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Green roofs for noise reduction : literature review and new approaches

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ABSTRACT

Green roofs are able to reduce sound exposure near or inside a building by mitigating diffracting sound waves over (parts of) roofs and by reducing sound transmission through the roof system. Absorption curves of green roof substrates reported in literature show a large variety in behavior, suggesting the possibility for optimization. Substrate moisture content has a strong effect on absorption as is shown by a set of well-controlled impedance tube measurements. However, a long-term real-life experiment near a building's edge showed that this not necessarily leads to a significant reduction in road traffic noise shielding. A re-analysis of actually measured spectral insertion losses at 5 green roofs showed that road traffic noise insertion losses are expected in between 2.3 and 5.5 dBA at a (partly) shielded building facade. Recent findings state that there is no need for competition for roof space between green roofs and solar panels. Numerical simulations further show that the presence of such acoustically rigid panels enhance the green roof's noise reducing performance at larger solar panel inclination angles. The new idea of shapeable and groweable foams as substrates is numerically evaluated in this work. The existing literature on the acoustic insulation of green roofs stresses its potential due to their relatively large surface mass density, low stiffness and pronounced damping properties. Especially their performance in the low-frequency range is worth mentioning. An acoustically damped cavity below the green roof strongly increases the overall insulation performance.

Keywords: green roofs, vegetated roof tops, quiet facades, roof insulation, absorption I-INCE Classification of Subjects Number(s): 23, 24

1. INTRODUCTION

In the build-up environment, building skins are typically (close to) acoustically rigid. As a consequence, there is often a strong increase in sound pressure level due to the multiple reflections in between opposing building facades and on the street surface. This amplification not only affects the most-exposed facade, but also levels at the shielded building side directly connected to the source canyon. In addition, (rigid) roof reflections might lead to pressure doubling during diffraction. Although a closed row of houses could be a rather efficient noise barrier, the combination of a busy urban street, street reverberation and roof reflections leads to exposure levels that are often too high to fully benefit from the quite side effect (1).

2. REVIEW

2.1 Green roof absorption characteristics

2.1.1 General

The green roof's constituting layers with an impact on sound absorption are the porous growing substrate, the presence of air voids, water storage/retention fabrics, and the plant layer. Together, they form a multi-layered system with a complex acoustic behavior. Furthermore, their properties significantly change over time due to water dynamics, plant community development and compaction.

Measured absorption characteristics of green roof systems reported in literature (2-6) show a large variability, suggesting that substrates can be engineered to optimize sound absorption.

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2.1.2 **Water content**

Adding water to any porous material deteriorates its absorbing properties. Various complex effects might appear like a reduction in the effective layer depth, substrate particles swelling, clogging of pores and exchange of water in between the different layers constituting the green roof system. When fully saturated, the substrate surface approaches a perfectly reflecting plane. Impedance tube measurements during (unforced) evaporation (indoors) of an initially fully saturated green roof clearly show (see Fig. 1) the increase in absorption coefficient with decreasing soil moisture content. Especially in the higher frequency range a large variation is observed, covering the full range between no absorption at all and full absorption.

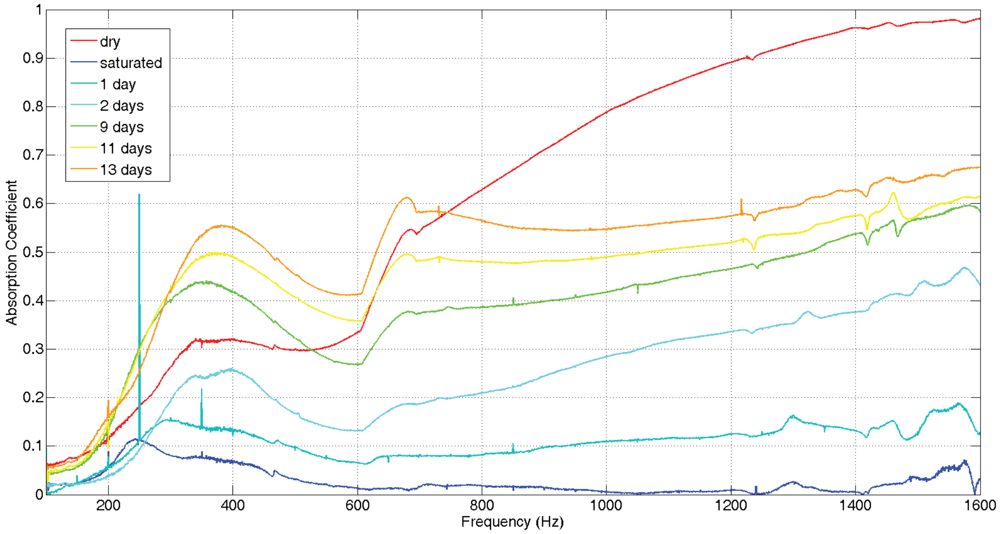

Figure 1 – Absorption characteristic of a green roof system (including a 2.5-cm thick water retention mat and a 6-cm granular substrate) during unforced evaporation (impedance tube measurement, normal incidence).

2.1.3 **Plant layer**

The influence of the plant layer on absorption is less obvious. Although it was recently shown that specific plants are able to absorb sound quite well (7), the acoustic system formed by plants on top of a porous material is more complex. Measurements (4,5,8) typically show that in the low frequency range, there is a slight enhancement of the absorption of the plant-substrate system, while at higher sound frequencies plants lead to a decreased absorption relative to uncovered substrates. A large pack of leaves on a porous substrate, however, was measured to increases the absorption coefficient at all sound frequencies (9).

2.2 Sound diffraction over green roofs

2.2.1 **General**

In order to benefit from green roof absorption, there has to be a dominant sound path interacting with the roof, which is possible after a single edge diffraction or multiple edge diffractions (10). In case of single edge diffraction, a building extension with a green roof on it may shield part of a facade.

Diffraction theory stipulates that the absorption characteristics of the faces constituting the diffracting object have an important effect on the sound pressure levels in shielded zones. The largest effects are expected when sound waves propagate at grazing angle over the green roof. Following simplified ray-theory, this leads to cancelling of the waves shearing over the roof and those reflected from the substrate (11). In practice, this cancelling will be incomplete since sound waves arrive at the roof's edge after diffraction and due to the presence of so-called ground waves that are prominent mainly at lower frequencies (11). Full-wave numerical techniques are therefore needed to accurately study the potential noise reduction obtained by a green roof, including the modeling of the substrate as a non-locally reacting material.

2.2.2 **Simulations**

Simulations (12) with the finite-difference time-domain (FDTD) technique predicted useful positive insertion losses (relative to a fully rigid roof) at frequencies above 250 Hz, a linear relation between sound level reduction and the fraction of the roof covered by the green roof, and the presence of an optimum substrate depth in function of sound frequency (for shallow substrates). In addition, a numerical study with the focus on road traffic noise (13) showed that with increasing vehicle speed, the green roof insertion loss becomes larger given the shift to more high frequent source power spectra.

Noise shielding by buildings in an urban setting is influenced by roof shape, even under the assumption of equal building volume (14). Simulations (3,13) showed that the positive effect of placing a green roof on a non-flat roof is stronger than on a flat roof. This can be explained by the additional interaction length between sound waves and the green roof in such cases.

2.2.3 **Measurements**

A set of in-situ measurements of sound propagating over flat, extensive green roofs is described in Ref. (15) and here recalculated to total A-weighted road traffic noise insertion losses (see Table 1). These measurements were performed just before and just after the placement of the green roof (dry state) with an identical source-receiver configuration, allowing a direct measurement.

Table 1 – Overview of the in-situ measurements as reported in Ref. (15), recalculated to global green roof road traffic noise (30-70 km/h, 5 % heavy traffic) insertion loss.

Building geometry	Substrate depth (mm)	Propagation path length interacting with green roof (m)	Vegetation cover	Low microphone position (dBA)	High microphone position (dBA)
Single diffraction case 1	20-30	8	> 75 % (sedum + mosses)	4.1	1.0
Single diffraction case 2	50-60	2.5	< 5 % (sedum shoots)	2.3	-2.4
Single diffraction case 3	180	4.5	50 % (grasses)	5.5	2.1
Double diffraction case 4	30-40	25	> 90 % (sedum)	3.1	2.2
Double diffraction case 5	80-100	25	< 5 % (sedum shoots)	3.4	5.1

For less shielded receivers, a change in interference pattern is often observed, leading to positive or negative effects in specific frequency ranges, relative to a non-vegetated (rigid) roof top. For the double diffraction cases (flat roofs) the green roof improvement showed to be less frequency-dependent (15).

Another flat green-roof in-situ measurement (16) and a street canyon scale model at scale one tenth (17) confirmed the noise reduction of near 2-4 dBA in enclosed courtyards.

A long-term in-situ diffraction experiment (18) near the edge of a building equipped with an extensive green roof, subject to natural precipitation, showed that sound propagation was especially sensitive to the substrate’s volumetric water content (VWC) in the frequency range between 250 Hz and 1250 Hz. The difference in the green roof’s noise attenuation between a relatively dry (10% VWC) and fully saturated state ranged up to 10 dB (18). When combing the experimental attenuations with a typical road traffic noise spectrum, the impact of the substrate’s water content on the A-weighted total road traffic sound pressure level abatement was predicted to be much more moderate (up to 1.5 dBA) (18).

2.3 Sound transmission through the roof system equipped with a green roof

Due to their relatively large surface mass density, their low stiffness and pronounced damping properties, a green roof is an interesting sound insulation material.

Reported scientific research assessing the additional transmission loss by a green roof, on top of a standard roof system, is scarce. Two elaborate studies have been reported in peer-reviewed scientific literature (19,20). Connelly and Hodgson (19) studied sound insulation in a specifically designed test-facility for green roofs. Galburn and Scerri (20) experimented in a vertical (standard) sound transmission suite in an acoustic lab. Ref. (19) reported an increased transmission loss relative to non-vegetated reference roofs up to 10 dB and 20 dB in the low and mid frequency range. Galbrun and Scerri (20) measured lightweight green roofs on top of a (poorly performing) plywood panel. The measured total sound reduction index was in between 20 dB (at 63 Hz) and 30 dB (at 1 kHz), leading to a maximum weighted sound reduction index R_w equal to 35 dB.

Ref. (19) pointed at the increased acoustic insulation of the roof system at low frequencies, which is otherwise difficult to achieve after construction. In both experiments (19,20), moisture content did not have a significant influence on the transmission loss, as was also found earlier (21). The presence of a plant community influences both mass loading and substrate porosity to some extent; as a result, transmission loss could (slightly) increase or decrease based on species choice (19). In contrast, in Refs. (20) and (21), no net effect of placing a vegetation layer on top of the substrate was reported.

By allowing a 50-mm cavity filled with mineral wool below the green roof, a mass-spring-mass system is constructed, largely enhancing the overall acoustic insulation. In their experiments, an increase in R_w of 13 dB, relative to the absence of such a cavity, was measured in Ref. (20).

3. NEW APPROACHES

3.1 Solar panels and green roofs

Recent finding indicate that there is no need for competition for roof space between green roofs and solar panels. Green roofs were even found to enhance solar panel performance due to their cooling effect (22), while specific plant species can easily colonize shaded zones on roofs (22). Furthermore, shade variations over the roof area may increase biodiversity (22).

Rigid solar panels could influence sound waves diffracting over the porous green roof. This effect is studied here by means of detailed numerical simulations. The same building setting as described in Ref. (3) is chosen, consisting of two coupled urban canyons, 19.2-m wide and 19.2-m high. The building connecting the canyons has a width of 9.6 m and a flat roof (case D in Fig. 2 in Ref. (3)). Simulations are here performed in 2D, assuming an infinite long source and receiver canyon and a coherent line source of infinite length. A detailed discussion on the insertion losses in full 3D vs the 2D approach for specific roof measures in such an urban geometry can be found in Ref. (3).

The green roof substrate under study is limestone-based and has a thickness of 10 cm. The measured absorption spectrum can be found in Ref. (3) and in Fig. 3.

The solar panels are modelled as fully rigid, with a width of 1 m and thickness of 6 cm (see Fig. 2). Given the 2D simulations, it is assumed that these are infinitely long as well in the third dimension, or equivalently, a large number of such panels are put in parallel without any gaps in between them. Six rows of panels are distributed over the building width. Inclination angles in between -45° and 45° were modelled. The distance between the bottom of the panel and the green roof is 10 cm in all cases.

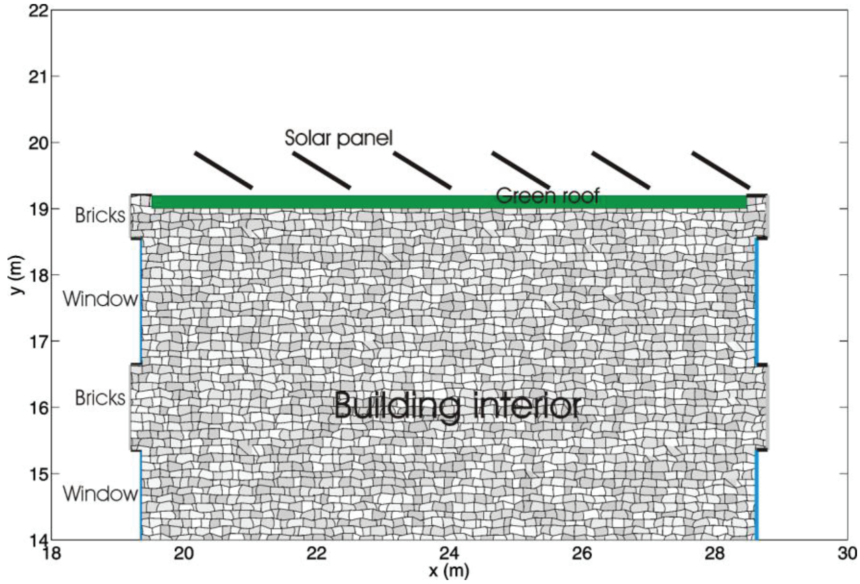

Figure 2 – Detail of cross-section of the building equipped with both a green roof and solar panels (inclination -30°).

Predictions of the insertion loss of the solar panels for urban road traffic, averaged over all facades (along the windows) and along a horizontal receiver line at 1.5 m in the shielded canyon, for vehicles speeds ranging from 30 to 70 km/h (5% heavy traffic), yield values less than 1 dBA (see Table 2). The spatially averaged green roof effect, relative to a rigid flat roof, in this case (but without solar panels) was predicted to be 2.1 dBA (in 2D) and 2.4 dBA (in 3D) (3).

Similar calculations have been performed in case of a fully rigid flat roof equipped with solar panels, yielding a similar range of effects. For some solar panel inclinations, negative (but limited) insertion losses are predicted. The largest improvement found here is 0.9 dBA and predicted in case of an inclination of 45° (lowest part of the panel towards source canyon) or -45° (lowest part of the panel towards receiver canyon). The presence of rigid solar panels, averaged over all angles considered, do not generally lead to a deterioration of the acoustical green roof effect for sound waves diffracting over buildings, and in case of stronger inclinations to a significant improvement.

Table 2 – Predicted solar panel insertion losses for various panel inclinations, averaged over all receivers in the shielded canyon, for urban road traffic (30-70 km/h, 5% heavy traffic).

	15°	30°	45°	-15°	-30°	-45°
Rigid flat roof	0.0 dBA	-0.1 dBA	0.9 dBA	0.0 dBA	-0.3 dBA	0.9 dBA
Green roof on flat roof	-0.3 dBA	0.3 dBA	0.9 dBA	-0.3 dBA	0.4 dBA	0.9 dBA

3.2 Shapeable green roof substrates

Numerical calculations (similar urban setup as described before) have been performed for sound propagation over a green roof substrate made of polyurethane foam. Such a material, injected with fertilizer, serves as a good substrate for many species, amongst them also sedum. Benefits are the huge water buffer capacity, their light weight and good thermal insulation. In addition, a single slab of such a material can replace the various layers typically used in a green roof system; grooves at the bottom can serve as a water evacuation layer.

Another advantage is that such a material can be shaped to almost any form, which opens possibilities for sound reduction. Literature shows that due to scattering of sound at irregularities rigid materials behave acoustically softer (23).

The absorption coefficient of a 5-cm thick (dry) slab of green roof substrate foam (see Fig. 3), including the water evacuation layer, has been measured in an impedance tube with a two-microphone technique.

As an example calculation, a trapezium-like surface has been modeled, as detailed in Fig. 4. The overall insertion loss, relative to a rigid flat roof, is limited to 1.3 dBA (see Section 3.1 and Ref. (3) for details on the processing). Compared to the limestone substrate, a poor absorption performance below 500 Hz is obtained with the PU foam. Note that the sound field in the shielded canyon is dominated by low frequencies. To increase the acoustic performance, much thicker slabs should therefore be used. An additional calculation with a similar trapezium like shape, but with a height of 0.5 m instead of 0.1 m, gives 2.1 dBA.

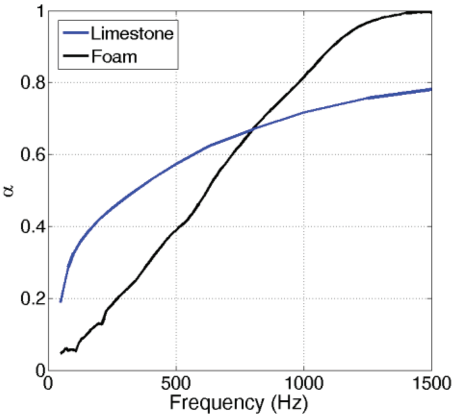

Figure 3 – Measured (impedance tube) absorption coefficient α of limestone substrate (see Section 3.1) and PU green roof slab at normal incidence.

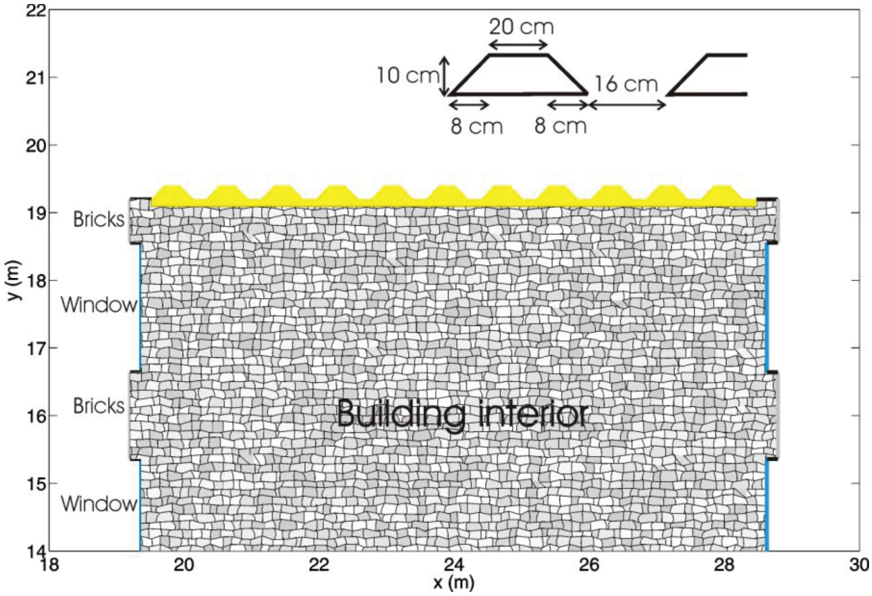

Figure 4 – Detail of cross-section of the building equipped with a shapeable PU foam green roof substrate.

4. CONCLUSIONS AND DISCUSSION

A green roof shows to be useful for both reducing sound waves diffracting over (parts) of buildings, and to decrease sound transmission through the roof system. For both applications, complex acoustical effects are present since green roofs are multi-layered systems. The contribution of the different layers constituting the green roof system, and in particular the vegetation layer, is not fully understood. Increasing such knowledge could help improving their acoustical performance.

Numerical simulations show that solar panels do not deteriorate the green roof performance so competition between both ecological measures for roof space is actually not at hand. For larger solar panel inclinations, a significant improvement is predicted. The new approach of shapeable all-in-one foam substrates has been explored numerically based on measured absorption spectra.

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