at frequencies greater than 250 Hz, suggesting that improvements in low frequency performance provided by joists would probably not have affected R_w values. Other limitations of the small sample size used include low modal density at low frequencies and diffraction effects that can increase the sound insulation of

smaller panels below the critical frequency. These limitations should be kept in mind when analysing results.

The materials making up the green roof samples tested are listed in Table 1 and shown in Fig. 3. A plywood plate was used as the base, with a roof thermal insulation board (Kingspan 50 mm Thermaroom TR27 (Kingscourt, Ireland)) over it. A waterproof membrane (DMP damp-proof membrane by Capital Valley Plastics (Gwent, United Kingdom)) was placed over the latter, protecting the roof from moisture penetration. The membrane used was composed of low density polyethylene. A drainage membrane (Oldroyd Xv 20 GreenXtra (Whitley Bridge, United Kingdom)) made of polypropylene (0.8 mm thick) was placed over the waterproof membrane, allowing water to be retained within pockets (20 mm deep). Alternative drainage layers made of pebbles (49 kg/m²) or gravel (53 kg/m²) were also tested. A filter fleece (Oldroyd Tp) was installed over this to help prevent the passage of soil into the drainage layer, and the substrate was placed over the fleece. Sterilised top soil (Homebase Top Soil (Milton Keynes, United Kingdom)) was used as the substrate for all the tests carried out. A sedum mat (Edengro roof sedum mat (Herford, United Kingdom)) was then installed on top, and acted as the vegetation layer. This was made of a needle punched recycled polyester fibre mat (approximately 3 mm thick), with a thin layer of recycled green roof substrate (composted green waste, crushed recycled brick, composted bark and recycled loam) in which the sedum plants could grow. A sample with an additional 50 mm cavity was also tested (15 kg/m² of top soil and no sedum used in the tests): the cavity was built between the plywood plate and the thermal insulation board, using three timber battens (50 mm thickness, 38 mm width, 24 kg/m² surface density and 0.35 m spacing between battens) resting over the plywood plate, with mineral wool placed in between the battens and a 1 m² medium-density fibreboard (MDF) plate (15 mm thickness and 12 kg/m² surface density) laid over the battens (no nails/screws used).

2.2 Procedures and equipment

The sound reduction index, R , of each green roof sample was measured in the vertical transmission suite following the standard procedures given in ISO 10140-2 [27]. This required sound pressure level measurements in both the source and receiving rooms, and reverberation time measurements in the receiving room only, as the sound reduction index, R (dB), can be calculated from

$$R = L_1 - L_2 + 10 \log \frac{S}{A} \quad (1)$$

where L_1 is the sound pressure level in the source room (dB re 2×10^{-5} Pa), L_2 is the sound pressure level in the receiving room (dB re 2×10^{-5} Pa), S is the surface area of the separating element between the rooms (m²) and A is the equivalent absorption area in the receiving room (m²). The latter was calculated from reverberation time measurements, using the equation

$$A = \frac{0.161V}{T} \quad (2)$$

where V is the volume of the receiving room (m³) and T is the reverberation time in the receiving room (sec). Background noise correction was also applied to the L_2 measurements [28].

The lower room was chosen as the source room, because of its larger volume [26], and space averaging was applied to L_1 , L_2 (equation (1)) and T (equation (2)). For sound pressure level measurements, four loudspeaker positions were used (number determined following ISO 10140-5 [26]), together with five microphone positions (as recommended in ISO 10140-4 [28]). For reverberation time measurements, two source positions and three microphone positions were used, following the engineering accuracy method of ISO 3382-2 [29]. The sound pressure level and reverberation time values were recorded in 1/3 octave bands, and in order to obtain a single number, the weighted sound reduction index R_w was calculated following the standard procedure

given in ISO 717-1 [30]. Sound pressure level and reverberation time were measured using an integrating-averaging sound analyser Brüel & Kjaer type 2250 (Naerum, Denmark), an omnidirectional sound source made of 12 loudspeakers, and a Brüel & Kjaer power amplifier type 2706.

In practice, measurements included transmission through both the green roof sample and the floor surrounding it. In other words, the sound reduction index measured quantified sound transmission through the 12 m² composite element comprising both the green roof sample and the highly insulated floor. This corresponds to a composite sound reduction index that is the combination of two elements, and can be calculated from the sound reduction indices of these two elements using the equation [16, p. 483]

$$R_T = -10 \log \left(\frac{S_G \times 10^{-R_G/10} + S_F \times 10^{-R_F/10}}{S_T} \right) \quad (3)$$

where R_T is the sound reduction index of the composite element comprising the 1 m² green roof and the 11 m² highly insulated floor (dB); R_G is the sound reduction index of the green roof sample (dB); R_F is the sound reduction index of the highly insulated floor (dB); S_T is the total area of the floor (m²), i.e. $S_T = 12$ m²; S_G is the area of the sample (m²), i.e. $S_G = 1$ m²; and S_F is the area of the highly insulated floor (m²), i.e. $S_F = 11$ m². The sound reduction index of the 1 m² sample, R_G , can then be isolated from equation (3), and is found to be equal to

$$R_G = -10 \log \left(\frac{S_T \times 10^{-R_T/10} - S_F \times 10^{-R_F/10}}{S_G} \right) \quad (4)$$

Equation (4) shows that the sound insulation properties of the green roof sample could be calculated from the sound insulation measurements of the 12 m² composite floor (R_T) and the highly insulated floor (R_F), the latter having been measured prior to the testing of green roof samples. It should however be pointed out that sound reduction indices used in equation (3) cannot always be scaled to different areas, which is why some limitations in accuracy can be expected. Furthermore, it can be noted that equation (4) is different from the correction equation given in ISO 10140-2 [27] (method assuming a specific type of flanking construction and ignoring surface areas), and was applied across all the frequency bands measured.

2.3. Experiments conducted

Six different experiments were carried out to address the objectives listed in section 1. More specifically, objective 1 was addressed by tests 1-3 listed below, while objectives 2 and 3 were addressed by tests 4-6.

- **Test 1 - Reproducibility:** green roofs based on identical specifications can be expected to show some variability in the uniformity of the substrate's distribution. The reproducibility tests carried out here aimed to specifically examine the variability of the green roof's sound insulation when the top soil is removed and put back in place. This might occur during maintenance periods, when the substrate is removed to inspect layers under it. Furthermore, these measurements can provide some insight into the behaviour of identical green roofs installed in different places. In this test, 15 kg/m² of top soil were used as the substrate, without a sedum mat on top.
- **Test 2 - Compaction:** the level of compaction of the top soil can evolve over time, due to either rainfall or people walking over the roof when carrying out maintenance, a reason why compaction was another factor worth examining. A first measurement was made without compaction, using 15 kg/m² of top soil and the sedum mat. Then, the top soil was manually compacted over three stages (5 kg/m² at a time), using a small plywood plate and a hammer,

and the sedum mat was added on top. The thickness of the soil was 25 mm before compaction, and 15 mm after compaction, and the density of the soil changed from 600 kg/m³ to 1000 kg/m³.

- **Test 3 - Evolution over time:** extensive green roofs do not need regular watering. Therefore, the water content of such roofs (i.e. their mass) can vary significantly over time. An extreme case is represented by very heavy rainfall followed by a long period with no rain. This experiment aimed to quantify the variability in sound insulation over time, after very heavy rainfall has occurred. 15 kg/m² of top soil and the sedum mat were initially saturated in water (water floating close to the top), and measurements were then taken over 18 days, without adding any water. The roof's weight decreased from 55 kg on day 1 to 40 kg on day 18.
- **Test 4 – Mass:** this experiment aimed at identifying the influence of the green roof's mass on its sound insulation. Measurements were initially made with no top soil and no sedum mat used in the system. Then, the sedum mat was placed on top of the roof, without any top soil under it. This was followed by measurements with different amounts of top soil used under the sedum mat: 5 kg/m², 10 kg/m² and 15 kg/m², corresponding to a thickness of approximately 8 mm, 17 mm and 25 mm respectively.
- **Test 5 - Drainage layer:** different materials can be used as a drainage layer. In addition to manufactured drainage membranes, materials like gravel and pebbles can be used. For this experiment, the manufactured drainage membrane was compared with a drainage layer made of gravel or pebbles. The surface density of the gravel and pebbles laid was 53 kg/m² and 49.5 kg/m² respectively, and corresponded to an identical volume (1 m x 1 m x 0.025 m). The void ratio (volume of voids over volume of solids) of the gravel and pebbles was measured as 0.80 and 0.65 respectively. 15 kg/m² of top soil and the sedum mat were used in the experiments.
- **Test 6 - Added cavity:** a 50 mm deep insulated cavity was added to the green roof system (see section 2.1 for construction details), in order to quantify the effectiveness of an added cavity in terms of sound insulation. The test was made with 15 kg/m² of top soil as the substrate, and with no sedum mat on top.

It can be noted that a full green roof system was used in tests 2-5, whilst no sedum mat was used in tests 1 and 6 (unavailable at the time when these tests were carried out). Although this limits the direct comparability of sound insulation results obtained for tests 1 and 6 with results obtained for tests 2-5, it is important to note that this does not affect the validity of any of the findings discussed in the following section. Furthermore, it can be noted that, with the exception of test 3, the water content of the top soil was always in the order of 35% of the mass (water content of top soil when purchased).

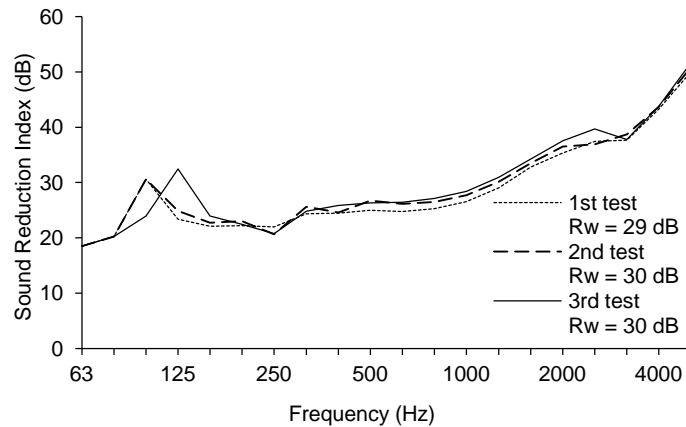
3. Results and analysis

3.1. Test 1 - Reproducibility

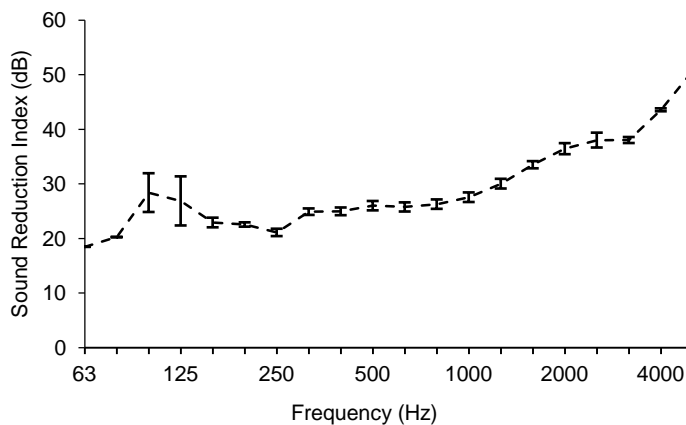
Three tests were carried out (top soil removed and put back in place in between tests) and the corresponding sound reduction indices are shown in Fig. 4(a). The large variations observed below 250 Hz, and in particular the peaks observed at 100 Hz and 125 Hz, are related to the few modes present at such frequencies in the 1 m² sample and in particular the plywood plate. Furthermore, the dip observed at 3150 Hz corresponds to the critical frequency of the system. The R_w values show a slight variation of 1 dB between the first (29 dB) and the other two tests (30 dB), a small deviation that can also occur in tests repeated on an identical sample, i.e. a sample untouched in between tests (ISO 12999-1 [31]). Maximum differences occur towards low frequencies, with a large difference of 9 dB recorded at 125 Hz, whilst much smaller differences of around ± 2 dB can be seen for frequencies greater than 125 Hz.

Fig. 4(b) displays the arithmetic mean of the three tests, together with the 95% confidence interval of the measurements. Intervals of ± 4.5 dB and ± 5.5 dB occur at 100 Hz and 125 Hz

respectively, whilst at mid and high frequencies the intervals are much narrower, with deviations of around ± 1 dB across most frequencies. It can be noted that the extent of some of these variations is due to measurements' uncertainties, rather than variations in the sample's arrangement, as these spectral trends and variations are fairly typical of repeatability tests [31]. Overall, these results suggest that removing and putting back the soil did not have a significant impact on the sound insulation properties of the green roof.



(a) Sound reduction index spectra.



(b) Arithmetic mean and 95% confidence interval.

Fig. 4. Sound reduction index data of the three reproducibility tests.

3.2. Test 2 - Soil compaction

Fig. 5 compares the sound reduction index of the green roof system with 15 kg/m^2 of top soil not compacted vs. 15 kg/m^2 of top soil compacted. The curves are very similar and the R_w values are identical (35 dB). Although the density of the material increased from 600 kg/m^3 to 1000 kg/m^3 (after compaction), its surface density remained unchanged (as the thickness decreased from 25 mm to 15 m). This justifies the similarity of the results, and suggests that other properties affected by the compaction, such as porosity and void ratio, did not affect the sound insulation properties of the substrate.

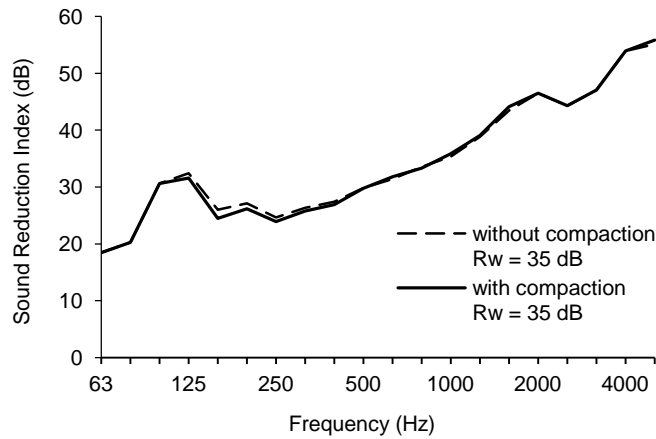


Fig. 5. Influence of substrate’s compaction.

3.3. Test 3 - Evolution over time

Fig. 6 illustrates the evolution of the lightweight green roof’s sound reduction index over 18 days (day 1: green roof saturated in water; no water added on the following days). Due to the limited variations observed between most of the 8 measurements carried out over that period, only three results are shown in Fig. 6 (days 1, 7 and 18). At day 1, the total surface density of the sedum mat and top soil was 55 kg/m^2 : 15 kg/m^2 of top soil (including water), 18 kg/m^2 for the sedum mat (including water) and 22 kg/m^2 of water added to reach saturation. At day 18, this weight had decreased to 40 kg/m^2 : 17 kg/m^2 of top soil (including water), 21 kg/m^2 for the sedum mat (including water) and 2 kg/m^2 of water in the drainage layer. Therefore, 15 kg/m^2 of water evaporated over the 18 days.

The results of Fig. 6 indicate that the sound reduction index did not change significantly over the 18 days. Noticeable changes only occurred over limited frequency ranges. At 125 Hz - 250 Hz, no conclusions can be drawn, as differences are smaller than the repeatability values of Fig. 4. At frequencies greater than 2.5 kHz, the sound insulation was higher at day 18 than at day 1 (up to +5 dB), because of the higher porosity provided by the air present within the substrate, compared to the water initially filling the voids within the top soil and sedum mat.

Overall, R_w results show a difference of 1 dB only, i.e. the variation in water content had a very limited impact on the sound insulation of the lightweight green roof, which is consistent with the findings of Connelly and Hodgson [25]. These results are also in line with the predictions of R_w vs surface density which are presented in section 3.4 (see logarithmic equation displayed on Fig. 8 (regression curve)): this equation estimates a R_w of 36 dB for the roof’s mass at day 1, and a R_w of 34 dB for the roof’s mass at day 18.

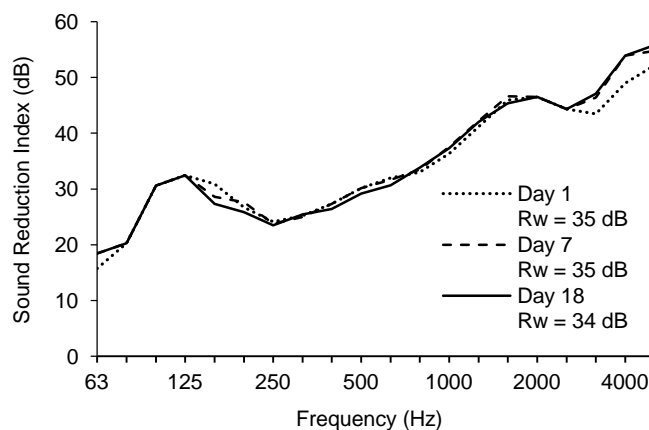


Fig. 6. Evolution of the sound reduction index over time (decreasing water content).

3.4. Test 4 – Mass

Fig. 7 shows sound reduction indices obtained for different configurations and weights of the green roof system. These include the system of Table 1 without the sedum mat and top soil (11.5 kg/m^2 (total surface density of the green roof)), with the sedum mat (29.5 kg/m^2), and with 5 kg/m^2 , 10 kg/m^2 and 15 kg/m^2 of top soil under the sedum mat (total surface density of 34.5 kg/m^2 , 39.5 kg/m^2 and 44.5 kg/m^2 respectively). Most sedums are resistant enough to grow without any substrate layer (the soil in the mat containing enough nutrients), which is why a system without top soil was initially tested, followed by relatively shallow thicknesses of top soil (8 mm, 17 mm and 25 mm).

Results indicate that the sound insulation increases with the mass of the system for frequencies greater than 250 Hz. The curves suggest that the system is stiffness or resonance controlled below 250 Hz and mass controlled above that frequency and up to approximately 1.6 kHz, after which it is damping controlled (with a dip at 3.15 kHz corresponding to the critical frequency, which shifts with changes in mass, as shown by the lower f_c of the 15 kg/m^2 case). These frequency limits are derived from thin plate theory [32] and are purely based on the observation of Fig. 7, two reasons why they cannot be considered exact (and which is why the delimitation between the stiffness and resonance controlled regions is not given); however, they provide some justification of the behaviour observed with changes in mass. For example, mass controlled behaviour should extend towards much lower frequencies than 250 Hz in large roofs, which is one of the reasons why the small size of the sample area tested is a limitation of the present research. Mass controlled behaviour at lower frequencies could actually be estimated by assuming a 6 dB drop per octave below 250 Hz (mass law [16]): this led to a reduction in R_w of 1 dB at most, for the samples of Fig. 7 (0 dB change for the 'no sedum and no soil' case and for the 'sedum + 10 kg/m^2 ' case; 1 dB change for the remaining 3 cases tested). Such a small reduction was due to the fact that, for the samples tested, unfavourable deviations from the reference curve used to calculate R_w [30] occurred only across the limited mid-frequency range 250 Hz – 1250 Hz. Furthermore, such estimations simply assumed an extension of the frequency range that is mass controlled, ignoring diffraction effects that can significantly increase the sound reduction index of smaller panels below the critical frequency [33]. Therefore, a reduction of more than 1 dB should actually be expected for larger panels. Only large scale measurements of the systems considered here could therefore accurately quantify the reductions in dB between the 1 m^2 samples tested and larger systems; such tests would also eliminate the other limitations of the 1 m^2 samples (low modal density at low frequencies and absence of joists) and will therefore be needed to identify the accuracy of the results presented here.

Fig. 8 illustrates results in terms of the weighted sound reduction index, R_w , where the regression curve shows a logarithmic relation between the surface density of the system and R_w . This logarithmic behaviour is comparable to single leaf systems, although increases in R_w per doubling of surface density (+4.3 dB according to the regression equation) are slightly lower than what is normally found in heavyweight constructions (around +5 dB). Furthermore, results suggest that increases in the surface density of the substrate need to be substantial in order to significantly increase sound insulation, as for the cases considered, an increase of only 3 dB was observed for R_w (from 0 mm to 25 mm thickness of substrate). For green roofs built over a concrete base, much larger loads of substrate tend to be used (100 mm thickness typically): these can accommodate vegetation with deeper roots, as well as provide large levels of sound insulation. Based on the regression curve of Fig. 8, the lightweight green roof tested would achieve R_w values of 35 dB and 38 dB for top soil thicknesses of 50 mm and 100 mm respectively (30 kg/m^2 and 60 kg/m^2). This corresponds to an increase in R_w of 7 dB (no top soil vs. 100 mm of top soil), which is significantly higher than the 3 dB increase observed with the 25 mm of top soil. This might then justify using large amounts of substrate for purely acoustical reasons.

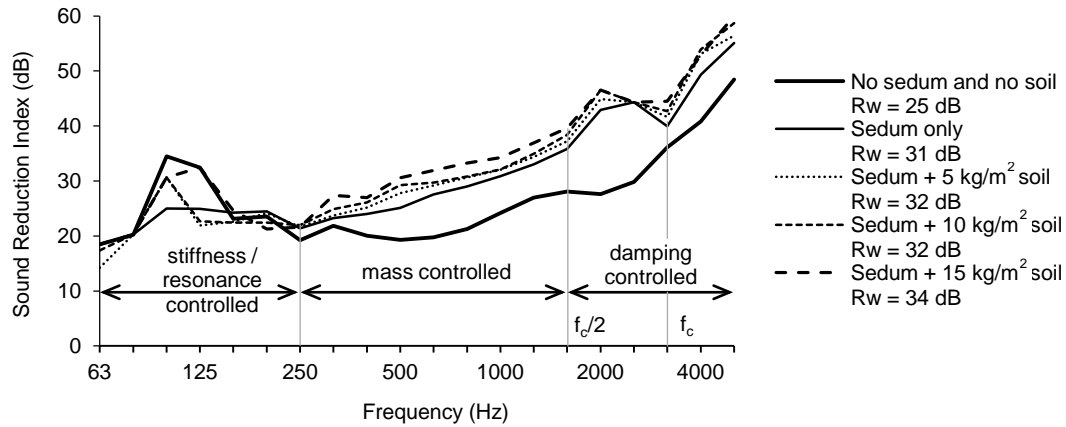


Fig. 7. Influence of mass on sound insulation (sound reduction index) for the five different samples tested.

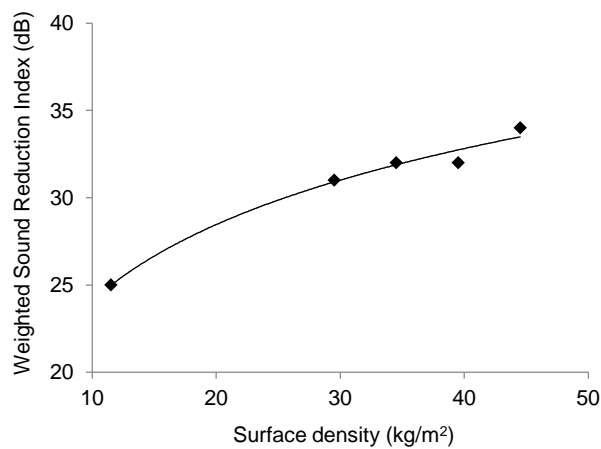


Fig. 8. R_w vs. surface density (data markers and logarithmic regression curve).

3.5. Test 5 - Drainage layer

Several materials can be used as a drainage layer. Manufactured drainage membranes, such as the one shown in Fig. 3(e), are commonly used, but other materials can provide comparable drainage properties. In this section, two aggregates often used for drainage (gravel and pebbles) are compared to the membrane of Fig. 3(e). Results obtained for these three drainage layers are given in Fig. 9, where it can be seen that large variations in the sound reduction index can occur when different materials are used for drainage. These differences vary significantly with frequency: below 125 Hz (sound insulation stiffness/resonance controlled), results are identical, but the gravel and pebbles provide significantly better sound insulation (up to + 10 dB) towards low-mid frequencies (160 Hz – 400 Hz), comparable performance ($\sim \pm 2$ dB) at mid-frequencies (500 Hz – 1 kHz), and poorer performance (up to – 8 dB) at mid-high frequencies (1.25 kHz – 4 kHz). The surface densities of the gravel (53 kg/m^2) and pebbles (49 kg/m^2) were much higher than that of the lightweight membrane (0.9 kg/m^2), which justifies the significantly better sound insulation provided by the gravel and pebbles at 160 Hz – 400 Hz, where sound transmission is mainly mass controlled. However, a dip is observed around 500 Hz for the gravel and pebbles, which suggests the presence of a new resonance in the system, possibly a new critical frequency. At 1.25 kHz – 4 kHz the membrane provides better sound insulation because of its higher damping (non-rigid coupling), and the gravel achieves a better sound insulation than pebbles, which also suggest higher damping of the gravel compared to the pebbles. The latter is expected to be due to a decrease in coupling caused by the higher void ratio of the gravel (0.80) compared to pebbles (0.65). Overall, the high mass of the gravel, as well as its high

void ratio indicate that these can contribute to increase the sound insulation of lightweight green roofs, compared to lightweight drainage membranes or pebbles (R_w increase of up to 3 dB).

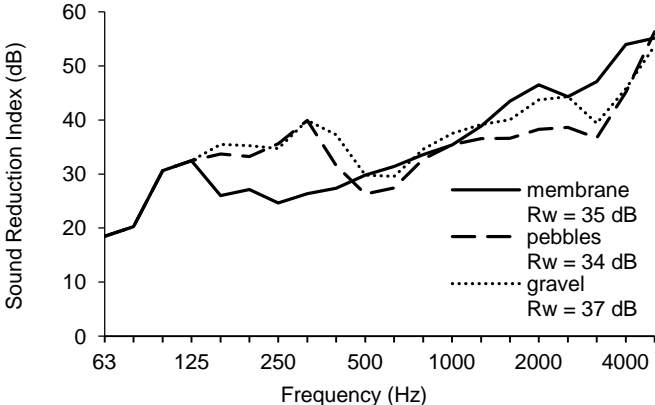


Fig. 9. Influence of drainage layer on the sound reduction index.

3.6. Test 6 - Insulated cavity

Fig. 10 shows that the addition of a sound insulated cavity increases significantly the sound reduction index across most frequencies. At 125 Hz and below no changes occur (sound insulation stiffness/resonance controlled), but above that frequency, increases vary between approximately 5-15 dB. The largest improvements occur at 315 Hz – 1.6 kHz, where differences are consistently close to 15 dB. It can also be noted that the critical frequency is more pronounced and is one 1/3 octave band lower (2.5 kHz instead of 3.15 kHz) in the green roof sample with the cavity, due to an increase of the plate stiffness by the timber battens. The R_w value increased by as much as 13 dB after the cavity was added, which highlights the fact that it represents the most effective solution for increasing sound insulation. It is important to note that the mass of the layers over the cavity do affect the mass-spring-mass resonance of the cavity system and therefore its sound insulation: the heavier the top layer is, the lower the resonance frequency is and the better the sound insulation is. Therefore, a cavity placed under larger amounts of soil could provide even better improvements, whilst a cavity placed under smaller amounts of soil might not provide the benefits found here.

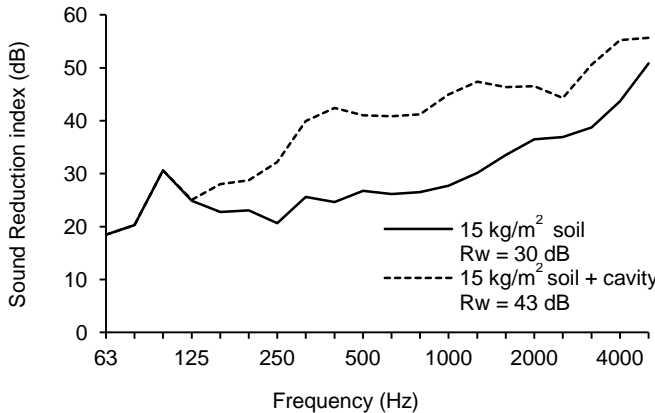


Fig. 10. Sound reduction index comparison without and with an insulated cavity.

4. Discussion

All tests carried out for objective (1) indicated that the sound insulation properties of lightweight extensive green roofs are only slightly affected by the substrate's distribution and uniformity, as well as by its compaction level and water content, as variations in R_w were never greater than 1 dB (Test 1 - Reproducibility: 1 dB; Test 2 - Compaction: 0 dB; Test 3 – Evolution over time: 1 dB). The variable conditions of the substrate and vegetation layer therefore have little impact on the overall sound insulation performance of lightweight extensive green roofs.

Tests carried out for objective (2) showed that increasing the surface density of a lightweight green roof can be achieved by increasing the thickness of the substrate and vegetation layer, although large quantities of substrate are not normally needed for systems using sedum mats. Improvements obtained from such increases in mass (test 4) were not very substantial, as the absence or presence of a 25 mm thick substrate improved R_w by only 3 dB. It can be noted that such improvements are controlled by the dynamic stiffness of the interlayers and surface density of the top layer: increasing those increases sound insulation, as it lowers the resonance frequency and increases decoupling. The logarithmic relation found between the sound reduction index and the surface density of the system suggested that an increase in R_w of 7 dB might have been achieved if 100 mm of substrate had been used, which is significantly higher than the 3 dB increase observed with the 25 mm substrate. This might then justify using large amounts of substrate for purely acoustical reasons, as sedum mats do not actually require deep substrates. Results obtained in test 5 indicated that drainage layers also affect sound insulation, with a variability in R_w of 3 dB between the three layers tested. Gravel was found to be the most effective drainage layer (R_w 2 dB higher than when the drainage membrane was used), especially towards low and mid frequencies, due to its heavier mass. Its high void ratio also provided adequate damping towards mid-high frequencies. Crucially, test 6 showed that the addition of a sound insulated cavity was by far the most effective solution, as it improved R_w by as much as 13 dB, with consistent improvements of around 15 dB across most mid-high frequencies. It should however be noted that cavity improvements are largely affected by the mass-spring-mass resonance of the cavity system, i.e. by the cavity depth and surface density of the top layer. In that respect, a cavity placed under larger amounts of soil could provide even better improvements than those found here, whilst a cavity placed under smaller amounts of soil might not provide the benefits found here. Overall, results obtained indicate that surface density (test 4), drainage layers (test 5) and cavities (test 6) can all contribute to increase sound insulation, although to different extents, added cavities clearly providing the largest increase in sound insulation.

For objective (3), it should first be noted that the application of a green roof system, with regard to its sound insulation, is a function of the building's usage and the outdoor noise level (i.e. R_w values required from roofs can vary). For the best system tested (roof with cavity of test 6), the R_w was equal to 43 dB; this did not include a sedum mat which might have further increased R_w to a maximum of 47 dB (based on the 4 dB increase observed in the system without a cavity (with (test 4) vs. without (test 1) sedum mat)). These values are comparable to a standard pitched roof with tiles on felt ($R_w = 43$ dB for 100 mm absorber on plasterboard ceiling [34]; $R_w = 47$ dB for wood-lath and plaster ceiling [34]), or a flat timber-joint roof ($R_w = 45$ dB for asphalt on boarding, 12 mm plasterboard ceiling and thermal insulation [34]), all of which are roofs commonly used in residential buildings. This suggests that the system including a cavity should be acceptable for most types of constructions, even those where outdoor noise annoyance might be more prominent (e.g. residential buildings). In constructions where outdoor noise and annoyance might be particularly high (e.g. next to airports), better sound insulation might be needed compared to what was obtained for the cavity system tested (for instance, a flat 100 mm concrete roof achieves an R_w of 52 dB [34] and represents a highly insulated roof). Improved sound insulation could then be achieved by increasing the depth of the cavity. For example, a much larger cavity of around 200 mm depth (including at least 80 mm of mineral wool) should achieve a sound reduction index larger than 50 dB, based on comparisons with lightweight floors of similar depth and mass [34]. Further tests will however be required to identify

the exact sound reduction indices values of green roof systems including larger cavities. For commercial buildings, such as retail and leisure developments, workshops and other industrial buildings, a cavity might not be needed in the roof, as outdoor noise annoyance due to airborne sound transmission is rarely a concern. The system of Table 1 with a substrate thickness of 25 mm could then be used ($R_w = 34$ dB). Overall, the results obtained indicate that lightweight green roof systems, such as those tested here, can be used in both commercial and residential constructions.

Finally, it should be noted that the small sample area tested was an important limitation of the present research, because of the low modal density of the system at low frequencies and the diffraction effects that might have overestimated sound insulation below the critical frequency [33]. Predictions suggested that the low modal density might have had a limited impact on R_w values (which were found to be at most 1 dB higher than what was obtained when mass controlled behaviour was extended to lower frequencies). However, previous research [33] suggests that diffraction effects might reduce the sound insulation of larger systems more significantly. Furthermore, joists were not installed in the system because of the limited depth available in the floor's opening: joists can increase stiffness and low frequency insulation, although results obtained here indicated that R_w values were only affected by poor insulation at frequencies greater than 250 Hz, suggesting that improvements in low frequency performance would probably not have affected R_w values. Previous work [25] suggests that larger lightweight extensive green roofs provide good levels of sound insulation, but it is clear that large systems comparable to those examined in this paper should however be tested in the future to validate the findings obtained here. Such large scale tests will allow quantifying differences in sound insulation between the 1 m² samples tested and larger systems, and identifying the extent to which limitations of the current tests affected the accuracy of the results obtained.

5. Conclusions

Overall, the study proved the reliability of lightweight extensive green roof constructions from a sound insulation point of view, as well as their appropriateness and acceptable sound insulation performance for a variety of applications, although the accuracy and validity of the results obtained will need to be identified through comparisons with large scale tests. More specifically, main findings can be summarised as follows for each of the objectives listed in section 1:

- Objective 1: the variable conditions of the substrate and vegetation layer do not significantly affect the sound insulation properties of lightweight extensive green roofs (variations in R_w of no more than 1 dB for the tests carried out).
- Objective 2: the addition of a cavity represents the most effective solution for improving the sound insulation of a lightweight extensive green roof (+13 dB in R_w). The added sound insulation provided by a cavity will vary in practice: the larger the depth of the cavity and the mass of the top layer, the better the sound insulation. Sound insulation can also be increased with the thickness of the substrate and vegetation layer, as well as by using a heavier drainage layer, but changes tend to be much more limited (+3 dB for a 25 mm increase in substrate and +2 dB for gravel vs. lightweight drainage membrane). Large amounts of substrate could further improve sound insulation (e.g. +7 dB for 100 mm increase in thickness), but might not be justifiable from a non-acoustic perspective (depth of substrate not required for growing vegetation and unnecessary increase in the load of the system).
- Objective 3: most commercial buildings (e.g. large retail and leisure developments) do not require high levels of sound insulation against external noise, so that simple systems not comprising a cavity should be appropriate (e.g. R_w of 34 dB for the system of Table 1 with a substrate thickness of 25 mm). However, a cavity should be incorporated when the green roof will be used in buildings where outdoor noise annoyance might occur (e.g. residential buildings). A shallow cavity of 50 mm should then guarantee a R_w of at least 43 dB (no sedum mat used in test), which is comparable to common pitched roof constructions. Larger cavities should be used

when high levels of sound insulation are required (e.g. 200 mm cavity with mineral wool for R_w values larger than 50 dB).

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