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## Effective sound absorbers?

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# Evaluating mosses on bioreceptive concrete: Effective sound absorbers?

M. Veeger *, M. Ottelé, H.M. Jonkers

*Delft University of Technology, Faculty of Civil Engineering and Geosciences, Department of Materials, Mechanics Management & Design (3MD), Materials and Environment section, Stevinweg 1 Delft, 2628CN, the Netherlands*

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ABSTRACT

Moss-covered bioreceptive concrete is a novel green vertical structure which can be applied to a wide variety of structures due to its low structural and maintenance requirements. One of the potential benefits of using moss-covered concrete is its ability to absorb sound, the extent of which is currently unknown. Therefore, the effectiveness in attenuating (urban) noise of six moss species in different hydration states was assessed and compared to bare concrete and other vertical green structures. Results show that using moss-covered concrete increases sound absorption compared to bare concrete in nearly all situations. The best-performing mosses overall were acrocarp species, particularly *P. capillare*, which reached a peak sound absorption coefficient of 0.86 and an average of up to 0.48 (50–6400 Hz). Its results are also relatively constant across hydration states. On the other hand, *G. pulvinata* outperformed *P. capillare* when dry, but not when hydrated or wet. The pleurocarp species showed the lowest sound absorption. Finally, the thickness of the moss layer has a minor impact on absorption. The acrocarp moss species compare favourably to (in)direct vertical green structures using climbing plants, whereas the sound absorption of the pleurocarp species is slightly lower. However, the sound absorption of moss-covered concrete is significantly lower than that of vertical green structures using a growing substrate (Living Wall Systems), as the substrate provides the bulk of the absorption in this case. In conclusion, the moss-covered bioreceptive concrete presents a viable alternative to (in)direct green structures, although benefits are mostly limited to frequencies above 1000 Hz.

## 1. Introduction

Environmental noise pollution is a pressing issue in Europe, ranking second only to air pollution by particulate matter in terms of disease burden [1]. The World Health Organization (WHO) estimates that around 1 million healthy life years are lost annually in Europe alone due to noise pollution, especially road traffic noise, leading to conditions such as ischaemic heart disease, cognitive impairment in children, sleep disturbance, tinnitus, and annoyance [2]. The WHO's guidelines for the European region recommend limiting average exposure to traffic noise to 53dB(A), with nightly exposure not exceeding 45dB(A) [3]. However, a 2020 report revealed that within the European Economic Area, an estimated 113 million people are exposed to long-term day-evening--night traffic noise levels exceeding 55dB(A), underscoring the need for effective noise reduction measures [4].

One possible measure to mitigate noise pollution is to incorporate more greenery into the urban fabric. As space is at a premium in cities, this is done increasingly not through ground-level green but in the form of green vertical structures, where the plants are attached either directly or indirectly to urban structures [5]. Noise absorption of urban structures can be significantly increased by adding plants, and especially a substrate (which provides the bulk of the sound absorption) to their surface [6]. There are two ways in which these vertical green structures can attenuate noise. The first and most important one is that both the substrate in which the plants grow, as well as the plant itself, act as a porous absorber [7]. A porous absorber consists of a material that contains air pockets (pores) into which sound waves can enter. A porous absorber then consumes that incoming sound energy through three principles [8], collectively called visco-thermal damping: (1) the vibration of air molecules in the pores causes friction with the pore walls, converting it into heat; (2) the air in the pores is periodically compressed and released, consuming energy in the transformation process; (3) the resonance of the pore wall causes a conversion to mechanical and heat energy. The second way in which plants can attenuate noise is through a scattering of sound waves by the structure of the plant, which may lead to destructive interference at higher frequencies [7]. As such, the

* Corresponding author.
*E-mail address:* M.I.A.Veeger@tudelft.nl (M. Veeger).

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combination of the open porosity, pore size distribution, substrate thickness, air flow resistivity, tortuosity (pore network complexity), and moisture content of the substrate, as well as the leaf area density and the orientation and dimensions of the leaves of the plant together determine the acoustical performance [7].

However, the adoption of these green building systems is often held back by issues such as perceived high costs and uncertain benefits [9]. As such, a new green typology is being developed, which is based around bioreceptive concrete. Bioreceptive concrete consists of a concrete mixture that has been adjusted to allow for the growth of biological material directly on the concrete surface, eliminating the need for the plants to be soil-bound or require long-term irrigation and a costly support structure [10] (Fig. 1). Rather than vascular plants, which are commonly used for other urban green structures, one of the potential groups of organisms that could grow on this bioreceptive concrete is moss. Moss could provide several benefits to the urban environment, including improved rainwater management, heat reduction, air filtration and noise attenuation [10]. However, while mosses also belong to the Plant kingdom, they differ from other plants in several ways, which may affect their sound absorption performance.

First, compared to most vascular plants, mosses have a larger amount of small, densely packed leaves, which gives them a very high LAI (Leaf Area Index; the area of leaf per area of substrate occupied by the plant) [11]. Leaf area density has, in turn, been found to be one of the main determinants of sound absorption performance by plants [12]. Furthermore, in a bid to protect themselves from desiccation, mosses have several structural adaptations (porose leaf cells, ridges, folds, sheathing leaf bases, rhizoids, tomentum) to increase water storage [13]. All these adaptations are meant to create capillary spaces for water storage. However, these pores can also be expected to cause the moss to act as a more efficient porous absorber. Furthermore, some species of moss clump together to form structures, such as cushions, which further increase the number of capillary spaces for water storage and, in turn, may affect the acoustic performance of the species once again. It is, therefore, likely that mosses do have noise attenuation capabilities. However, it will differ from most other urban green structures, as it relies on the plant rather than the substrate, which is often the main contributor to the acoustic performance of these green structures [14, 15]. Instead, they grow on concrete, a hard material with minimal sound absorption [16]. Furthermore, the sound absorption of moss will likely depend on the structure of the moss species and the moss's hydration level, as when the capillary spaces are filled, its noise-attenuating properties are expected to decrease, similar to what is seen in the substrates used for other green typologies such as green roofs and green façades [7].

So far, research into the acoustic performance of mosses has been minimal. Reethof, et al. [17] found that forest floors with moss covering had higher acoustic absorption than those with leaf litter or bare soils, although no quantitative data are presented. Similarly, Li, et al. [18] found that the sound absorption of tree bark was higher when moss was present, although the total sound absorption of both moss and bark stayed below 0.1 in their tested frequency range (0–2000 Hz). The use of moss in artificial noise absorbers has also seen some limited testing, with Kim, et al. [19] finding noise reduction coefficients of up to 0.189 in the 250–2000 Hz frequency range when using a mixture of moss and either beer or buttermilk and Sleinus, et al. [20] achieving a sound absorption coefficient of 0.1 at 250 Hz and up to 0.95 at 4000 Hz when mixing *Sphagnum* moss with flax and organic lake sediment.

This then reinforces the hypothesis that moss does indeed have noise-absorbing capabilities. However, no literature was found where quantitative data are available on the acoustic properties of living moss (either on bioreceptive concrete or other substrates). It will, therefore, be of great interest to investigate whether bioreceptive concrete performs less, equally, or even better than more common green typologies, such as green facades and green roofs, as a mitigation measure or alternative.

Therefore, this paper aims to determine the effectiveness of moss growing on concrete in attenuating urban noise pollution and compare these results to those found for other contemporary vertical green structures to assess whether moss-covered bioreceptive concrete is a viable alternative. As moss exhibits different structural properties depending on its hydration level and species, which is expected to affect its sound absorption potential, the experiments described in this paper were conducted on several moss species across varying hydration levels.

## 2. Methodology

### *2.1. Test set-up*

The acoustical measurements were performed with a Bruel & Kjaer 4206 impedance tube kit, as this allows for reliable testing on small test samples. This kit consists of one larger tube (100 mm diameter), which measures direct incidence sound absorption coefficient (α; i.e. the fraction of sound energy absorbed when the sound waves are perpendicular to the absorption plane) in the 50–1600 Hz range, and one smaller tube (29 mm diameter), which measures direct incidence acoustic absorption in the 500–6400 Hz range, both according to ISO 10,534–2 and ASTM E1050–12 (Fig. 2).

### *2.2. Sample preparation*

To accommodate the two impedance tubes, a total of 56 concrete samples were produced, comprising 21 samples with a 100 mm diameter for use in the larger tube (three per tested moss species) and 35 samples with a 29 mm diameter for use in the smaller tube (five per tested moss species). First, a plastic mould was 3D-printed in FormFutura ePLA with an outer diameter of either 100 mm or 29 mm and a wall thickness of 0.5 mm using vase-mode FDM printing. This was done to ensure a tight fit inside the impedance tubes used for the acoustic measurements. These moulds were then filled with a previously developed bioreceptive concrete mixture consisting of CEMIII/B, 0–4 mm recycled concrete aggregate and bone ash. The concrete was then cured for 28 days, after which the samples were ready for the application of the moss layer.

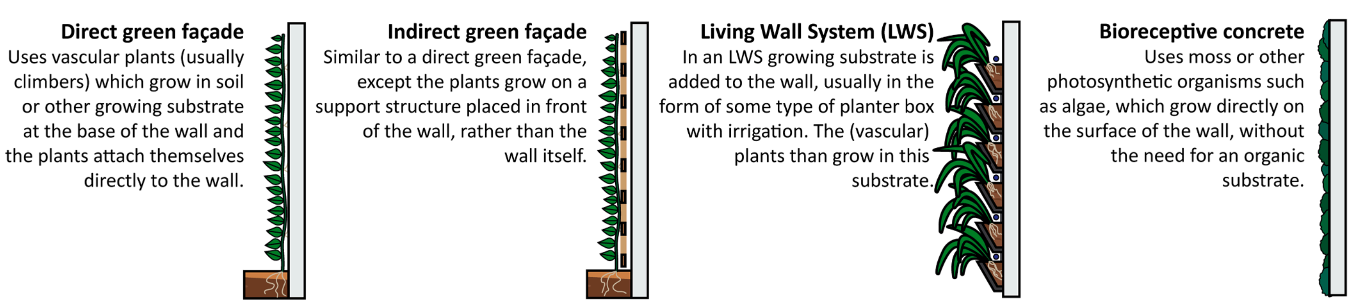


**Fig. 1.** Overview of bioreceptive concrete as compared to other vertical green structures. The classification of green vertical structures is based on [5].

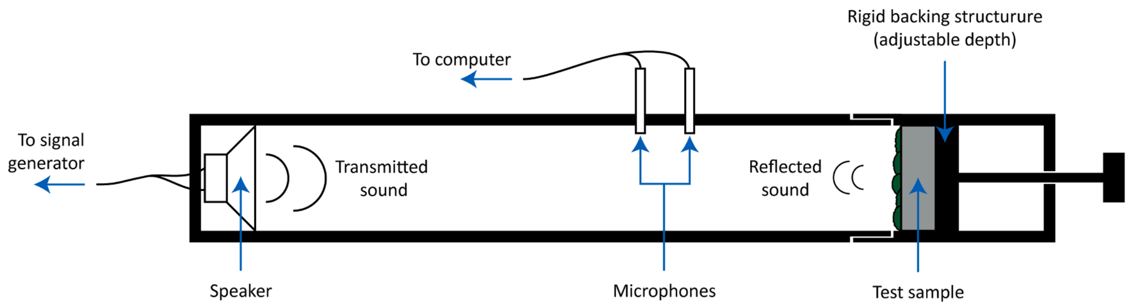


**Fig. 2.** Working principle of an impedance tube, as specified in ISO 10,534–2.

### 2.3. *Moss application*

For this research, six moss species were tested (Table 1). These six species were selected as they have previously been found to be common pioneers of urban concrete surfaces [21], indicating that they would be well suited for the colonisation of bioreceptive concrete structures. Colonies of these mosses were first harvested from existing concrete structures. These colonies were then applied to the surfaces of the concrete samples using methylcellulose glue (Fig. 3). This glue is non-toxic to the moss, and preliminary testing showed it to have no significant effect on the acoustical measurements. Three large (100 mm) and five small (29 mm) samples were prepared for each species (Table 1). Additionally, in the case of *G. pulvinata*, two sets of samples were prepared: one with a smaller (less than 10 mm) thickness of the moss layer and one with a higher (more than 15 mm) layer thickness. After moss application, the mosses were kept in a growth chamber where they received daily water and were kept underneath a Vipar-Spectra XS1000 grow light set at 130 μmol $m^{-2}$ $s^{-1}$ PAR for three weeks until the start of the acoustical measurements.

### 2.4. *Acoustical measurements*

The concrete samples were placed inside the impedance tube so that the top of the samples was level with the lip of the impedance tube. The borders of the samples were covered with Vaseline to ensure an airtight fit. First, a measurement was done on all samples before applying the moss to determine the baseline absorption of the bare concrete. Then, as the hydration level of the moss affects its structure and porosity, which was expected to affect its noise absorption, this was followed by three sets of measurements on the concrete samples covered with increasingly drier moss. The first of these measurements was performed after the moss was applied, directly following a watering event where water was placed on top of the moss until it was no longer absorbed into the moss colony (hereafter called ‘saturated’). When water is applied to moss, the voids between the moss leaves are (partially) filled with water to act as storage, which causes the overall porosity of the moss structure to decrease. The mosses were then air-dried at room temperature until they were towel-dry (when a paper towel is laid on top of the moss, no water is absorbed into the towel). After this first drying period, the samples were tested a second time to determine the acoustic performance when the moss was turgid, but the voids between the leaves were empty, which increases the porosity of the moss colony (hereafter called ‘hydrated’). The third and final test was done when the mosses were entirely desiccated. To achieve this, they were air-dried until fully desiccated (hereafter called ‘dry’). As moss dries, the structure of the moss plant changes to avoid damage during desiccation, which leads to an altered colony structure. Furthermore, moss loses its Photosystem II function and thus loses its light-induced fluorescence [22]. As such, a Walz MINI-PAMII was used to measure the maximum potential quantum efficiency of Photosystem II (Fv/Fm) after 20 min of dark adaptation during the drying process. Once this value had fallen below 0.1, indicating severe (water) stress, the moss was considered sufficiently desiccated, and the fourth acoustical test was performed.

**Table 1**
Overview of test samples produced and moss species used for the acoustical experiment.

| Species | Growth form | No. of samples | |
|---|---|---|---|
| | | 100 mm diameter | 29 mm diameter |
| ***Brachythecium rutabulum* (Hedw.) Schimp** | Pleurocarp (mat) | 3 | 5 |
| ***Grimmia pulvinata* (Hedw.) Sm.** | Acrocarp (large cushion) | | |
| Layer thickness <10mm | | 3 | 5 |
| Layer thickness >15mm | | 3 | 5 |
| ***Orthotrichum diaphanum* Schrad. Ex Brid.** | Acroarp (small cushion) | 3 | 5 |
| ***Ptychostomum capillare* (Hedw.)** | Acrocarp (large cushion) | 3 | 5 |
| ***Rhynchosteium confertum* (Dicks.) Schimp.** | Pleurocarp (mat) | 3 | 5 |
| ***Tortula muralis* Hedw.** | Acrocarp (small cushion) | 3 | 5 |

### 2.5. *Data analysis*

Raw absorption data from the impedance tubes was combined for each moss species’ hydration state using a 1200–1600 Hz crossover and a 2 Hz resolution calculated using the PULSE software by Bruel & Kjaer. The absorption per 1/1 octave band was extracted from this data using the centre extraction method in the same software package. Average sound absorption ($\alpha_{avg}$) was calculated by taking the arithmetic mean of the sound absorption values across the entire tested frequency spectrum (50–6400 Hz).

Kruskal-Wallis analyses with a post-hoc Conover-Iman tests and a Benjamini-Hochberg correction were performed to determine the differences in acoustic absorption per octave band between individual moss species and between the species and bare concrete for their three different hydration states (dry, hydrated and saturated). This was done in *R* version 4.4.3 [23] using the *PMCMRplus* package [24].

## 3. Results

### 3.1. *Sound absorption curves per moss species*

B. rutabulum

In both its dry and hydrated states, sound absorption increases roughly linearly with frequency (Fig. 4), reaching average values across the entire frequency spectrum of $\alpha_{avg} = 0.17$ (dry) and $\alpha_{avg} = 0.21$ (hydrated) while peaking at the end of the tested spectrum (6400 Hz) with $\alpha = 0.28$ (dry) and $\alpha = 0.41$ (hydrated). When this moss was saturated, average sound absorption was higher than the other states, with an average $\alpha_{avg} = 0.22$, but this was primarily due to a pronounced peak in sound absorption at 5940 Hz ($\alpha = 0.72$), with absorption values

**Fig. 3.** Test samples (100 mm) after application of moss layer. Species from left to right: G. pulvinata (layer thickness < 10 mm), G. pulvinata (layer thickness > 15 mm), O. diaphanum, B. rutabulum, R. confertum, P. capillare, and T. muralis.

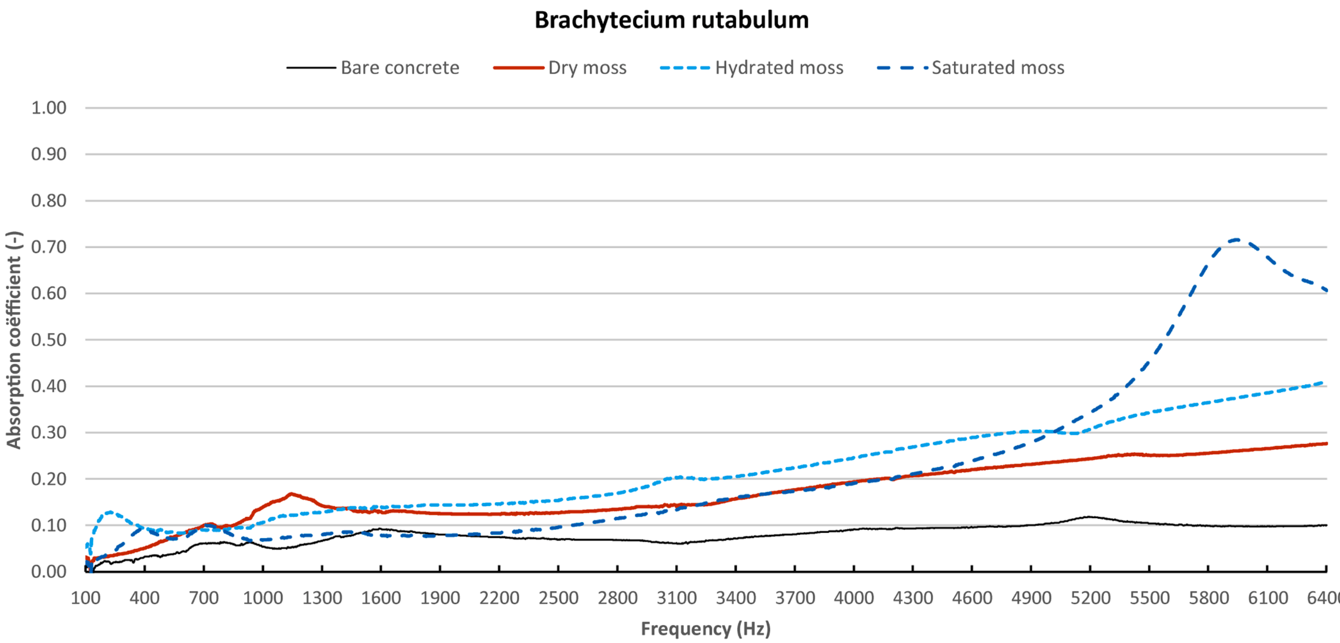


**Fig. 4.** Sound absorption results for B. rutabulum.

for the lower frequencies below those found for the other states.

G. pulvinata

When using a thicker moss layer (>15 mm), *G. pulvinata* shows an increase in sound absorption with increasing frequency (Fig. 5), with a peak at the end of the test spectrum (6400 Hz) for both its dry ($\alpha = 0.88$) and hydrated ($\alpha = 0.732$) state and average absorption values of $\alpha_{avg} = 0.55$ (dry) and $\alpha_{avg} = 0.41$ (hydrated). The initial slope of their absorption graphs is similar, although the graph for the hydrated state tapers off in the higher frequencies, leading to lower overall sound absorption. For thinner layers (<10 mm), the moss again showed similar

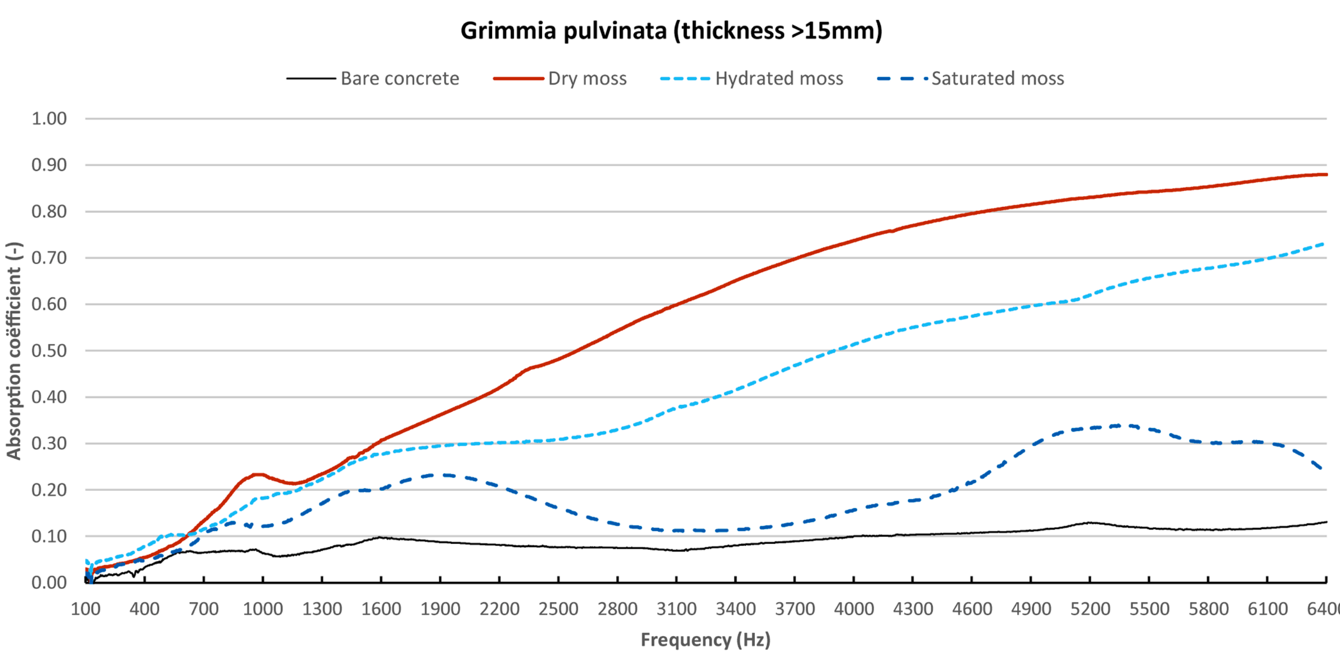


**Fig. 5.** Sound absorption results for G. pulvinata with a layer thickness of more than 15 mm.

sound absorption in its dry and hydrated state (Fig. 6), although in this case, the hydrated state had slightly higher overall sound absorption at an average of $\alpha_{avg} = 0.36$ and an absorption peak at 6080 Hz ($\alpha = 0.73$) as compared to its dry state, where the average absorption was $\alpha_{avg} = 0.33$, with a peak at 6400 Hz of $\alpha = 0.67$. For both layer thicknesses, *G. pulvinata* showed significantly lower absorption in its saturated state than in its other states. The higher layer thickness resulted in an average absorption of only $\alpha_{avg} = 0.19$, with a primary absorption peak at 5364 Hz ($\alpha = 0.34$) and a smaller secondary peak at 1900 Hz ($\alpha = 0.23$). The average for the smaller layer thickness was $\alpha_{avg} = 0.18$, with a primary peak at 5176 Hz ($\alpha = 0.39$) and a smaller secondary peak at 1588 Hz ($\alpha = 0.26$).

O. diaphanum

*O. diaphanum* showed the lowest overall sound absorption in its dry state (Fig. 7), with an average absorption of $\alpha_{avg} = 0.17$ and its peak at 6400 Hz ($\alpha = 0.31$). Sound absorption increased in its hydrated state, with an average of $\alpha_{avg} = 0.230$ and peak absorption at 6400 Hz ($\alpha = 0.47$). *O. diaphanum* showed the highest peak absorption ($\alpha = 0.76$ at 6352 Hz) in its saturated state but had the lowest sound absorption of all its states up until 2500 Hz, after which absorption increased relatively strongly with frequency, thus still resulting in the highest average sound absorption overall ($\alpha_{avg} = 0.29$).

P. capillare

In both its dry and hydrated state, *P. capillare* shows a strong, roughly linear increase in sound absorption with frequency (Fig. 8), resulting in average absorption values of $\alpha_{avg} = 0.36$ (dry) and $\alpha_{avg} = 0.48$ (hydrated). In both states, sound absorption peaked at the end of the tested spectrum (6400 Hz), with the dry moss showing a slightly lower peak absorption ($\alpha = 0.703$) than the hydrated moss ($\alpha = 0.86$). The performance of the moss in its saturated state is roughly identical to its hydrated state with an average absorption of $\alpha_{avg} = 0.47$, although this time, sound absorption peaks at 5890 Hz ($\alpha = 0.85$).

R. confertum

In its dry and hydrated states, *R. confertum* showed similar sound absorption, with both the dry ($\alpha = 0.26$) and hydrated ($\alpha = 0.31$) moss showing peak absorption at 6400 Hz (Fig. 9) and average absorption values of $\alpha_{avg} = 0.16$ (dry) and $\alpha_{avg} = 0.16$ (hydrated). The saturated moss showed no increase in sound absorption compared to the bare concrete up to around 5200 Hz, after which sound absorption rose sharply, peaking at 6400 Hz ($\alpha = 0.40$), resulting in an average sound absorption of just $\alpha_{avg} = 0.10$.

T. muralis

In both its dry and hydrated states, T. muralis exhibited similar sound absorption up until approximately 2500 Hz, after which the sound absorption in its hydrated state showed a more substantial increase in relation to frequency than its dry state (Fig. 10). In its dry state, the average sound absorption was $\alpha_{avg} = 0.24$, with a peak absorption at 6400 Hz ($\alpha = 0.49$). In its hydrated state, average absorption was higher at $\alpha_{avg} = 0.32$ and a peak at 6384 Hz ($\alpha = 0.80$). Absorption in its saturated state was mostly lower than in its hydrated state, averaging at $\alpha_{avg} = 0.219$, with two absorption peaks, similar to the results observed for *G. pulvinata*. The largest was at 4968 Hz ($\alpha = 0.48$) and a smaller one at 3176 Hz ($\alpha = 0.27$).

### *3.2. Sound absorption per octave band*

All species showed increasing sound absorption in each subsequent octave band, with most of the sound absorption occurring in the 2000 Hz and 4000 Hz octave bands for all species (Fig. 11). Furthermore, in most cases, the spread of sound absorption values found was relatively large within samples from the same species. Differences between species and bare concrete were statistically significant for all octave bands and all moss species hydration states (see Fig. 12, Fig. 13 and Fig. 14). In almost all cases, the sound absorption of moss-covered concrete was significantly higher than that of bare concrete. With the dry and hydrated moss especially, there were only very few exceptions to this, limited to a few instances at the lower octave bands (Fig. 12 and Fig. 13). When saturated moss was used, the mosses performed worse overall (Fig. 14), with no significant differences between bare concrete and moss-covered concrete for *B. rutabulum, G. pulvinata* (<10 mm and >15 mm), *O. diaphanum*, and *R. confertum* at 125 Hz, *G. pulvinata* (<10 mm) at 500 Hz, *G. pulvinata* (<10 mm and >15 mm) and *T. muralis* at 500 Hz, all species at 1000 Hz, *B. rutabulum, G. pulvinata* (<10 mm and >15 mm), *O. diaphanum, R. confertum* (which performed significantly worse that concrete at this octave band) and *T. muralis* at 2000 Hz and finally *G. pulvinata* (>15 mm) and *R. confertum* at 4000 Hz.

When looking at the differences between species, in their dry and hydrated state (Fig. 12 and Fig. 13), the larger acrocarp species of *P. capillare* and *G. pulvinata* (both at <10 mm and >15 mm layer thickness) perform best, especially at the higher frequencies, with no

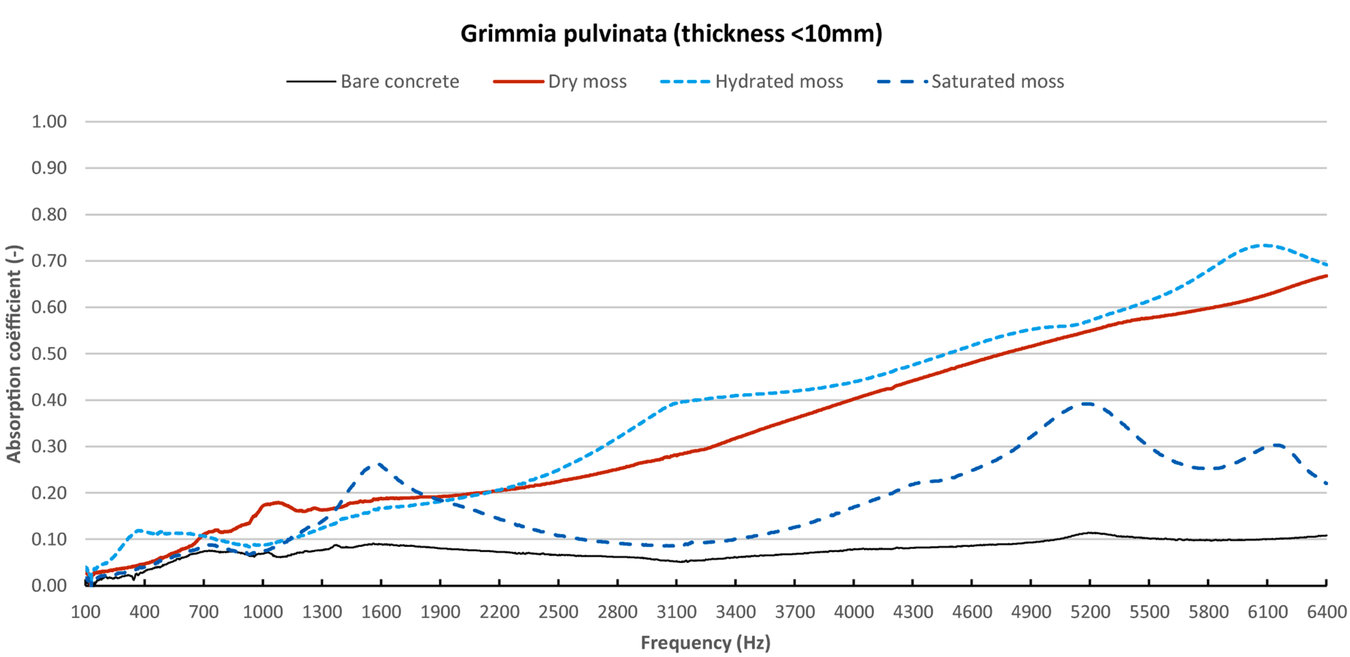


**Fig. 6.** Sound absorption results for G. pulvinata with a layer thickness of less than 10 mm.

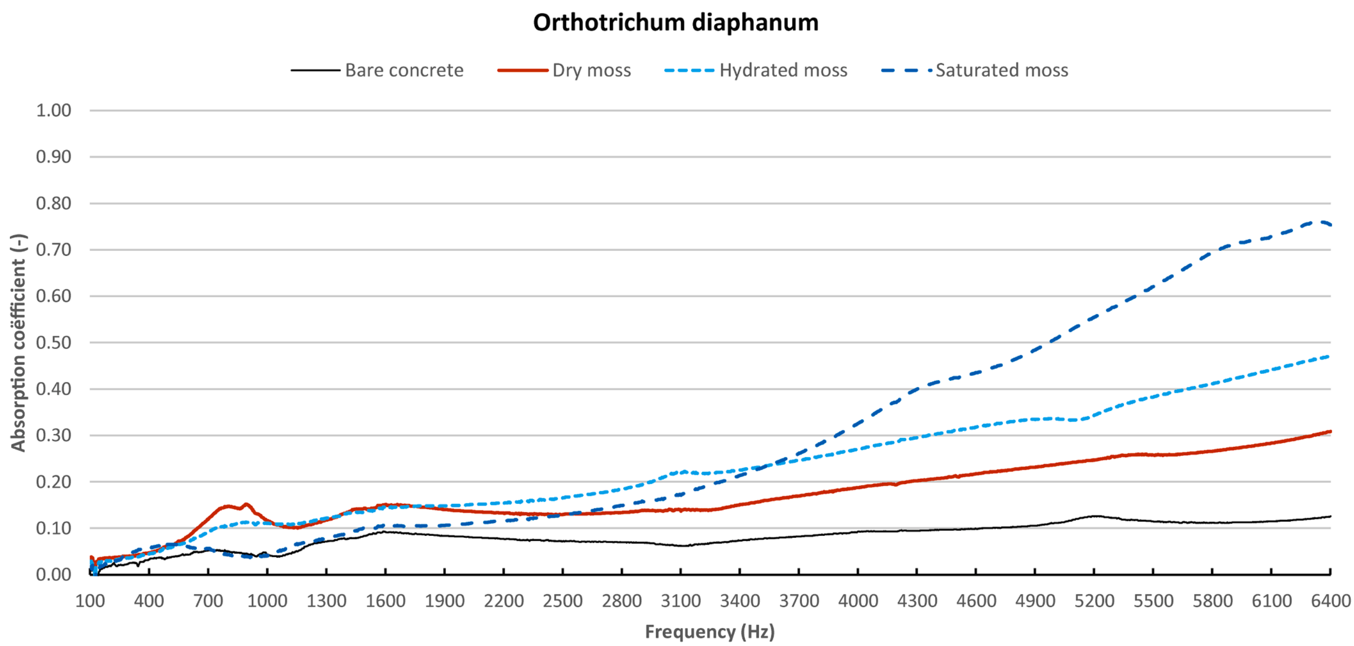


**Fig. 7.** Sound absorption results for O. diaphanum.

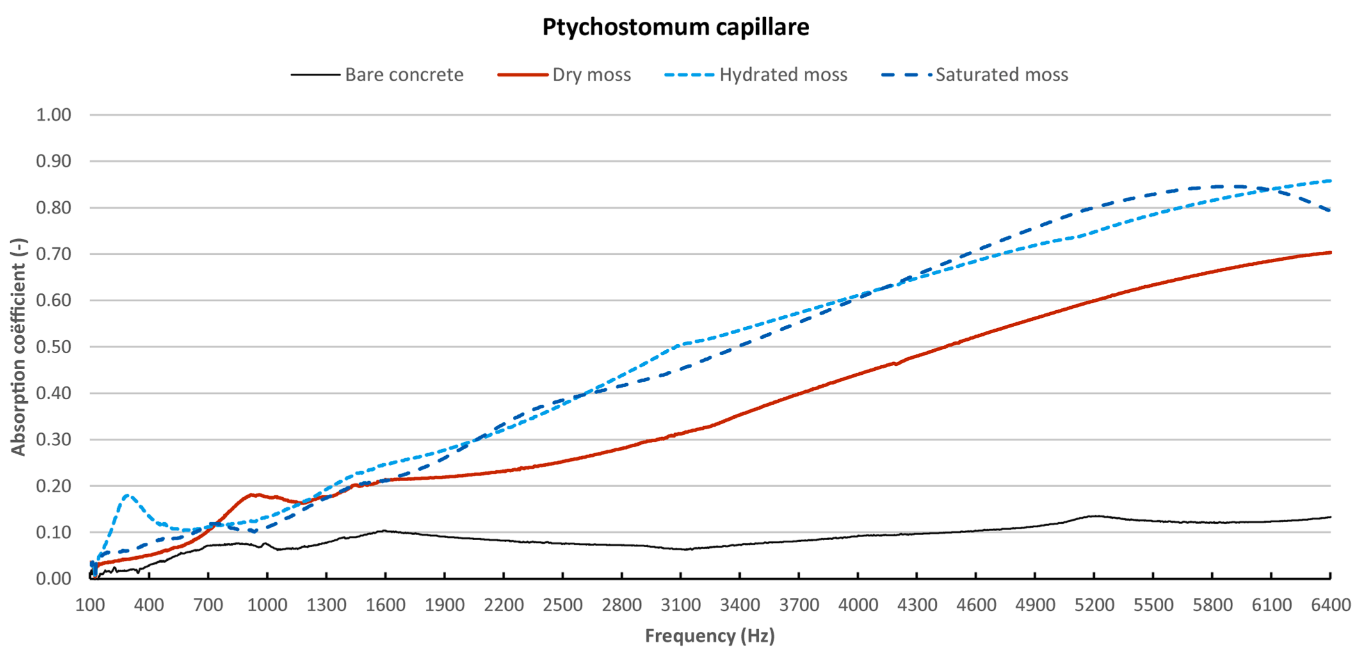


**Fig. 8.** Sound absorption results for P. capillare.

statistically significant differences between them, except for *G. pulvinata* (>15 mm) and *P. capillare* at 4000 Hz when dry, where the former outperformed the latter. This is followed by the smaller acrocarp species of *O. diaphanum* and *T. muralis*, which perform similarly, except in their dry state at 2000 Hz. The worst performers in these states are the pleurocarp species *B. rutabulum* and *R. confertum*, although the differences with the previous group are not always statistically significant.

When the mosses are saturated (Fig. 14), the rankings change somewhat. *P. capillare* is not strongly affected by being saturated with water and mostly even performs better than when dry. The sound absorption of *G. pulvinata* (<10 mm and >15 mm) is drastically reduced, mostly equalising the performance between it and the other acrocarp mosses, plus *B. rutabulum*. The other mosses are also affected, although not as strongly as *G. pulvinata*. Interestingly, *O. diaphanum* is strongly negatively affected in the lower frequencies but positively affected in the higher frequencies. Overall, *P. capillare* is the best-performing moss species across the board, *R. confertum* is the worst, and the other moss species have roughly the same sound absorption.

## 4. Discussion

### 4.1. *Moss as a sound absorber*

The obtained results suggest that mosses indeed act as sound absorbers, although the bulk of their absorption occurs at higher frequencies. The sound absorption graphs further suggest that moss does, indeed, function as a porous absorber. As such, the fact that the bulk of the sound absorption takes place at the higher frequencies is not

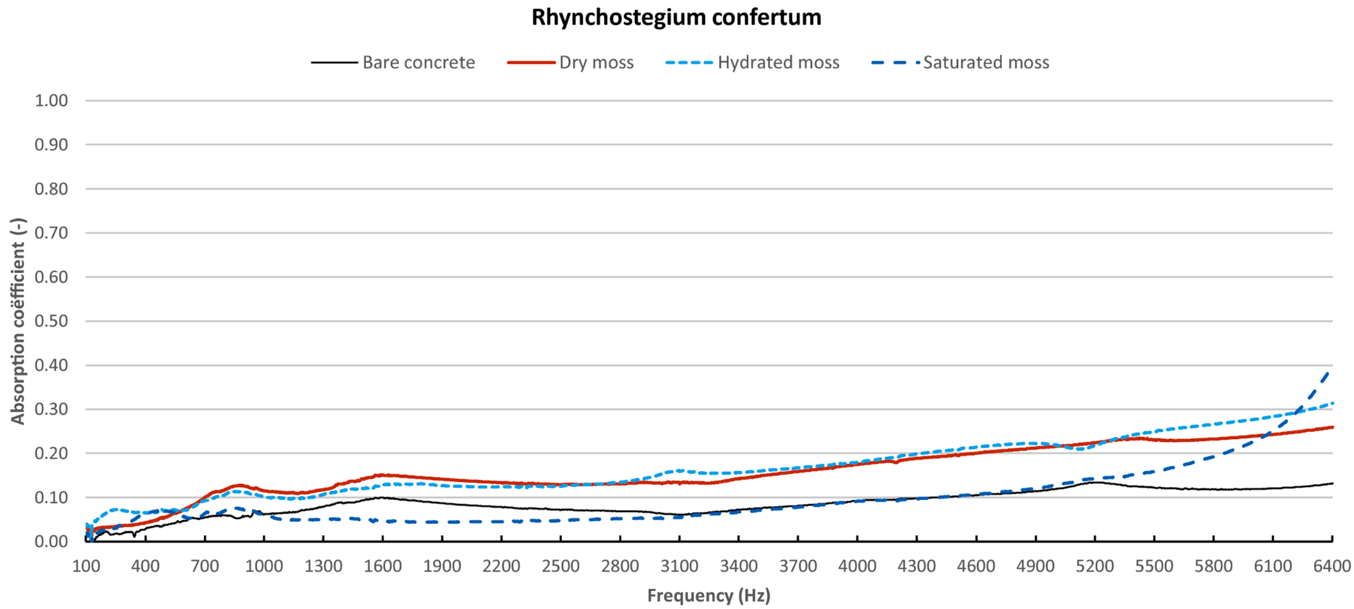


**Fig. 9.** Sound absorption results for R. confertum.

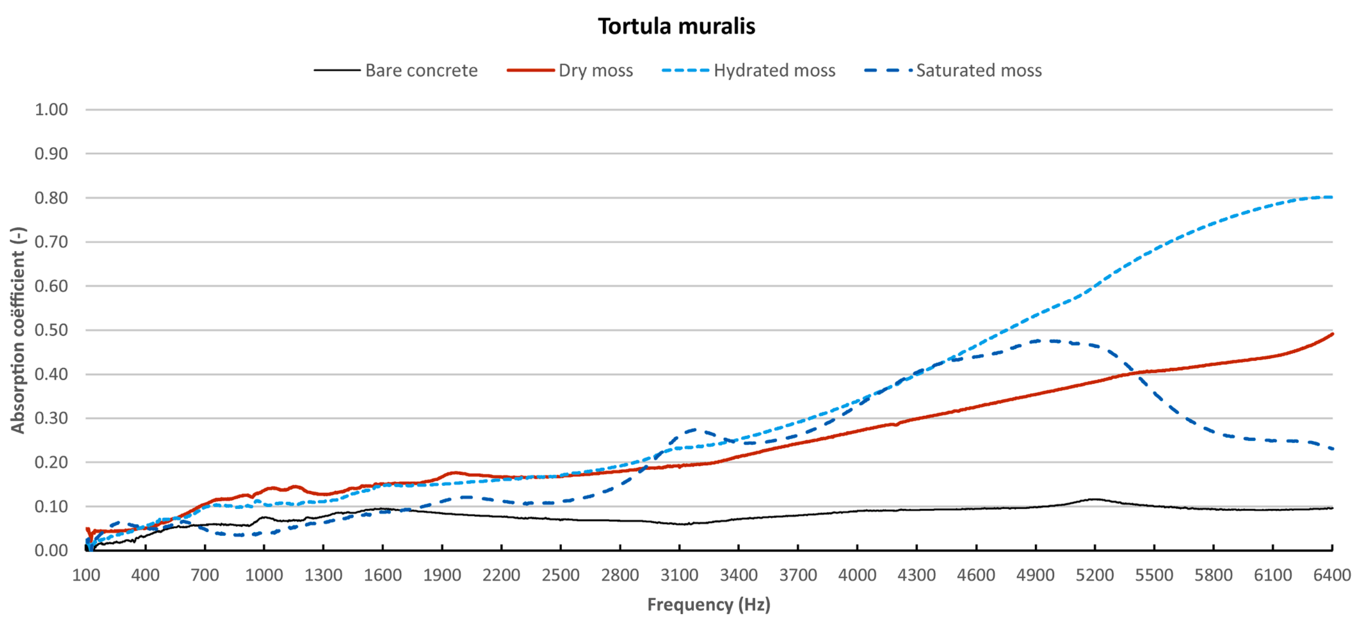


**Fig. 10.** Sound absorption results for T. muralis.

unexpected, as the sound absorption below frequencies of 2000 Hz is strongly related to the material thickness [25], something which is minimal in most moss species. Mosses being porous absorbers also explains why performance is best in most species when the moss is hydrated, but not fully saturated (Table 2). When the moss is saturated, the pores created by the leaves of the moss are at least partially blocked, reducing the effective porosity of the moss colony, which in turn reduces the acoustic performance [26]. This effect is less pronounced or absent in *B. rutabulum, P. capillare* and *O. diaphanum*, likely because they have looser growth forms, creating larger pore spaces between leaves, in which water is not retained as well compared to the other species. When drying, most mosses change their leaf structures, contorting them or curling them inwards [13]. This also changes the leaf surface area and porosity of the moss colony, in most cases leading to a slightly reduced sound absorption when the moss is dry as compared to when it is hydrated. This reduction in sound absorption when dry is particularly pronounced in *P. capillare* and *O. diaphanum*, the two species which also have the strongest structural response to desiccation (Fig. 15). The sole exception to this is *G. pulvinata* (>15 mm), which performs better in its dry form than when hydrated (Table 2). However, as this effect is not seen in the thinner layer of *G. pulvinata*, this may be due to some of the deeper voids in G. pulvinata (>15 mm) still being filled in their hydrated state, reducing their sound absorption.

Overall, the best-performing moss species are acrocarpous species, especially those that form large dense colonies (Fig. 16a), such as the acrocarpous species *G. pulvinata* and *P. capillare*, especially when they form thicker layers, as can be observed from the larger average sound absorption values found for the thicker layer of *G. pulvinata* (Table 2), as compared to the thinner layer (although, notably, the differences per octave band were not statistically significant between the two). These dense colonies form a more extensive and complex pore network, which, in turn, enhances acoustic absorption [7]. Other acrocarpous species,

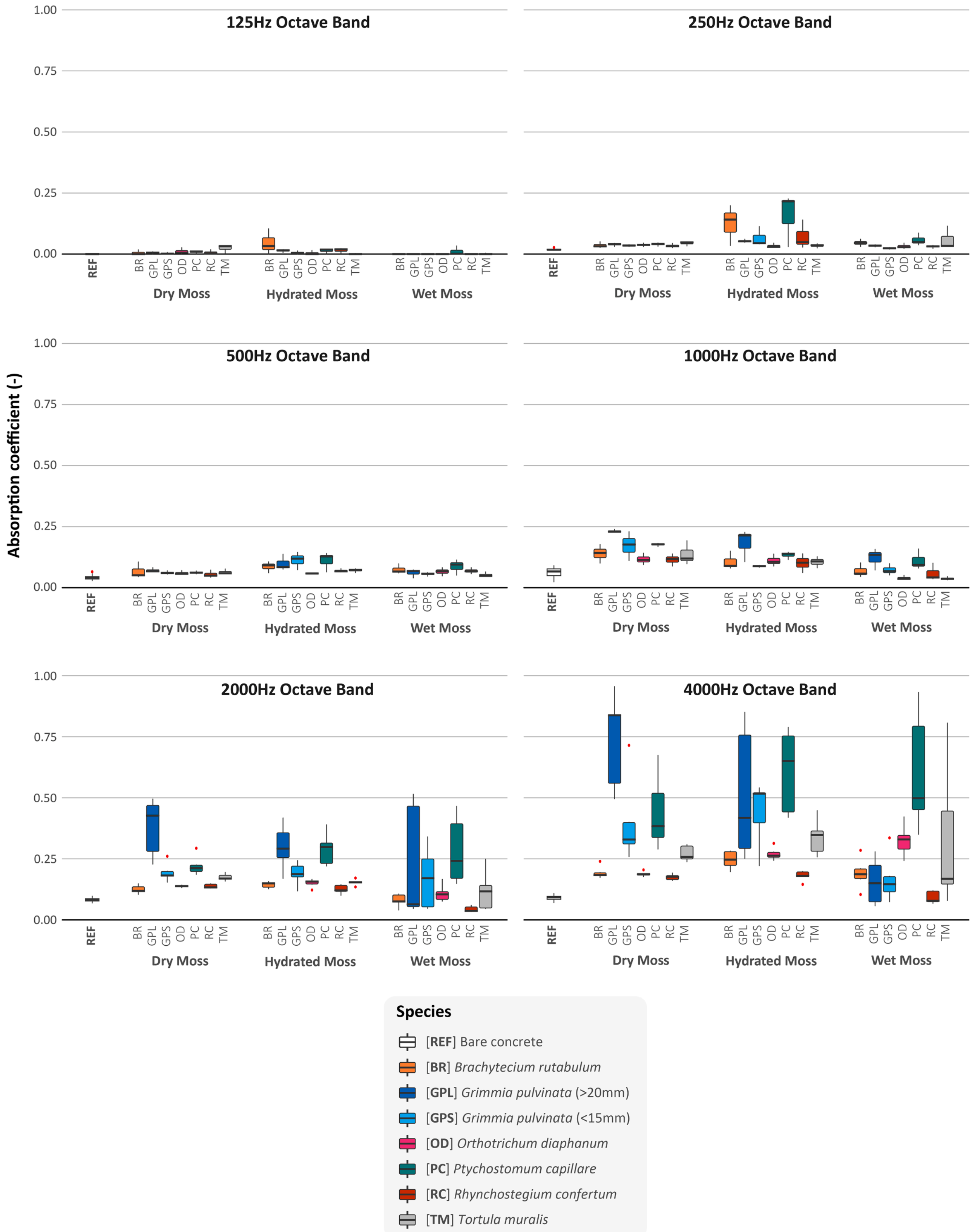


**Fig. 11.** Sound absorption results per octave band for all moss species and hydration states.

such as *T. muralis* and *O. diaphanum*, form smaller colonies (Fig. 16b) and perform somewhat worse. Overall, the pleurocarpous species exhibit the lowest overall sound absorption. This last can likely be attributed to their different growth form. Rather than the acrocarpous species, which grow perpendicular to the substrate they inhabit and often form dense cushions to trap water, pleurocarpous species grow primarily parallel to the substrate instead, forming relatively loose mats (Fig. 16c). As such, the pore network formed by their leaves is much less

# Absorption data per Octave band (Dry state)

### 125Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 27.603$, $p < 0.001$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.00 | 0.00 | 0.00 | 0.00 | a b |
| *BR* | 0.00 | 0.00 | 0.01 | 0.01 | a b |
| *GPL* | 0.01 | 0.00 | 0.01 | 0.00 | b c |
| *GPS* | 0.00 | 0.00 | 0.00 | 0.00 | b c |
| *OD* | 0.01 | 0.00 | 0.02 | 0.01 | b c |
| *PC* | 0.01 | 0.01 | 0.01 | 0.01 | b c |
| *RC* | 0.00 | 0.00 | 0.01 | 0.01 | b c |
| *TM* | 0.03 | 0.02 | 0.03 | 0.02 | c |

### 250Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 31.114$, $p < 0.001$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.02 | 0.02 | 0.02 | 0.00 | a |
| *BR* | 0.03 | 0.03 | 0.04 | 0.01 | b |
| *GPL* | 0.04 | 0.04 | 0.04 | 0.01 | b |
| *GPS* | 0.04 | 0.03 | 0.04 | 0.00 | b |
| *OD* | 0.04 | 0.03 | 0.04 | 0.01 | b |
| *PC* | 0.04 | 0.04 | 0.04 | 0.01 | b |
| *RC* | 0.03 | 0.03 | 0.04 | 0.01 | b |
| *TM* | 0.05 | 0.04 | 0.05 | 0.01 | b |

### 500Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 23.693$, $p = 0.001$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.04 | 0.04 | 0.05 | 0.01 | a |
| *BR* | 0.05 | 0.05 | 0.08 | 0.03 | a b |
| *GPL* | 0.07 | 0.07 | 0.08 | 0.01 | b |
| *GPS* | 0.06 | 0.06 | 0.07 | 0.01 | b |
| *OD* | 0.06 | 0.06 | 0.06 | 0.01 | b |
| *PC* | 0.06 | 0.06 | 0.07 | 0.01 | b |
| *RC* | 0.05 | 0.05 | 0.06 | 0.01 | a b |
| *TM* | 0.06 | 0.06 | 0.07 | 0.01 | b |

### 1000Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 33.512$, $p < 0.001$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.07 | 0.05 | 0.08 | 0.03 | a |
| *BR* | 0.14 | 0.12 | 0.16 | 0.04 | b c |
| *GPL* | 0.23 | 0.23 | 0.24 | 0.01 | c |
| *GPS* | 0.18 | 0.14 | 0.20 | 0.06 | b c |
| *OD* | 0.11 | 0.10 | 0.13 | 0.02 | b |
| *PC* | 0.18 | 0.17 | 0.18 | 0.01 | b c |
| *RC* | 0.12 | 0.10 | 0.13 | 0.03 | b |
| *TM* | 0.12 | 0.11 | 0.16 | 0.05 | b c |

### 2000Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 59.241$, $p < 0.001$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.08 | 0.08 | 0.09 | 0.01 | a |
| *BR* | 0.12 | 0.12 | 0.14 | 0.02 | b |
| *GPL* | 0.43 | 0.28 | 0.47 | 0.19 | e |
| *GPS* | 0.18 | 0.18 | 0.20 | 0.02 | d e |
| *OD* | 0.14 | 0.14 | 0.14 | 0.00 | b c |
| *PC* | 0.21 | 0.20 | 0.23 | 0.03 | d e |
| *RC* | 0.13 | 0.13 | 0.15 | 0.02 | b |
| *TM* | 0.17 | 0.17 | 0.18 | 0.02 | c d |

### 4000Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 59.237$, $p < 0.001$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.09 | 0.08 | 0.10 | 0.01 | a |
| *BR* | 0.18 | 0.18 | 0.19 | 0.02 | b c |
| *GPL* | 0.84 | 0.56 | 0.84 | 0.28 | e |
| *GPS* | 0.33 | 0.31 | 0.40 | 0.09 | d e |
| *OD* | 0.19 | 0.18 | 0.19 | 0.01 | b c |
| *PC* | 0.38 | 0.34 | 0.52 | 0.18 | c d |
| *RC* | 0.18 | 0.16 | 0.18 | 0.02 | b |
| *TM* | 0.26 | 0.25 | 0.30 | 0.06 | c d |

### Legend

| | | | |
|---|---|---|---|
| **Bare** | Bare concrete | **OD** | *Orthotrichum diaphanum* |
| **BR** | *Brachythecium rutabulum* | **PC** | *Ptychostomum capillare* |
| **GPL** | *Grimmia pulvinata* (>15mm) | **RC** | *Rhynchostegium confertum* |
| **GPS** | *Grimmia pulvinata* (<10mm) | **TM** | *Tortula muralis* |

**Fig. 12.** Medians, 1st (Q1) and 3rd (Q3) quartiles, as well as the inter-quartile range (IQR) of the noise absorption results per octave band of bare concrete and the moss species in their dry state. Also included are the Kruskal-Wallis test results and the homogeneous subsets created using the post-hoc Conover-Iman test with an alpha level of 0.05.

# Absorption data per Octave band (Hydrated state)

### 125Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 23.229$, $p = 0.002$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.00 | 0.00 | 0.00 | 0.00 | a |
| *BR* | 0.03 | 0.02 | 0.07 | 0.05 | b |
| *GPL* | 0.02 | 0.01 | 0.02 | 0.01 | b |
| *GPS* | 0.00 | 0.00 | 0.01 | 0.01 | a b |
| *OD* | 0.00 | 0.00 | 0.01 | 0.01 | a b |
| *PC* | 0.02 | 0.01 | 0.02 | 0.01 | b |
| *RC* | 0.02 | 0.01 | 0.02 | 0.01 | b |
| *TM* | 0.00 | 0.00 | 0.00 | 0.00 | a b |

### 250Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 32.515$, $p < 0.001$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.02 | 0.02 | 0.02 | 0.00 | a |
| *BR* | 0.14 | 0.09 | 0.17 | 0.08 | b |
| *GPL* | 0.05 | 0.05 | 0.06 | 0.01 | b |
| *GPS* | 0.05 | 0.04 | 0.08 | 0.04 | b |
| *OD* | 0.03 | 0.03 | 0.04 | 0.01 | b |
| *PC* | 0.22 | 0.12 | 0.22 | 0.10 | b |
| *RC* | 0.05 | 0.04 | 0.09 | 0.06 | b |
| *TM* | 0.04 | 0.03 | 0.04 | 0.01 | b |

### 500Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 31.97$, $p < 0.001$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.04 | 0.04 | 0.05 | 0.01 | a |
| *BR* | 0.09 | 0.08 | 0.10 | 0.02 | b c |
| *GPL* | 0.08 | 0.08 | 0.11 | 0.03 | c |
| *GPS* | 0.12 | 0.10 | 0.13 | 0.04 | c |
| *OD* | 0.06 | 0.06 | 0.06 | 0.00 | b |
| *PC* | 0.13 | 0.10 | 0.13 | 0.04 | c |
| *RC* | 0.07 | 0.07 | 0.07 | 0.01 | b c |
| *TM* | 0.07 | 0.07 | 0.08 | 0.01 | b c |

### 1000Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 27.366$, $p < 0.001$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.07 | 0.05 | 0.08 | 0.03 | a |
| *BR* | 0.09 | 0.08 | 0.12 | 0.03 | b |
| *GPL* | 0.21 | 0.16 | 0.22 | 0.06 | b |
| *GPS* | 0.09 | 0.09 | 0.09 | 0.00 | b |
| *OD* | 0.11 | 0.10 | 0.12 | 0.02 | b |
| *PC* | 0.14 | 0.13 | 0.14 | 0.01 | b |
| *RC* | 0.10 | 0.08 | 0.12 | 0.04 | b |
| *TM* | 0.11 | 0.09 | 0.12 | 0.02 | b |

### 2000Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 57.962$, $p < 0.001$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.08 | 0.08 | 0.09 | 0.01 | a |
| *BR* | 0.15 | 0.13 | 0.15 | 0.02 | b c |
| *GPL* | 0.29 | 0.25 | 0.36 | 0.11 | d |
| *GPS* | 0.19 | 0.17 | 0.22 | 0.05 | c d |
| *OD* | 0.16 | 0.15 | 0.16 | 0.01 | b c |
| *PC* | 0.30 | 0.23 | 0.32 | 0.09 | d |
| *RC* | 0.12 | 0.12 | 0.14 | 0.03 | b |
| *TM* | 0.15 | 0.15 | 0.16 | 0.00 | b c |

### 4000Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 57.622$, $p < 0.001$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.09 | 0.08 | 0.10 | 0.01 | a |
| *BR* | 0.25 | 0.22 | 0.28 | 0.06 | b c |
| *GPL* | 0.42 | 0.29 | 0.76 | 0.47 | d e |
| *GPS* | 0.52 | 0.40 | 0.52 | 0.13 | c d e |
| *OD* | 0.26 | 0.26 | 0.28 | 0.02 | b c d |
| *PC* | 0.65 | 0.44 | 0.76 | 0.31 | e |
| *RC* | 0.18 | 0.18 | 0.20 | 0.02 | b |
| *TM* | 0.35 | 0.28 | 0.37 | 0.09 | c d e |

### Legend

| | | | |
|---|---|---|---|
| **Bare** | Bare concrete | **OD** | *Orthotrichum diaphanum* |
| **BR** | *Brachythecium rutabulum* | **PC** | *Ptychostomum capillare* |
| **GPL** | *Grimmia pulvinata* (>15mm) | **RC** | *Rhynchostegium confertum* |
| **GPS** | *Grimmia pulvinata* (<10mm) | **TM** | *Tortula muralis* |

**Fig. 13.** Medians, 1st (Q1) and 3rd (Q3) quartiles, as well as the inter-quartile range (IQR) of the noise absorption results per octave band of bare concrete and the moss species in their hydrated state. Also included are the Kruskal-Wallis test results and the homogeneous subsets created using the post-hoc Conover-Iman test with an alpha level of 0.05.

# Absorption data per Octave band (Saturated state)

### 125Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 21.341$, $p = 0.003$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.00 | 0.00 | 0.00 | 0.00 | a |
| *BR* | 0.00 | 0.00 | 0.00 | 0.00 | a b |
| *GPL* | 0.00 | 0.00 | 0.00 | 0.00 | a b |
| *GPS* | 0.00 | 0.00 | 0.00 | 0.00 | a b |
| *OD* | 0.00 | 0.00 | 0.00 | 0.00 | a b |
| *PC* | 0.00 | 0.00 | 0.02 | 0.02 | c |
| *RC* | 0.00 | 0.00 | 0.00 | 0.00 | a b |
| *TM* | 0.00 | 0.00 | 0.00 | 0.00 | b c |

### 250Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 30.454$, $p < 0.001$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.02 | 0.02 | 0.02 | 0.00 | a |
| *BR* | 0.05 | 0.04 | 0.05 | 0.01 | b c |
| *GPL* | 0.03 | 0.03 | 0.04 | 0.00 | b c |
| *GPS* | 0.02 | 0.02 | 0.03 | 0.00 | a b |
| *OD* | 0.03 | 0.03 | 0.04 | 0.01 | b c |
| *PC* | 0.05 | 0.04 | 0.07 | 0.02 | c |
| *RC* | 0.03 | 0.03 | 0.03 | 0.01 | b c |
| *TM* | 0.03 | 0.03 | 0.07 | 0.04 | b c |

### 500Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 22.838$, $p = 0.002$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.04 | 0.04 | 0.05 | 0.01 | a |
| *BR* | 0.07 | 0.06 | 0.08 | 0.02 | b |
| *GPL* | 0.07 | 0.05 | 0.07 | 0.02 | a b |
| *GPS* | 0.06 | 0.05 | 0.06 | 0.01 | a b |
| *OD* | 0.07 | 0.06 | 0.07 | 0.02 | b |
| *PC* | 0.09 | 0.07 | 0.10 | 0.03 | b |
| *RC* | 0.07 | 0.06 | 0.07 | 0.01 | b |
| *TM* | 0.05 | 0.05 | 0.06 | 0.01 | a b |

### 1000Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 17.897$, $p = 0.012$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.07 | 0.05 | 0.08 | 0.03 | a b |
| *BR* | 0.06 | 0.05 | 0.08 | 0.03 | a b |
| *GPL* | 0.14 | 0.10 | 0.15 | 0.04 | b |
| *GPS* | 0.07 | 0.06 | 0.08 | 0.02 | a b |
| *OD* | 0.04 | 0.04 | 0.04 | 0.01 | a |
| *PC* | 0.09 | 0.09 | 0.13 | 0.04 | b |
| *RC* | 0.04 | 0.04 | 0.07 | 0.03 | a b |
| *TM* | 0.04 | 0.03 | 0.04 | 0.01 | a |

### 2000Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 22.621$, $p = 0.002$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.08 | 0.08 | 0.09 | 0.01 | b |
| *BR* | 0.08 | 0.07 | 0.10 | 0.03 | a b |
| *GPL* | 0.06 | 0.05 | 0.47 | 0.42 | b |
| *GPS* | 0.17 | 0.05 | 0.25 | 0.20 | b c |
| *OD* | 0.11 | 0.08 | 0.12 | 0.03 | b c |
| *PC* | 0.24 | 0.17 | 0.40 | 0.23 | c |
| *RC* | 0.04 | 0.04 | 0.05 | 0.02 | a |
| *TM* | 0.12 | 0.05 | 0.14 | 0.10 | b c |

### 4000Hz Ocave band

**Kruskal-Wallis:** $\chi^2(7) = 37.084$, $p < 0.001$

| *Species* | Median | Q1 | Q3 | IQR | Homogeneous subset |
|---|---|---|---|---|---|
| *Bare* | 0.09 | 0.08 | 0.10 | 0.01 | a |
| *BR* | 0.19 | 0.17 | 0.21 | 0.04 | c d e |
| *GPL* | 0.15 | 0.07 | 0.23 | 0.15 | a b c |
| *GPS* | 0.15 | 0.11 | 0.18 | 0.07 | b c d |
| *OD* | 0.33 | 0.29 | 0.35 | 0.06 | d e |
| *PC* | 0.50 | 0.45 | 0.80 | 0.35 | e |
| *RC* | 0.08 | 0.07 | 0.12 | 0.05 | a b |
| *TM* | 0.17 | 0.15 | 0.45 | 0.30 | c d e |

### Legend

| | | | |
|---|---|---|---|
| **Bare** | Bare concrete | **OD** | *Orthotrichum diaphanum* |
| **BR** | *Brachythecium rutabulum* | **PC** | *Ptychostomum capillare* |
| **GPL** | *Grimmia pulvinata* (>15mm) | **RC** | *Rhynchostegium confertum* |
| **GPS** | *Grimmia pulvinata* (<10mm) | **TM** | *Tortula muralis* |

**Fig. 14.** Medians, 1st (Q1) and 3rd (Q3) quartiles, as well as the inter-quartile range (IQR) of the noise absorption results per octave band of bare concrete and the moss species in their saturated state. Also included are the Kruskal-Wallis test results and the homogeneous subsets created using the post-hoc Conover-Iman test with an alpha level of 0.05.

**Table 2**
Average and peak sound absorption coefficients across the entire tested frequency spectrum (50–6400 Hz) for all species in all their hydration states.

| | Average sound absorption coefficient | | | Peak sound absorption coefficient | | |
|---|---|---|---|---|---|---|
| Species | Dry | Hydrated | Saturated | Dry | Hydrated | Saturated |
| *B. rutabulum* | 0.17 | 0.21 | 0.22 | 0.28 @ 6400Hz | 0.41 @ 6400Hz | 0.72 @ 5940Hz |
| *G. pulvinata* (>15 mm) | 0.55 | 0.41 | 0.19 | 0.88 @ 6400Hz | 0.73 @ 6400Hz | 0.34 @ 5364Hz |
| *G. pulvinata* (<10 mm) | 0.33 | 0.36 | 0.18 | 0.67 @ 6400Hz | 0.73 @ 6080Hz | 0.39 @ 5176Hz |
| *O. diaphanum* | 0.17 | 0.23 | 0.29 | 0.31 @ 6400Hz | 0.47 @ 6400Hz | 0.76 @ 6352Hz |
| *P. capillare* | 0.36 | 0.48 | 0.47 | 0.70 @ 6400Hz | 0.86 @ 6400Hz | 0.85 @ 5890Hz |
| *R. confertum* | 0.16 | 0.16 | 0.10 | 0.26 @ 6400Hz | 0.31 @ 6400Hz | 0.40 @ 6400Hz |
| *T. muralis* | 0.24 | 0.32 | 0.22 | 0.49 @ 6400Hz | 0.80 @ 6384Hz | 0.48 @ 4968Hz |

**Fig. 15.** When *P. capillare* is desiccated (left), the leaves curl up around the stem, thereby reducing leaf surface area and opening up the pores between the individual plants in the colony. When *P. capillare* is hydrated (right), the leaves uncurl again, increasing leaf surface area and creating porous structures between the individual plants in the colony.


**Fig. 16.** (a) Larger acrocarp species, such as *G. pulvinata* (depicted) and *P. capillare*, form large cushions, growing perpendicular to the substrate. (b) Smaller acrocarp species, such as *O. diaphanum* (depicted) and *T. muralis*, form smaller cushions while still growing perpendicular to the substrate. (c) Pleurocarp species, such as *B. rutabulum* (depicted) and *R. confertum*, form large mats growing parallel to the substrate.

extensive and complex. Another potentially contributing factor is the angle of their leaves as compared to the incoming sound. The angle between incoming sound and the leaves of pleurocarpous moss species is much smaller than that of acrocarpous moss species, which, in turn, negatively affects their ability to absorb acoustic energy [12].

In practice, this means that larger acrocarp species are most suitable for noise-mitigating structures, with species selection dependent on the location where the structure is to be placed. In locations with a moister (micro)climate, where the moss can be expected to be wet or hydrated for most of the time, *P. capillare* is the most suitable species, as it will perform best under these conditions. It can also be expected to yield the best results when the conditions are highly variable, as it had the most consistent results. On the other hand, if the moss is expected to be dry for the majority of the time, the use of *G. pulvinata* will likely yield better results.

The primary limitation of using moss as an acoustic absorber in an urban environment is its absorption spectrum. The frequency spectrum of traffic and railway noise, two of the major components of urban noise pollution, have broad emission spectrums with a peak at around 1000 Hz [27]. Conversely, mosses have the bulk of their sound absorption in the 2000 Hz and 4000 Hz octave bands, with a smaller effect in the 1000 Hz octave band. Noise pollution in these higher (1000 Hz, 2000 Hz, and 4000 Hz) octave bands, in turn, has been linked to adverse health effects, such as sleep disturbance [28], depression [29], metabolic syndrome [30], and hypertension [31,32]. As such, moss can help mitigate these issues. However, noise pollution in the lower octave bands is also not without its deleterious effects, such as annoyance, sleep disturbance, mental fatigue and headaches [33,34]. And, while in most cases the addition of moss also resulted in a statistically significant increase in sound absorption compared to bare concrete in the lower frequency spectrum, the positive effect of the addition of moss on these lower octave bands was comparatively small. Furthermore, it should be noted that these results were obtained in an impedance tube, which measured normal incidence sound absorption only. Whereas in practice, random incidence of sound can be expected. Although results from impedance tube measurements and reverberation room measurements (which measure under random incidence) correlate relatively well with one another, both under- and overestimations can occur with impedance tube testing [35,36]. In turn, noise absorption results under field conditions may differ from these values, warranting further investigation.

The final limitation lies in the biological nature of the moss. Even with samples from the same species, a large spread in sound absorption values was observed, especially for the best-performing species. Furthermore, differences in moisture content can also affect the sound absorption of moss, as shown in this research. Finally, over time, some moss may detach from a bioreceptive structure, either due to plant senescence or mechanical stressors. As reduced plant coverage has previously been demonstrated to lead to a reduction in sound absorption [37], a similar effect can be expected for a reduction in moss coverage. It is therefore likely that there will be not only a spatial, but also a temporal variation in the sound absorption by moss-covered bioreceptive concrete, a phenomenon which is also present in other green structures [38].

### 4.2. Moss-covered bioreceptive concrete compared to other vertical green structures

The green vertical structure that is most similar to bioreceptive concrete in terms of monetary, structural, and maintenance requirements is the (in)direct green vertical structure. In a direct green vertical structure system, the plants—usually climbing plants—grow directly on the vertical structure, whereas in an indirect green vertical structure, an additional support structure for the plants, such as a mesh, is added [5]. Because of this, the sound absorption provided by the green structure is solely related to the plants used. Some limited research on the acoustic performance of climbing plants (without a substrate) is available. Research by Horoshenkov, et al. [12], who used an impedance tube to measure the acoustic performance of plants without their substrate, shows that the *H. helix* (Common Ivy), a commonly used climbing plant in direct green facades, has a sound absorption profile below 0.2 throughout the tested frequency spectrum (50–1600 Hz), which is slightly lower than what was found by our testing for the largest acrocarp species (*G. pulvinata* and *P. capillare*), similar to the smaller acrocarp species (*O. diaphanum* and *T. muralis*), and slightly higher than the pleurocarp species (*B. rutabulum* and *R. confertum*). Testing done by Yang, et al. [39] in a reverberation chamber and on a broader frequency spectrum (100–5000 Hz) found that, similar to the moss-covered concrete, the sound absorption of their tested plant species increased with increasing sound frequencies. In their testing, the *H. helix* reached a maximum of 0.49 at 5000 Hz when using a 200 mm layer thickness and 0.39 at 4000 Hz with a 50 mm layer thickness, the latter of which is more similar to what can be found in practice. Again, this is (in some cases substantially) lower than the results for the larger pleurocarp species and similar to the results for the smaller acrocarp species. This means that *H. Helix* leaves have significantly larger size and mass than moss, two properties which both contribute to higher sound absorption [40]; overall sound absorption is either lower than or similar to the acrocarpous moss species. This likely has to do with the higher leaf area index (LAI; the ratio between one-sided leaf surface to covered substrate surface area) of moss, which is at the extreme higher end of plants [41], as this has been found to be another predictor of sound absorption by plants [12,42].

Whilst the sound absorption of moss-covered bioreceptive concrete compares favourably to that of plants used on (in)direct green vertical structures, the comparison changes when a growing substrate is added, as is the case for living wall systems (LWS) or green vertical structures using planter boxes [5]. In these plant-soil systems, the bulk of the sound absorption is provided not by the plants but by the substrate [43]. This is visible in the aforementioned research by Horoshenkov, et al. [12], where, when added to a lightweight substrate, *H. helix* had a sound absorption of between 0.7 and 0.9 for most of the 50–1600 Hz frequency spectrum, up from the lower than 0.2 sound absorption value of the plant alone. At some frequencies, the addition of the plants even reduced the sound absorption as compared to the substrate alone, an effect that has been found to happen under certain circumstances by other researchers as well [44]. As such, sound absorption for these green structures is mostly dependent on the characteristics of the substrate, such as open porosity, pore size distribution, thickness, air flow resistivity, tortuosity and moisture content [7]. This means that (very) high sound absorption values are possible, with D'Alessandro, et al. [14] finding sound absorption values of above 0.9 at 1200 Hz, after an initial peak of around 0.75 at 400 Hz when combining *N. Exaltata* (Boston fern) with a 10 cm thick layer of perlite and coconut fibre, Thomazelli, et al. [37] finding a sound absorption of 1 above 1000 Hz when using the same type of substrate and combining it with *C. repens* (Turtle vine), and Davis, et al. [45] finding sound absorption values of 1 above 250 Hz, using *N. Exaltata* (Boston fern) on a substrate consisting of potting soil, coco chips and *Sphagnum* moss. All in all, these values are far beyond what moss is capable of. However, the need for a growing substrate does dramatically increase the costs and carbon footprint as compared to an (in)direct green vertical structure (and in extension bioreceptive green structures, which have similar requirements) [46,47]. As such, moss-covered bioreceptive structures are still a viable alternative to an LWS for sound absorption when cost and carbon footprint are a concern.

## 5. Conclusion

This research set out to determine whether moss growing on concrete effectively mitigates urban noise pollution and whether it can be considered a viable alternative to other contemporary vertical green structures. Based on the results, the following conclusions can be drawn:

- Larger acrocarp moss species exhibit the largest sound absorption capacity, followed by smaller acrocarp species, with pleurocarp species showing the lowest sound absorption capacity of all moss species tested;
- Considering all hydration states (dry, hydrated, and saturated), *P. capillare* exhibits the highest overall sound absorption efficiency and is recommended to be used in under moist or variable conditions, whereas *G. pulvinata* is recommended for use under dry conditions;
- Although sound absorption values as high as 0.88 were recorded, and statistically significant differences were found between bare and moss-covered samples in most conditions, the greatest sound absorption potential of moss is observed in the higher frequency range (1000 Hz octave band and above), while its impact on lower frequencies remains minimal;
- Moss-covered concrete compares favourably to other (in)direct vertical green structures without substrates when one of the (larger) acrocarp species is used, as these acrocarp species exhibit higher sound absorption values than those of the vascular climbing plants often used in vertical green structures without substrates;
- However, moss-covered bioreceptive concrete cannot match the sound absorption of other vertical green structures with substrates, such as living wall systems, as moss-covered bioreceptive concrete lacks the substrate that primarily contributes to their acoustic performance.

However, it should be noted that the presented results in this study were obtained from tests performed under normal incidence, whereas in practice, most urban noise will hit a structure under random incidence, which may change these results. Furthermore, concrete samples were always fully covered with moss in these tests. In practice, especially for acrocarp species, coverage will change over time due to moss detaching from the bioreceptive surface, which is expected to reduce its overall sound absorption. Therefore, while these results are promising, future research should focus on in-situ testing of natural moss growth.

## CRediT authorship contribution statement

**M. Veeger:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Ottelé:** Writing – review & editing, Supervision, Methodology, Conceptualization. **H.M. Jonkers:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: M. Veeger reports a relationship with ReSpyre B.V. that includes: consulting or advisory. M. Ottele reports a relationship with ReSpyre B.V. that includes: equity or stocks. H.M. Jonkers reports a relationship with ReSpyre B.V. that includes: equity or stocks. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data is available on Mendeley Data under the following DOI:10.17632/d37ybrw4mh.1.

## References

[1] O. Hänninen, et al., Environmental burden of disease in Europe: assessing nine risk factors in six countries, Environ. Health Perspect. 122 (5) (2014) 439–446, https://doi.org/10.1289/ehp.1206154, 2014/05/01.
[2] WHO Europe, Burden of Disease from Environmental noise: Quantification of Healthy Life Years Lost in Europe, WHO Regional Office for Europe, Copenhagen, Denmark, 2011 [Online]Available, https://publications.jrc.ec.europa.eu/repository/handle/JRC64428.
[3] WHO, WHO Environmental Noise Guidelines For the European region, World Health Organization, Regional Office for Europe, Copenhagen, 2018 [Online] Available, https://www.who.int/europe/publications/i/item/9789289053563.
[4] E. Peris, Environmental Noise in Europe — 2020, 1, Luxembourg, 2020 [Online] Available, https://www.eea.europa.eu/publications/environmental-noise-in-europe.
[5] K. Perini, M. Ottelé, E. Haas, R. Raiteri, Greening the building envelope, facade greening and living wall systems, Open J. Ecol. 1 (2011) 1–8, https://doi.org/10.4236/oje.2011.11001.
[6] V. Oquendo-Di Cosola, F. Olivieri, L. Ruiz-García, A systematic review of the impact of green walls on urban comfort: temperature reduction and noise attenuation, Renew. Sustainable Energy Rev. 162 (2022) 112463, https://doi.org/10.1016/j.rser.2022.112463, 2022/07/01.
[7] J. Bakker, M. Lugten, M. Tenpierik, Applying vertical greening systems to reduce traffic noise in outdoor environments: overview of key design parameters and research methods, Build. Acoust. 30 (3) (2023) 315–338, https://doi.org/10.1177/1351010X231171028, 2023/09/01.
[8] L. Cao, Q. Fu, Y. Si, B. Ding, J. Yu, Porous materials for sound absorption, Compos. Commun. 10 (2018) 25–35, https://doi.org/10.1016/j.coco.2018.05.001, 2018/12/01.
[9] S. Sarabi, Q. Han, A.G.L. Romme, B. de Vries, R. Valkenburg, E. den Ouden, Uptake and implementation of nature-based solutions: an analysis of barriers using interpretive structural modeling, J. Environ. Manage. 270 (2020) 110749, https://doi.org/10.1016/j.jenvman.2020.110749, 2020/09/15.
[10] M. Veeger, A.A.N. Nabbe, M. Ottelé, H.M. Jonkers, Bioreceptive concrete: state of the art and potential benefits, HERON 68 (1) (2023) 47–76 [Online]Available, http://heronjournal.nl/68-1/4.pdf.
[11] A.J. Johnson, C.I. Davidson, E. Cibelli, A. Wojcik, Estimating leaf area index and coverage of dominant vegetation on an extensive green roof in Syracuse, NY, Nature 3 (2023) 100068, https://doi.org/10.1016/j.nbsj.2023.100068, 2023/12/01.
[12] K.V. Horoshenkov, A. Khan, H. Benkreira, Acoustic properties of low growing plants, J. Acoust. Soc. Am. 133 (5) (2013) 2554–2565, https://doi.org/10.1121/1.4798671, 2013/05/01.
[13] J. Glime, Chapter 7 - water relations, in: J. Glime (Ed.), Bryophyte Ecology, Volume 1: Physiological Ecology, 2017.
[14] F. D'Alessandro, F. Asdrubali, N. Mencarelli, Experimental evaluation and modelling of the sound absorption properties of plants for indoor acoustic applications, Build Environ. 94 (2015) 913–923, https://doi.org/10.1016/j.buildenv.2015.06.004, 2015/12/01.
[15] F. Asdrubali, F. D'Alessandro, N. Mencarelli, and K.V. Horoshenkov, "Sound absorption properties of tropical plants for indoor applications," in Proceedings of the 21st International Congress on Sound and Vibration, China, 2014.
[16] N. Neithalath, Development and Characterization of Acoustically Efficient Cementitious Materials, PhD, Purdue University, 2004 [Online]Available, https://docs.lib.purdue.edu/dissertations/AAI3150808/.
[17] G. Reethof, L. Frank, and O. McDaniel, "Sound absorption characteristics of tree bark and forest floor," in Proceedings of the Conference on Metropolitan Physical Environment, USDA Forest Service General Technical Report NE-2, 1977.
[18] M. Li, T. Van Renterghem, J. Kang, K. Verheyen, D. Botteldooren, Sound absorption by tree bark, Appl. Acoust. 165 (2020) 107328, https://doi.org/10.1016/j.apacoust.2020.107328, 2020/08/01.
[19] B.G. Kim, M.H. Yoon, J. Kim, and J.H. Oh, "All-natural moss-based microstructural composites in deformable form for use as graffiti and artificial-porous-material replacement," Materials, vol. 15, no. 24, doi: 10.3390/ma15249053.
[20] D. Sleinus et al., "Properties of sound absorption composite materials developed using flax Fiber, Sphagnum Moss, Vermiculite, and Sapropel," Materials, vol. 16, no. 3, doi: 10.3390/ma16031060.
[21] M. Veeger, E.M. Veenendaal, J. Limpens, M. Ottelé, H.M. Jonkers, Moss species for bioreceptive concrete: a survey of epilithic urban moss communities and their dynamics, Ecol Eng 212 (2025) 107502, https://doi.org/10.1016/j.ecoleng.2024.107502, 2025/02/01.
[22] U. Heber, W. Bilger, R. Bligny, O.L. Lange, Phototolerance of lichens, mosses and higher plants in an alpine environment: analysis of photoreactions, Planta 211 (6) (2000) 770–780, https://doi.org/10.1007/s004250000356, 2000/11/01.
[23] R Core Team, R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2023 ed.
[24] PMCMRplus: calculate pairwise multiple comparisons of mean rank sums extended. (2024).
[25] S. Amares, E. Sujatmika, T.W. Hong, R. Durairaj, H.S.H.B. Hamid, A review: characteristics of noise absorption material, J.Phys. 908 (1) (2017) 012005, https://doi.org/10.1088/1742-6596/908/1/012005, 2017/10/01.
[26] T. Van Renterghem, D. Botteldooren, Influence of rainfall on the noise shielding by a green roof, Build Environ. 82 (2014) 1–8, https://doi.org/10.1016/j.buildenv.2014.07.025, 2014/12/01.
[27] C. Buratti, E. Belloni, E. Moretti, Façade noise abatement prediction: new spectrum adaptation terms measured in field in different road and railway traffic conditions, Appl. Acoust. 76 (2014) 238–248, https://doi.org/10.1016/j.apacoust.2013.08.016, 2014/02/01.
[28] S. Myllyntausta, J. Virkkala, P. Salo, J. Varjo, L. Rekola, V. Hongisto, Effect of the frequency spectrum of road traffic noise on sleep: a polysomnographic study, J. Acoust. Soc. Am. 147 (4) (2020) 2139–2149, https://doi.org/10.1121/10.0000985.
[29] J.Y. Lin, W.J. Cheng, C.F. Wu, T.Y. Chang, Associations of road traffic noise and its frequency spectrum with prevalent depression in Taichung, Taiwan (in eng), Front. Public Health 11 (2023) 1116345, https://doi.org/10.3389/fpubh.2023.1116345.
[30] M. Khosravipour, H. Abdollahzad, F. Khosravi, M. Rezaei, H.Mohammadi Sarableh, Z. Moradi, The effects of exposure to different noise frequencies on the prevalence of metabolic syndrome, Eur. J. Prev. Cardiol. 27 (13) (2020) 1451–1454, https://doi.org/10.1177/2047487319866988.
[31] M. Khosravipour, F. Khosravi, H. Ashtarian, M. Rezaei, Z. Moradi, H. Mohammadi Sarableh, The effects of exposure to different noise frequency patterns on blood pressure components and hypertension, Int. Arch. Occup. Environ. Health 93 (8) (2020) 975–982, https://doi.org/10.1007/s00420-020-01545-2, 2020/11/01.
[32] C.S. Liu, L.H. Young, T.Y. Yu, B.Y. Bao, T.Y. Chang, Occupational noise frequencies and the incidence of hypertension in a retrospective cohort study (in eng), Am. J. Epidemiol. 184 (2) (2016) 120–128, https://doi.org/10.1093/aje/kwv333. Jul 15.
[33] C. Baliatsas, I. van Kamp, R. van Poll, J. Yzermans, Health effects from low-frequency noise and infrasound in the general population: is it time to listen? A systematic review of observational studies, Sci. Total Environ. 557-558 (2016) 163–169, https://doi.org/10.1016/j.scitotenv.2016.03.065, 2016/07/01.
[34] A.M. Abbasi, M. Motamedzade, M. Aliabadi, R. Golmohammadi, L. Tapak, Study of the physiological and mental health effects caused by exposure to low-frequency noise in a simulated control room, Build. Acoust. 25 (3) (2018) 233–248, https://doi.org/10.1177/1351010X18779518, 2018/09/01.
[35] Y. Tang, X.J. Chuang, Tuning of estimated sound absorption coefficient of materials of reverberation room method, Shock Vib. 2022 (1) (2022) 5192984, https://doi.org/10.1155/2022/5192984, 2022/01/01.
[36] C.W. Kang, E.S. Jang, S.S. Jang, H.Y. Kang, Comparison of transfer function method and reverberation room method in measuring the sound absorption coefficient of rice straw particle mat, J. Korean Wood Sci. Technol. 46 (4) (2018) 362–367, https://doi.org/10.5658/WOOD.2018.46.4.362.
[37] R. Thomazelli, F.D.N. Caetano, S.R. Bertoli, Acoustic properties of green walls: absorption and insulation, Proc.Meetings Acoust. 28 (1) (2017) 015017, https://doi.org/10.1121/2.0000426.
[38] E. Attal, N. Côté, T. Shimizu, and B. Dubus, "Analysis of environmental and seasonal effects on sound absorption by green wall systems," presented at the 23rd International Congress on Acoustics, ICA 2019, 2019.
[39] H.S. Yang, J. Kang, C. Cheal, Random-incidence absorption and scattering coefficients of vegetation, Acta Acustica United Acustica 99 (3) (2013) 379–388.
[40] M.J. Martens, P.P. Severens, H.A. Van Wissen, L.A. Van Der Heijden, Acoustic reflection characteristics of deciduous plant leaves, Environ. Exp. Bot. 25 (3) (1985) 285–292, https://doi.org/10.1016/0098-8472(85)90013-9, 1985/08/01.

[41] Ü. Niinemets, M. Tobias, Canopy leaf area index at its higher end: dissection of structural controls from leaf to canopy scales in bryophytes, New Phytol. 223 (1) (2019) 118–133, https://doi.org/10.1111/nph.15767, 2019/07/01.
[42] Z. Azkorra, et al., Evaluation of green walls as a passive acoustic insulation system for buildings, Appl. Acoust. 89 (2015) 46–56, https://doi.org/10.1016/j.apacoust.2014.09.010, 2015/03/01.
[43] F. Yan, J. Shen, W. Zhang, L. Ye, X. Lin, A review of the application of green walls in the acoustic field, Build. Acoust. 29 (2) (2022) 295–313, https://doi.org/10.1177/1351010X221096789, 2022/06/01.
[44] L. Ding, T. Van Renterghem, D. Botteldooren, K. Horoshenkov, A. Khan, Sound absorption of porous substrates covered by foliage: experimental results and numerical predictions, J. Acoust. Soc. Am. 134 (6) (2013) 4599–4609, https://doi.org/10.1121/1.4824830.
[45] M.J. Davis, M.J. Tenpierik, F.R. Ramírez, M.E. Pérez, More than just a green facade: the sound absorption properties of a vertical garden with and without plants, Build. Environ. 116 (2017) 64–72, https://doi.org/10.1016/j.buildenv.2017.01.010, 2017/05/01.
[46] K. Perini, P. Rosasco, Cost–benefit analysis for green façades and living wall systems, Build. Environ. 70 (2013) 110–121, https://doi.org/10.1016/j.buildenv.2013.08.012.
[47] M. Ottelé, K. Perini, A.L. Fraaij, E.M. Haas, R. Raiteri, Comparative life cycle analysis for green façades and living wall systems, Energy Build. 43 (12) (2011) 3419–3429, https://doi.org/10.1016/j.enbuild.2011.09.010, 2011/12/01.