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ACOUSTIC EVALUATION OF A NEW MODULAR SYSTEM FOR GREEN ROOFS AND GREEN WALLS

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Abstract

Environmental noise is a major problem that affects citizen's health and comfort mainly in densely populated urban areas. There are some ways to reduce environmental noise pollution through the use of materials with good acoustic insulation properties in buildings envelope. Recent studies have shown that green surfaces, e.g. in the form of green roofs and green walls, can contribute to decrease noise levels.

The aim of this research is to identify how factors such as substrate and plants, variety and height of plants, affect the sound absorption of a modular system for green surfaces in simulated conditions. The results show that introduction substrate (S2) can improve the weighted sound absorption coefficient in 15% and the addition of plants (S3) improves it 20% more. However, if a variety of smaller and higher plants is used (S4) the weighted sound absorption coefficient (α_W) can reach to 0.80 and an absorption class B can be obtained.

Streszczenie

Hałas środowiskowy jest jednym z ważniejszych problemów wpływających na zdrowie i komfort życia mieszkańców miast, szczególnie na terenach gęsto zaludnionych.

Jest kilka sposobów ograniczania zanieczyszczenia hałasem środowiskowym poprzez stosowanie materiałów elewacyjnych o dobrych parametrach akustycznych. Wiele opracowań pokazuje, iż powierzchnie zielone, np. w formie zielonych dachów czy zielonych ścian, mogą przyczyniać się do obniżenia poziomu hałasu.

Przedmiotem opracowania jest wskazanie jak czynniki takie jak podłoże, roślinność oraz zróżnicowanie wysokości roślin wpływa na pochłanianie dźwięku przez modułowy system powierzchni zielonych w warunkach laboratoryjnych. Wyniki wskazują, iż wypełnienie podłożem (S2) może poprawić jednoliczbowy wskaźnik pochłaniania dźwięku (α_W) o 15%. Udział roślinności (S3) poprawia ten parametr o ponad 20%. W przypadku wariantu zawierającego mniejszą i większą roślinność (S4) jednoliczbowy wskaźnik pochłaniania dźwięku (α_W) może osiągać wartości do 0.80 oraz klasę pochłaniania B.

Keywords: **Acoustic; Green roofs; Green walls; Modular system; Sound absorption coefficient.**

1. INTRODUCTION

Environmental noise is a major environmental problem that affects citizen's health and comfort mainly in densely populated urban areas [1-4]. The EU Directive 2002/49/EC defines the environmental noise as the unwanted or harmful outdoor sound created by human activities, including noise emitted by means of transport, road traffic, rail traffic, air traffic and from sites of industrial activity [5].

There are different methods of acoustic protection, such as noise barriers or special construction materials for roads [6-10]. However, these are often insufficient solutions.

One way to partially reduce noise levels in the environment is the use of appropriate solutions and materials in buildings construction. Dense urban areas often include highly reflective and low sound absorption construction materials that contribute to increase sound levels. However, materials with good absorbing performance can positively affect the acoustics of surrounding environment [11-12].

There is now a number of new approaches for the implementation of nature-based solutions including integrating living systems with built systems. Green roofs and green walls are seen as examples of these nature based solutions. These methods are centred on the importance of greening cities to reduce pollution, noise and improve health. And develop prevention and mitigation strategies that help reducing the impact of noise on society, focusing particularly on urban settings and areas in the vicinity of motorways [13].

Often good acoustic parameters are characteristic for materials containing vegetation. The integration of vegetation in the urban environment, either in the form of green roofs or green walls, brings many environmental benefits while helping to improve urban design [14] and to create a more sustainable urban environment [15-17].

In fact, green roofs and green walls contribute, among other benefits, to: improve human health and well-being, enhance biodiversity, mitigate the urban heat island effect [18], reduce flood and drought risk while helping in the use and distribution of rainwater [19], store carbon [20], protect surfaces from direct sunlight and contribute to the thermal performance of buildings [21]. As a matter of fact, green roofs increase the thermal mass and thus significantly improve the dynamic thermal properties of the flat roof. As a consequence, they improve the microclimate parameters of rooms under the flat roof [22].

Green roofs and green walls can be also a desired solution where green areas are scarce [14, 23] and citizens are exposed to high levels of environmental noise. Actually, green roofs and green walls can have an impact on long-distance noise propagation in the urban environment [24-25] resulting most likely from road traffic noise [26]. Recent investments in new systems led to the assessment of their acoustic characteristics [27, 28]. It was proven that green roofs can reduce the surrounding sound by providing increased acoustic insulation to buildings envelope and absorbing sound waves diffracting over roofs [29]. The acoustic contribution of green roofs and green walls depends not only of the presence of the vegetation [30,31] but also of the system, considering its mass, impenetrability and structural insulation of the support [32]. Several studies have also proven that the types of vegetation [33], the presence of substrate and vegetation cover percentage [27] have also an influence in the acoustic contribution of these systems.

This paper aims to analyse the influence of factors such as substrate and plants, variety and height of plants and how these affect the sound absorption of a modular system (GEOGREEN) for green surfaces in simulated conditions. For this purpose, an experimental study is prepared based on four different setups tested in a reverberation chamber under similar conditions. Results refer to a comparison of sound absorption coefficients α_S versus frequency between setups. These results are also compared with the sound absorption coefficient of a conventional acoustic insulation material and with the results obtained by similar studies.

2. CHARACTERISTICS OF THE MODULAR SYSTEM FOR VEGETATED SURFACES

2.1. Composition

GEOGREEN system is based on modular elements locked together to make a continuous vegetated surface. The system can be installed vertically, horizontally or in sloped surfaces. It can be set in the envelope or interior spaces of new and retrofitted buildings. This way it accounts the design particularities of each surface for creating green roofs or green walls. The system has a simple installation process allowing manual application and individual insertion and substitution of each module [34]. The modular system allows the support of plants and substrate using waste recycled industrial materials and expanded cork.

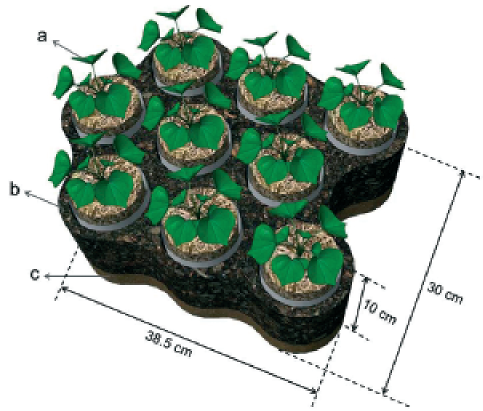

Figure 1.
GEOGREEN modular element design with plants and substrate: a. Adapted plant species; b. Upper plate in expanded cork board; c. Base plate of lightweight geopolymeric binder

Each module has 38.5 cm length, 30 cm width and 10 cm thickness, as presented in Figure 1. It consists of two layers of different materials. The bottom layer is a rigid base plate of 2 cm thickness made of mining waste-based geopolymeric lightweight binder incorporating granulated expanded cork [23]. It is produced by a curing period of 7 days at 60°C temperature in a proper mould. After curing, it shows low water absorption, low-density and good mechanical strength [35]. The upper layer consists of expanded cork board plate (ICB) obtained by CNC-cut with a bulk density in the range of 140-150 kg/m^3. The average total weight of each module including substrate and inserted plants is about 5,650 kg (divide as follows: 2.750 kg for base plate, 650 g for upper layer and 2.250 kg for soil and plants).

2.2. Thermal performance preliminary results

According to a study based on real climate tests performed in a dry mesomediterranean climate (dry and hot season, cold temperate season, large thermal gap between summer and winter seasons) the GEOGREEN system presents a good thermal performance. It attenuates the minimum and maximum interior surface temperatures up to 7°C; mitigates heat transfer, reducing the maximum incoming heat flux by 75% and maximum outgoing heat flux by 60%. Therefore it enhances the thermal insulation of external walls while increasing thermal delay between the exterior and the interior [36].

3. SOUND ABSORPTION TESTING

3.1. Modular system testing setups

The aim of this research is to identify how factors such as substrate and plants, variety and height of plants, affect sound absorption in simulated conditions. For this purpose, four different setups were prepared to be tested (see Table 1). The first consists of testing the modular elements without substrate and plants (S1). The second one includes the same modular elements containing substrate (S2). A third test was performed using the modular elements with substrate and plants with an average height of 7-8 cm (S3) (see Fig. 3). The latest has the same elements as setup S3, however, 10% of the plants with 7-8 cm high were replaced by plants with an average height of 25-30 cm (S4) (see Fig. 3). Additionally, the research aimed to establish a sound absorption comparison between the modular system and a mineral wool sample, set as a reference material (REF).

Acoustic properties testing for setups S1, S2, S3 and S4 were carried out using a surface of 25 GEOGREEN modular elements with a total area of 2.99 m^2. Mineral wool reference sample (REF) was assembled with 6 mineral wool plates with 5 cm thickness each in two layers creating a total area of 2.76 m^2. In all cases total area was calculated as a sum of upper area and lateral allowance.

Regarding setup S2, the holes in each module were filled with a conventional green roof substrate until about two thirds of its volume. This corresponds to the situation when the modules are filled with substrate but the plants are not yet grown.

The tested modular system samples positioning in the reverberation chamber is shown in Figure 2.

Table 1.
Sound absorption testing setups

Setup	Characteristics	Sample area (m^2)	Plants 7-8 cm	Plants 25-30 cm
S1	Modular elements (geopolymeric base plate + expanded cork board upper plate)	2.99	-	-
S2	Modular elements (setup S1) with substrate	2.99	-	-
S3	Setup S2 and plants (≈7-8 cm height)	2.99	100%	-
S4	Setup S2 and plants (90% ≈7-8 cm height and 10% ≈30 cm height)	2.99	90%	10%
REF	Mineral wool plates (2 layers, h=5cm each)	2.76	-	-

Figure 2.
Sound absorption testing in reverberation chamber: S1 (left); S4 (right)

Figure 3.
Sound absorption tests of modular elements with plants: S3 (left); S4 (right)

In setup S3 and S4 a diversity of 7 plant species were used, namely: *Nepeta* (Walker's Law), *Sedum cyaneum* (Stonecrop), *Sedum sediforme, Sedum sieboldii, Serum kamtchaticum, Sedum variegatum, Sedum spurium purpureum, Sedum reflexum, Serum Acre*.

Prior to sound testing the modular system samples were seasoned for a period of one week in similar climatic conditions (temperature and relative humidity) to the conditions inside the reverberation chamber.

3.2. Acoustic reverberation chamber characteristics

To determine the acoustic quality of sound absorbing products there are two popular ways among the standardized methods. Measurement of reverberation time based on the S.C. Sabin's formula in a reverberation chamber in accordance with the methodology included in ISO 354:2003 [37]. And measurement method of standing wave in impedance tube according to ISO 10534-1:1996 [38]. For this experiment the method of measuring the reverberation in a chamber was chosen.

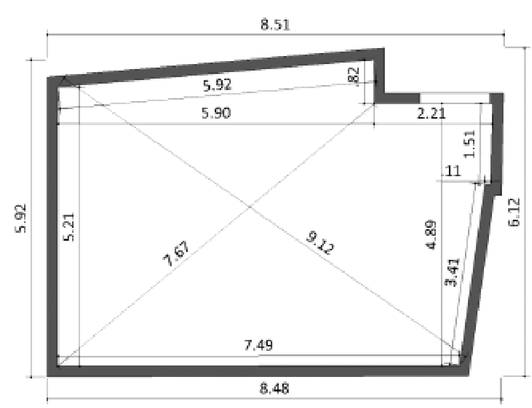

Figure 4.
Reverberation chamber floorplan

An experimental study for assessment of the sound absorption coefficient of the modular system under

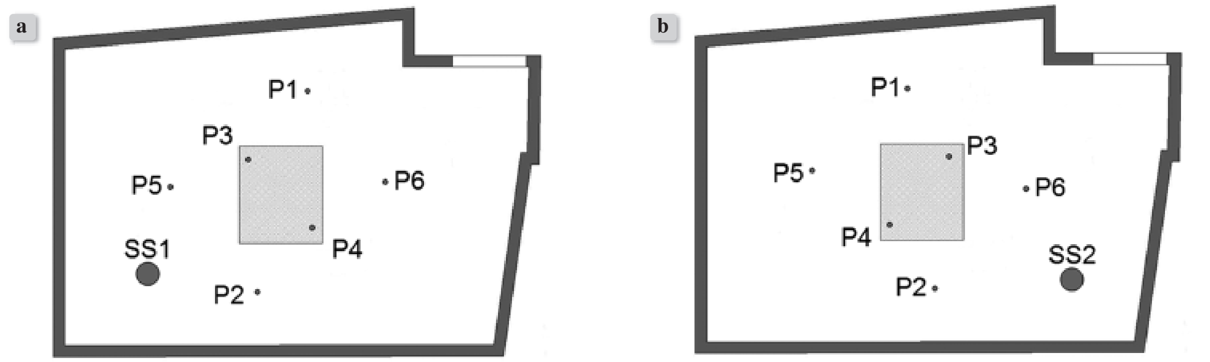

Figure 5.
Reverberation chamber scheme. Microphones positioning (P1 to P6); a) First sound source setting (SS1); b) Second sound source setting (SS2)

different conditions was developed in a reverberation chamber with a volume of 192.7 m^3 (Figure 4). The reverberation chamber follows the requirements contained in the standard ISO 354:2003 [37]. Its shape follows also the following condition:

$$I_{max} < 1.9\ V^{1/3} \tag{1}$$

where V is the volume of the chamber, I_{max} is the length of longest straight line in interior of the chamber. The materials used for finishes on walls, ceiling, and floors have very good scattering parameters. For proper diffusion of sound field inside of the chamber, nine scattering elements (partially visible on the Figure 2 as hanging boards) were used.

3.3. Instrumentation setup and sound absorption determination

According to ISO 354:2003 [37] studies can be carried out using the method of intermittent noise or impulse response integration method. The method of intermittent noise was chosen for the presented study. Table 2 summarises the instrumentation used to measure the sound absorption in the reverberation room. This includes a speaker with a spherical radiation pattern, a generator of pink noise and an amplifier to make the transmitting sound testing tracks, four channel sound level meters, used as receivers of the testing tracks, and two microphone preamplifiers as sound calibrators. All these devices fulfil the EN 61672-1:2014 standard [39].

Figure 5 schematically present the instrumentation and different setups adopted to carry the acoustic tests for assessing the sound absorption coefficient of different setups.

The samples were positioned at the centre of the chamber and the instrumentation setup positioning varies as shown in Figure 5.

Table 2.
Instrumentation for sound absorption measurements

Speaker	Sound source with a spherical radiation pattern	
Amplifier	Acoustic generator of pink noise	
Sound level meters	SVAN 958, no. 15810	
Microphones 1/2"	SV22 type, no. 4013121 and no. 0413114	
Microphone preamplifiers 1/2"	SV12L type, no. 24899 and no. 24898	Svantek
Sound calibrator	SV03A type, no. 2524	
Software	Software SvanPC Version 1.8c	
Temperature and humidity meter	Lufft T200	

The reverberation times were measured using a generator of pink noise (turned on for 12 seconds as it was considered the minimum time of sound propagation inside the chamber, to be identical or longer than the reverberation time), two speakers (SS1 and SS2) and six microphones placed on rotary columns in two starting positions (marked as a P1 to P6), 1.5m above the samples (see Fig. 5). Temperature and humidity were checked after each measurement.

The sound absorption coefficient (α_S) for each third octave band, between 0.100 kHz and 5 kHz, was determined according to UNE-EN ISO 354 standards. It results from the quotient of equivalent sound absorbing area of the measuring sample (A_T) and the sample area (S):

Table 3.
Summary of sound absorption testing results

Setup	Characteristics	α_w coefficient	Absorption class
S1	Modular elements (geopolymeric base plate + expanded cork board upper plate)	0.4 (H)	D
S2	Modular elements (setup S1) with substrate	0.55 (M H)	D
S3	Setup S2 and plants (≈7-8 cm height)	0.75 (H)	C
S4	Setup S2 and plants (90% ≈7-8 cm height and 10% ≈30 cm height)	0.8	B
REF	Mineral wool plates (2 layers, h=5cm each)	1.0	A

$$\alpha_s = \frac{A_T}{S} \tag{2}$$

$$A_T = 55.3V\left(\frac{1}{c_2T_2} - \frac{1}{c_1T_1}\right) - 4V(m_2 - m_1) \tag{3}$$

More necessary information is included in ISO 9613-1: 2010 standard [40]. The practical sound absorption coefficient α_{pi} for each octave band was also determined according to the equation:

$$\alpha_{pi} = \frac{\alpha_{i1}+\alpha_{i2}+\alpha_{i3}}{3} \tag{4}$$

The conversion of the frequency-dependent sound absorption coefficient to one number (α_w) is allowed by EN ISO 11654:1997 [41]. According to this norm the weighted sound absorption coefficient α_w is a mark of sound quality of acoustic materials.

4. RESULTS AND DISCUSSION

The sound absorption coefficient α_w and absorption class of each testing setup and the reference material are summarized in Table 3. According to ISO 11654:1997 the studied modular system for green roofs and green walls can be classified as absorbent, considering that α_w is higher than 0.15. While setups S1 and S2 are included in the absorption class D, setup S4 and S3 are included in the absorption class B and C, respectively. It is also relevant to mention that a shape indicator was added to α_w of setups S1, S2 and S3. Shape indicators inform that in some ranges the sound absorption coefficient is higher than values of shifted reference curve. In setups S1 and S3 the shape indicator H informs that the practical sound absorption coefficient α_p has exceeded the values of shifted reference curve by 0.25 in the frequency range of 2000 to 4000Hz. In setup S2 the

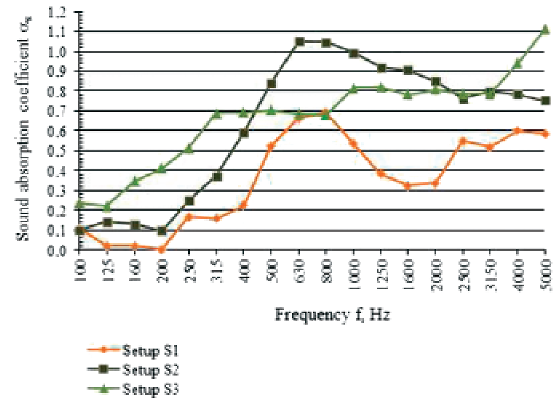

Figure 6.
Sound absorption coefficients α_S in frequency function for setup S1, S2 and S3

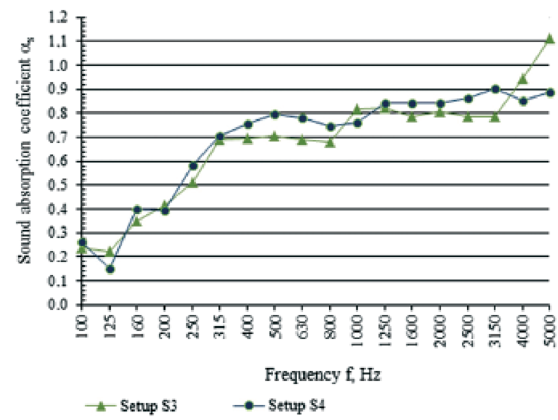

Figure 7.
Sound absorption coefficients α_S in frequency function for setups S3 and S4

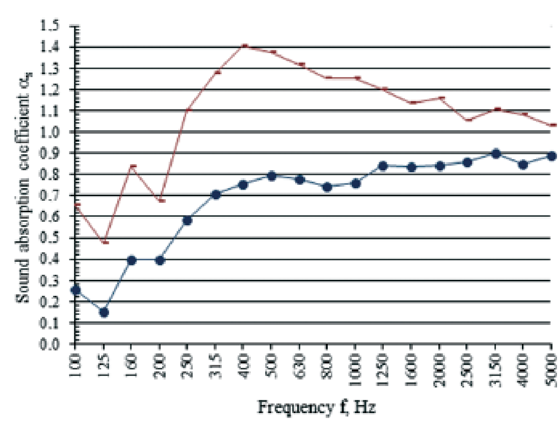

Figure 8.
Sound absorption coefficients α_S in frequency function for setup S4 and REF

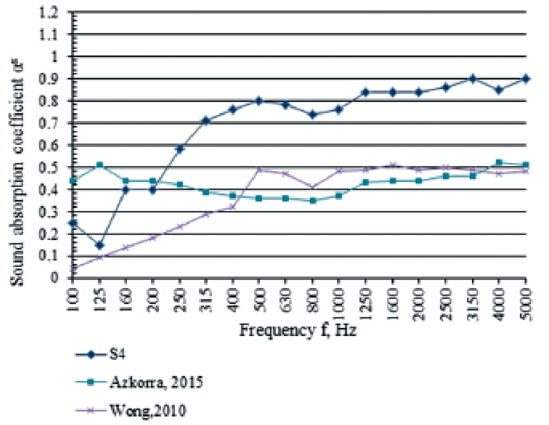

Figure 9.
Comparison of sound absorption coefficients α_s with other authors

higher than in S1, these are still decreasing from 630 Hz to 2500 Hz, like in setup S1. In relation to lower tones little improvement was achieved in S2 when compared with S1. In fact, the sound absorption coefficient α_w increased by 37% with the introduction of substrate in the modular elements, but setup S2 still remains in the absorption class D.

Finally, the results obtained for setup S3 (with plants inserted in the GEOGREEN modules) show a considerable improvement in the absorption parameters. The obtained result of a single number absorption coefficient α_w allows classifying the sample to the absorption class C. Besides, the insertion of plants indicates a significant improvement of the absorption properties in lower frequencies, when compared with the other two setups (S1 and S2).

shape indicators M and H show that the practical sound absorption coefficient α_p has exceeded the values of shifted reference curve by 0.25 in the frequency range of 500 to 1000 Hz and 2000 to 4000Hz.

4.1. The influence of substrate and plants in sound absorption

The sound absorption coefficients α_s versus frequency for setup S1, S2 and S3 are presented in Figure 6.

The GEOGREEN modular elements on their own, without any substrate and plants (setup S1) show higher values of sound absorption coefficient only in the frequency range of 630-800 Hz. In the other frequencies, either lower or higher, the sound absorption values are significantly reduced. However, its sound absorption is quite promising when compared to other cladding materials like brick, plaster or tiles, as Azkorra et al. has demonstrated [28]. It may result from the fact that the GEOGREEN system has a non-uniform top layer of expanded cork board, a highly porous material, which allows acoustic waves to be absorbed.

In setup S2 the GEOGREEN modules were partially filled with green roof substrate. This setup (S2) shows improved results of the absolute absorption coefficient values along all frequencies, when compared with S1. This demonstrates the absorbing capacities of the substrate. The results show also a smoother curve than S1 along all frequencies. However, in a similar way, the greatest values of the absorption coefficient for setup S2 were obtained for the frequency range of 630-800 Hz, reaching in this case to values higher than 1.0 (maybe due to the sample area). Although the absorption parameters are

4.2. The influence of plants variety and size in sound absorption

The comparison of results obtained in setup S3 and S4 (where 10% of 7-8 cm high plants was replaced by Sedum spectabile – Star Dust plants with approximately 30 cm high) are presented in Figure 7.

According to the results setup S4 can be classified as class B, the second highest absorption class. This indicates the acoustic potential for sound absorption of the tested setup. Setup S4, when compared to S3, shows a slight improvement of the sound absorption coefficient α_s in almost all frequencies. At the same time, the course of curve α_s for S4 is also smoother than for S3.

Although sound absorption values are similar in setups S3 and S4, it is known that vegetation development, shape and size interfere with the acoustical properties of the surface and sound absorption can increase along with vegetation density [27].

4.3. GEOGREEN potential as sound insulator

The results obtained in setups S1 to S4 were compared to a mineral wool sample (REF). Figure 8 compares the sound absorption coefficient versus frequency between setup 4 and REF. Mineral wool is known as an acoustic insulation material commonly used in construction sector to insulate buildings envelope, namely roofs and walls. This material has very good absorbing properties, obtaining a classification A as the best acoustic absorption category.

In this case REF α_w turned out to be only 20% better than S4, which indicates that S4 has potential good absorption properties. Assuming the course of an absorption curve α_s for REF, as reference, it can be noted that the general course of the absorption characteristics for sample S4 is similar to well-absorbing materials.

4.4. GEOGREEN comparison with other similar studies

Setup S4 is compared in Figure 9 with the results obtained by Wong et al. [27] and Azkorra et al. [28]. From this comparison it can be noticed that S4 is more effective than the others in higher frequencies reaching to a sound absorption coefficient of 0.8 at 500 Hz. In lower frequencies, less than 200Hz, S4 was not as sound insulator as the green wall tested by Azkorra et al.

5. CONCLUSIONS

In general, the studies for assessing the sound absorption of GEOGREEN modular system have shown it has good sound insulation characteristics, obtaining a classification as absorbent material in all setups.

The first setup, including the modules on their own (S1) obtained the lowest sound absorption coefficient (0.4). However, its results are quite promising when compared to other cladding materials like brick, plaster or tiles [28]. This may result from the fact that the GEOGREEN system has a non-uniform top layer of expanded cork board, a highly porous material, which allows acoustic waves to be absorbed.

Setup S2 demonstrates how the insertion of a low weight substrate can improve the weighted sound absorption coefficient of this system in 15%.

The impact of plants is also significant on the absorbing parameters of different tested setups. The presence of vegetation improves the parameters of sound absorption by one or even two classes. In these experiments, an improvement of 20% of weighted sound absorption coefficient (α_w) was achieved by setup S3, when compared to setup S2.

The application of an increased share of higher plants may be particularly promising in the potential of sound absorption. In this study replacing 10% of plants with 7-8 cm high by plants with 25-30cm high (S4) resulted in an improvement of 5% of its weighted sound absorption coefficient (α_w), which increased from 0.75 to 0.80. On the other hand, the variety of plants showed influence also in the absorption class, which reached a class B.

Through the comparison with other tested systems, it can be noticed that the GEOGREEN system with a variety of plants (S4) is more effective on sound absorption than the systems tested by Wong et al. [27] and Azkorra et al. [28], especially on higher frequencies, reaching to a sound absorption coefficient of 0.8 at 500 Hz.

The present study shows that the GEOGREEN system has good sound absorption properties. However, its contribution can still be improved based on the design and plants used, which can bring to new ways of further development and research directions.

Other studies have also demonstrated the noise reduction potential of green walls [27, 28, 42] and green roofs [29]. Therefore, further research can be performed to identify the actual contribution of this system to noise reduction in adjacent rooms.

Real case examples with the application of GEOGREEN elements in the external envelope of buildings. These would allow to, evaluate its performance in real conditions, considering the growth of different types of vegetation along the years.

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