EXPERIMENTAL EVALUATION OF ACOUSTIC CHARACTERISTICS OF BALE STRAW WALLS

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Résumé

Les fibres naturelles deviennent une alternative valable, à coût réduit, pour les traitements d'absorption acoustique. En effet, ces fibres présentent généralement de bonnes propriétés d'isolation et ne présentent aucun risque pour la santé. Pour isoler les bruits industriels, routiers et ferroviaires, des bottes de paille peuvent être envisagées comme matériaux d'isolation. Ainsi, cet article présente une recherche sur les caractérisations de murs acoustiques développés à partir des bottes de paille. Afin de protéger les fibres de paille et d'améliorer le comportement mécanique, une seconde variante de paroi en paille a été réalisée avec de la paille immergée dans du mortier de ciment. Les essais expérimentaux ont été menés dans un espace ouvert pour prédire les performances acoustiques et mesurer le coefficient d'absorption et le facteur de transmission. Les propriétés acoustiques sont déterminées expérimentalement pour des fréquences comprises entre 250 Hz et 4000 Hz. Les résultats montrent de très bonnes performances acoustiques pour la paroi de botte de paille, avec une absorption de plus de 70% du bruit incident pour les moyennes et hautes fréquences et un indice d'isolation atteignant 58 dB pour les hautes fréquences.

Mots clefs : réduction du bruit, fibre de paille, mur de botte de paille, mur anti-bruit, coefficient d'absorption, indice d'isolation

Abstract

Natural fibres are becoming a valid alternative to sound absorption treatments at a reduced cost. Indeed, these fibres generally present good insulation properties and present no health hazards. To insulate industrial, road traffic and railroad noises, straw bale can be envisaged as insulation materials. Thus, this paper investigates the characterizations of acoustic walls developed from straw bale. In order to protect straw fibres and improve the mechanical behaviour, a second variant of straw wall is made with bale straw immersed in the cement slurry. The experimental tests have been conducted in an open space to predict acoustic performances and measure absorption coefficient and insulation index. The acoustic properties are determined by experiments at frequency bands ranging between 250 Hz and 4000 Hz. Simulation shows excellent acoustic performances for the straw bale wall, with the absorption of more than 70 % of the incident noise for medium and high frequencies and an insulation index that reaches 58 dB for high frequencies.

Keywords: sound reduction, straw fibre, straw bale wall, noise barrier, absorption coefficient, insulation index

1 Introduction

Protection from the negative effects of the road traffic noise, and with the consideration of the ever-evolving of roads in cities, has become more and more needed. Indeed, one of the most common sources of noise pollution affecting the quality of life of residents near a road is traffic [1]. For this purpose, two solutions can be considered: (i) the improvement of the acoustic insulation of buildings and (ii) the creation of acoustic barriers. The latter is an effective solution to reduce traffic noise. A large amount of research is interested in predicting their performance and developing more effective barriers. Many researchers [1-4] determine the acoustic performance of noise barriers, basically their insulation and absorption, by in-situ measurements.

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The improvement of an acoustic barrier is essentially based on two principles: improving the acoustic performance of the materials and using new shapes.

To improve the acoustic performance of the barrier, many materials with high acoustic performance can be envisaged. Although concrete, wood, plastic or glass panels and earth berms are generally used to create noise barriers, a large number of absorbent materials made from synthetic fibres are acoustically efficient, but their use is expansive and can create environmental problems.

If the cost of synthetic products and the impact of their use on the environment and health is high, natural materials represent a very interesting alternative [5]. Among all natural materials that can be used in construction, the production of the natural fibres has a low environmental impact, a low level of emitted pollution and a low embodied energy [6]. In addition, natural fibres are characterised by a good sound insulation performances [7], and consequently, they may be considered in solution for noise control elements in a wide range of applications.

In addition to their cheap price [8], natural fibres are abundant, renewable and biodegradable [9]. Many studies have shown that natural fibres, retained from agricultural production, are acoustically similar to traditional porous materials and generally have good acoustic absorption properties at medium and high frequencies, while the acoustic absorption coefficient at low frequencies is weak [8], [10-11].

By consequence, materials such as coir, kenaf, bamboo, tea-leaf and straw fibres have been qualified as suitable as raw materials for acoustic solution [12-13].

Indeed, some research has found that tea-leaf fibre present better absorption properties than polypropylene and polyester fibre. And that compressed coconut coir fibre sheet is a high sound absorbent [8]. Oil palm fruit fibre has shown a good sound absorption coefficient for frequency 2500Hz and above [9].

Other studies conducted on straw bales building have shown that the weighted apparent sound reduction index in the range 42-53 dB.

However, many works mention that long term performance can be reduced due to the problems that may arise, such as moisture damages, fungi, parasites and fire hazards [22], [9]. Therefore, a straw treatment is recommended in order to improve its fire resistance and avoid other types of degradation.

One of the recommended treatments is the Alkali one (usually with KOH or NaOH) [23]. But also cement, with his alkaline characteristics, and its ability to reduce the amount of oxygen in the straw bale, it can improve the mechanical characteristics on the one hand, and improve the resistance to fire, fungi, parasites on the second hand. Thus, it can be used as treatment.

In this work, we are interested in the characteristics of acoustic walls developed from both treated and untreated straw bales. Thus, a treatment of straw bales is manually made with cement slurry. Then, in-situ tests are carried out to determine the characteristics of the sound reflection and the transmission of the built walls. An old and rough concrete wall, a hollow brick wall and a stone wall are considered as reference walls. For each, we associate two walls of straw of the same thickness, one treated and the other untreated.

The in-situ tests conducted in an open space allows to predict acoustic performances and to measure the absorption coefficient and the insulation index.

2 Materials

In this paper, oats straw is used. The straw bale has a dimension of 35 cm × 45 cm × 115 cm. The apparent density of the bale is about 120kg/m^3. The individual straw fibre diameter is lower than 50 mm, a cut on a straw fibre is shown in Figure 1.

The three reference walls are made from concrete, hollow brick and stone, and have thickness of 17, 19 and 45 cm respectively. In addition, six walls are constructed, three with untreated straw and three with treated one (Figures 2, 3, 4).

To build the treated straw walls, moulds with specified dimensions made out of wooden strips are constructed and cement slurry is prepared with Portland cement and water. The straw is, then, cut into the desired dimension, immersed in the slurry and then raised and fitted manually in the mould until the frame space is completely filled. The wooden frames are essential not only for constructing the wall with the right dimension but also to fix the wall during drying period in his place. After drying, the walls are ready to be used.

The used slurry is composed by one third of his weight of cement and two thirds of water. The untreated straw wall is constructed following the same procedure, but without immersing the straw in the slurry.

Figure 1: A cut on a straw fibre

Figure 2: References walls

Figure 3: Treated straw wall

Figure 4: Untreated straw wall

Table 1: The superficial density of straw walls (kg/m^2)

Thickness of wall	Untreated straw	Treated straw
17 cm	10.71	13.71
19 cm	12.35	16.85
45 cm	51.75	66.75

The superficial density of each straw wall is shown in Table 1. It should be noted that the construct process of the 17 and 19 cm thick walls, in which one is forced to open the straw bale, caused a decrease in its apparent density.

3 Method and setup

3.1 Introduction

Different methods exist to measure the acoustic characteristics of a wall, in the laboratory as well as in-situ. The results of the in-situ and laboratory measurements are generally comparable but not identical. However, many studies suggest a correlation between the two measurement methods results.

In the laboratory, sound absorption measurements are generally performed using the impedance tube method with the use of small samples.

In the case where a small sample does not represent the wall (wall of great thickness as an example), which does not allow to obtain the real characteristics, the in-situ methods remain the most adapted to obtain reliable characteristics.

For in-situ characteristics, many methods exist, and the must used method in literature is the impulse measurement methods. These methods require to measure, previously, the direct sound under free-field conditions, and to use the Fourier transformation to find the values of an equivalent real noise.

Theoretically, every method, capable of separating incident from reflected waves, can be used to measure the walls characteristics [24].

This is why, in what follows, we will determine the amplitude of the incident, reflected and transmitted waves without using the Fourier transformation. This will determine the desired acoustic characteristics.

3.2 Acoustic measurement setup

When a sound wave is incident on a wall, a part of the energy will be absorbed, another will be reflected and a part will be transmitted by the material (Figure 5).

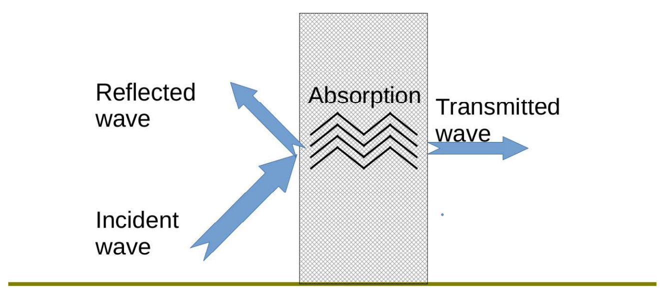

Figure 5: Sound wave paths in the presence of a wall

The acoustic performance of this wall is mainly determined by its acoustic insulation and its acoustic absorption. In fact, a good acoustic insulation permit to minimize transmission of sound through the wall, and a good acoustic absorption permit to minimize reflection of sound at the wall.

Absorption and insulation can be characterized by the absorption coefficient and the insulation index, which characterizes the material of each wall.

To determine the characteristics of the straw-based walls, in-situ measurements of sound reflection and insulation were performed.

The sound tests are carried out using an acoustic system comprises of a "BEHRINGER C-1U" omnidirectional microphone, a commercial loud speaker and a decibel meter application in the computer by the measurement of the sound intensity in a series of points as shown in Figure 6 for absorption test, were three positions for the microphone are chosen between the source and the wall.

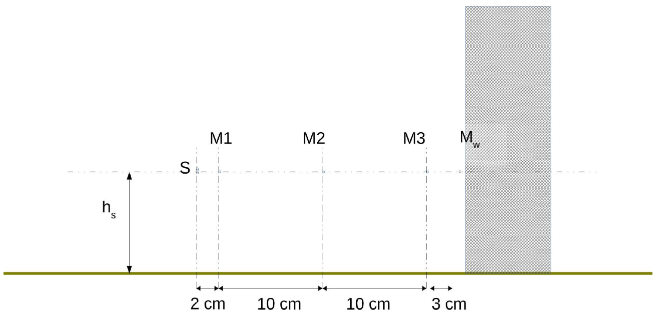

Figure 6: A schematic diagram of the measurement setup for absorption test.

For insulation test, two points are considered, one just before the wall and the other just behind (at 1 cm of the wall) as represented in Figure 7.

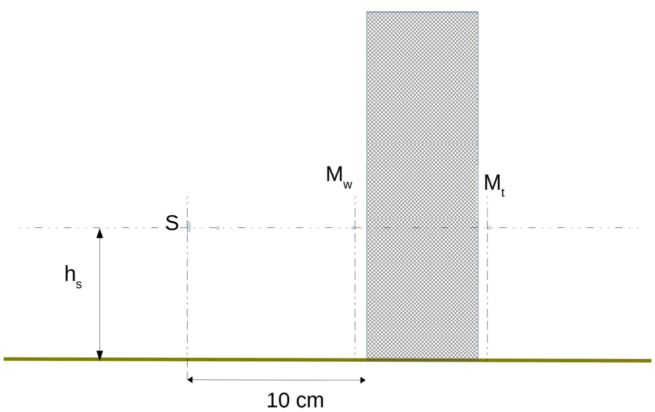

Figure 7: A schematic diagram of the measurement setup for transmission test.

All measurement points are in the same horizontal axis, located at a height h_s.

Low frequencies (250 Hz), lower middle (500 Hz), upper middle (1000 Hz), and high (2000 and 4000 Hz), were selected to be generated via the sound source. Using the microphone, we measure the incident noise, the background noises, transmitted noise and reflected noise by the wall.

For this in-situ octave band analysis, we assume that different sounds arriving at a point of measurement combine incoherently. The very small uncertainty, obtained in the results, between different measurement points, confirms this hypothesis.

Considering by I_i the sound intensity at the receiver location, the sound intensity level, L_I, is defined as in equation 1 ([25]).

$$L_I = 10\ Log_{10}\left(\frac{I_i}{I_0}\right) \quad (1)$$

Where I_0 represents the reference intensity, $I_0 = 10^{-12}$ Wm^{-2}.

Thus, in a point M_i before the wall, we have a combination of different sound intensities: the background intensity I_{b_i}, the direct intensity I_{d_i} the reflected intensity I_{r_i} and the ground-reflected intensity I_{g_i}.

The background intensity

The value of the incident intensity level is obtained by considering the measurement positions in a location free of reflections coming from nearby walls, and the background noises will be noted in all the measurement positions. For the rest of the paper, the value of the incident intensity will designates the measured value of the incident intensity with subtraction of the value of the background intensity.

The direct intensity

Incident intensity I_{in} can be written as the sum of direct and reflected from the ground intensities. Since at each point M_i, the ground-reflected intensity is closely related to the direct intensity, we can write the following relation:

$$I_{in_i} = Q_i I_{d_i} \quad (2)$$

Where Q_i is a correction factor which depends on the frequency of the sound, and the height of the point M_i from the ground.

In a location free of reflections coming from nearby walls, a first series of measurement, where the height of the measurement axis is varied, has been carried out. The figures 8 and 9 show that from a height of 65 cm, the effect of the ground becomes negligible.

Thus, using the equation 3, we can calculate the Q factor at any measuring point before the wall (for 45 cm of height). The results are shown in the Table 2.

$$Q_i = \frac{10^{\left(\frac{L_{I_i}}{10}\right)}}{10^{\left(\frac{L_{I_{i0}}}{10}\right)}} \quad (3)$$

Where $L_{I_{i0}}$ represents the sound level without ground effect (i.e. to a height of 85 cm) and L_{I_i} the sound level at the height of 45 cm.

Two remarks are noted: the first is that the values for the point M_1 are very close to 1, what is expected as the point is near the source. The second remark is that for points far away from the source, the values are greater than 3, this is due to the type of sound source that is not omni-directional.

The correction factor Q_i calculated, the equation 3 will be used to calculate the direct intensity and eliminate the soil effect.

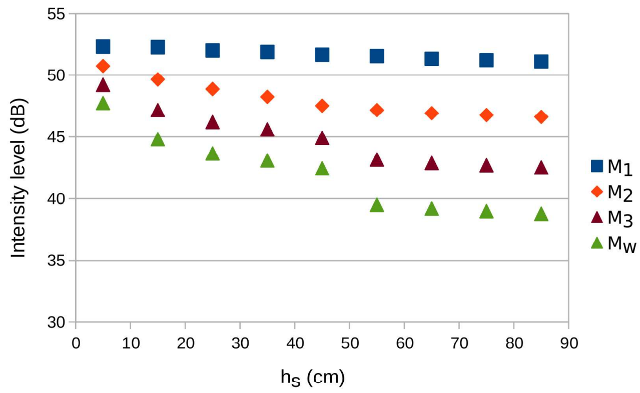

Figure 8: Effect of the ground-reflection in the intensity levels for 250 Hz.

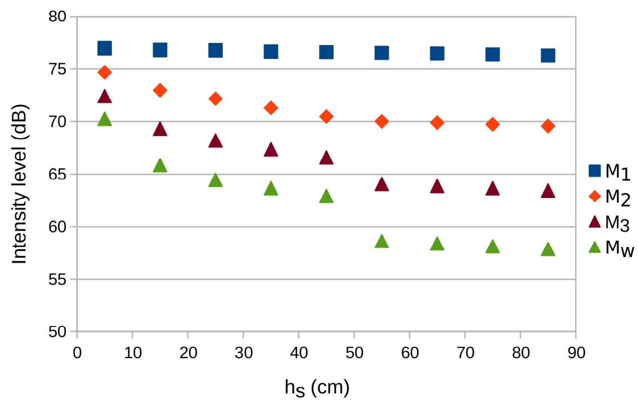

Figure 9: Effect of the ground-reflection in the intensity levels for 4000 Hz.

Table 1: Correction factor for different frequencies.

Frequency	M_1	M_2	M_3	M_w
250	1.133	1.233	1.737	2.328
500	1.153	1.264	1.840	2.534
1000	1.134	1.264	1.948	2.819
2000	1.115	1.259	2.026	3.044
4000	1.074	1.229	2.063	3.210

The reflected intensity

Between the source and the wall (whose characteristics are to be measured), we measure the sound level L_{I_i}. The effect of the ground reflections is assumed similar to the incident recordings (without wall). Thus, the subtraction of the two intensities should give the reflected intensity. The reflected intensity is deduced as shown in equation 4.

$$I_{r_i} = I_0(10^{(\frac{L_{I_i}}{10})} - 10^{(\frac{L_{b_i}}{10})} - 10^{(\frac{L_{in_i}}{10})}) \quad (4)$$

Where L_{b_i} is the background intensity level and L_{in_i} is the incident intensity level.

The sound absorption is calculated using the equation 5

$$\alpha = 1 - \frac{I_r}{I_d} \quad (5)$$

With I_r and I_d are the reflected and direct intensities at the surface of the wall (measurement point M_w). If I_d can be directly measured at the surface of the wall, the reflected intensities at the surface of the wall must be calculated using the recorded value at one point from M_1, M_2 and M_3 and using the equation 6 :

$$R_{r_i}^2 \cdot I_{r_i} = R_r^2 \cdot I_r \quad (6)$$

Where R_{r_i} represents the distance covered by the sound from source to the point M_i after reflection, and R_r is the distance between the source and the wall.

The transmitted intensity

The sound transmission factor τ of a wall is defined as the ratio of the two sound energies: transmitted by the wall to the incident upon the wall.

So, the transmission factor can be approximated using the equation 7,

$$\tau = \frac{I_t}{I_{d_w}} \quad (7)$$

With I_t is the transmitted intensity deduced from the intensity level measured in the point M_t behind the wall, and I_{d_w} is the direct intensity at the point M_w before the wall.

The insulation index R can be defined as:

$$R = 10\ Log_{10}\left(\frac{1}{\tau}\right) \quad (8)$$

Or more simply written directly as a function of the sound intensity level as:

$$R = L_{d_w} - L_t \quad (9)$$

4 Sound absorption measurement

4.1 The absorption factor

The intensity levels of sound at the various points in a free field without walls, and for different walls are measured. For the same frequency, the same sound intensity was used for all the walls. Raw data is available from the authors upon request.

The average of the measured level of background noise is 19.88 dB with a variation of no more than 0.9% throughout the tests.

The variation of the absorption coefficients as a function of the frequencies are plotted in the figures 10, 11 and 12. For all the walls, and for all the considered frequencies, the variations of the absorption coefficient between the three measurement points are lower than 0.8% in all cases.

The obtained results indicate that, like all natural fibres, treated and untreated straw have excellent acoustic absorption coefficients, especially at medium and high frequencies. We also note that the absorption coefficient of treated and untreated straw walls has very similar values. It is concluded that the effect of straw treatment on the absorption coefficient is minimal.

For low frequencies, the absorption coefficients of all walls, including reference walls, are very low. Indeed, the absorption coefficients are around 0.1 for the reference walls and 0.15 for the straw.

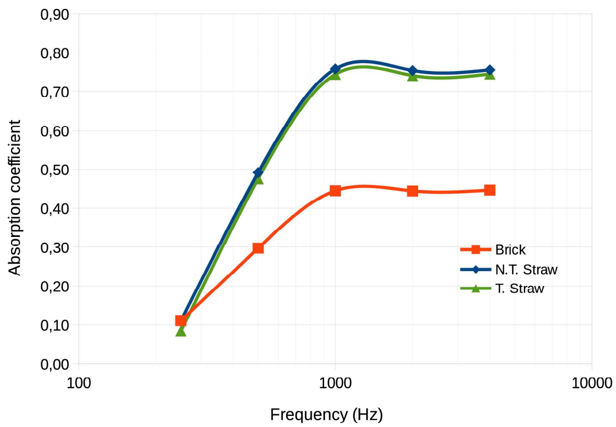

Figure 10: Absorption factor for 17 cm walls.

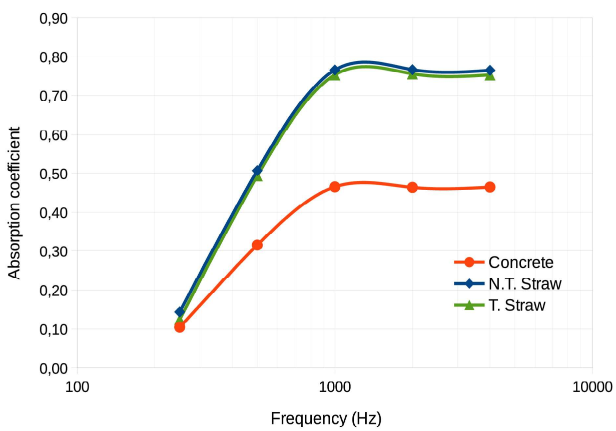

Figure 11: Absorption factor for 19 cm walls.

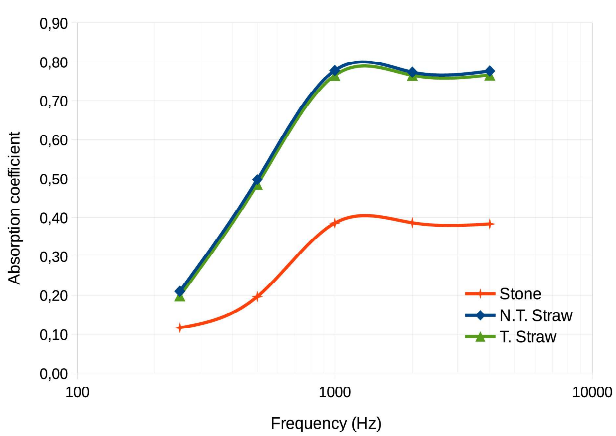

Figure 12: Absorption factor for 45 cm walls.

For the medium and high frequencies, the obtained results show that the absorption coefficient of the straw walls is much higher than that obtained for the reference walls. These last are characterized by a sound absorption coefficient which varies between 0.2 and 0.47 depending on the frequency and type of walls, while all values of the absorption coefficient of straw walls are greater than 0.5 for all frequency greater than 500 Hz. So, the obtained results show that, as all natural fibres, treated and untreated straw has excellent acoustic absorption coefficients at medium and high frequencies. Note that the obtained values for the concrete wall are very high compared to what is usually found in the literature; this is due to the degraded and rough state of the surface of the concrete wall.

The results of sound absorption measurements carried out on the straw by [10] using the impedance tube method are presented in the Figure 13. This last shows an identical shape curve to that obtained in this study. Contrariwise, values obtained in this study are lower than those obtained in [10]. In fact, if the curve of the Figure 13 shows a sound absorption value equal to 0.25 at 250 Hz, a peak value greater than 0.95 at 1200 Hz and reachs a value of 0.9 for 2000 Hz. The values obtained in this study varied from 0.1 to 0.3 for 250 Hz, show a peak value slightly lower than 0.8 for 1200 Hz and reach a value of 0.75 between 2000 Hz and 4000 Hz.

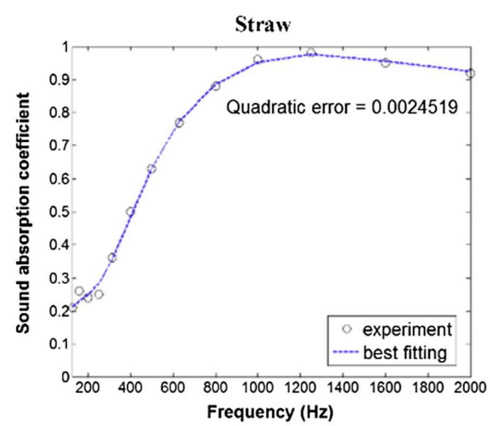

Figure 13: Sound absorption coefficient for straw [10].

4.2 The insulation index

Three measurements are considered for each frequency and in each point to calculate the insulation index *R*. The Figures 14, 15 and 16 show the insulation index for the different walls.

The experimental results indicated that at low frequency (250 Hz), the insulation index value was about 25 dB for the 19-cm-thick straw wall.

The insulation index values were higher for middle (f=500-1000 Hz) to high frequencies (> 1000 Hz). Thickest straw walls had a higher *R* value than other walls. The *R* value was greater than 25 dB, and it achieved a maximum of approximately 56 dB at a frequency of 4000 Hz for 19-cm-thick wall and 58 dB for of 45-cm-thick wall.

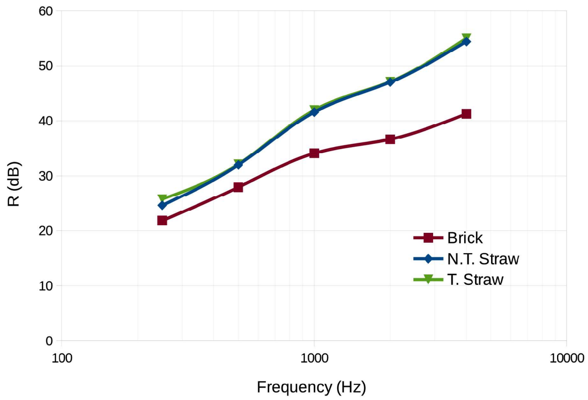

Figure 14: Transmission factor for 17 cm walls.

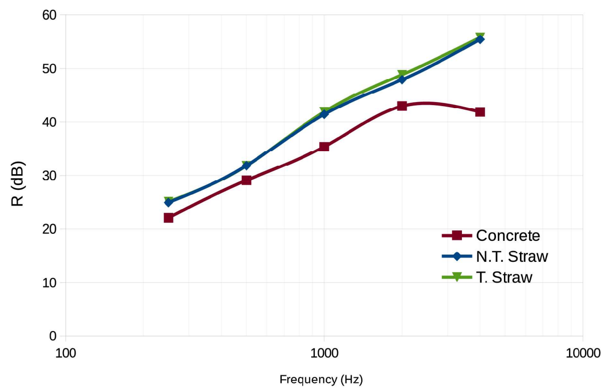

Figure 15: Transmission factor for 19 cm walls.

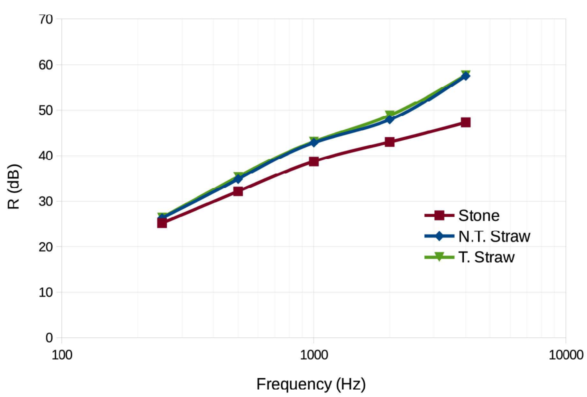

Figure 16: Transmission factor for 45 cm walls.

For low frequencies, the value obtained, although low, remains higher than that of the reference walls. For the frequency range between 1000 and 4000 Hz, differences with reference walls values in the range 5-13 dB are noted. We note that the effect of the thickness of the straw walls is small.

Similarly, we note also that the effect of the treatment of straw on the insulation index is negligible.

Compared to the reference walls, the straw walls are characterized by a higher insulation index. A difference that varies, depending on the frequency, between 4 and 14 dB with brick, 3 and 14 dB with concrete and 1 and 10 dB with stone.

5 Conclusion

In this paper, in-situ experimental tests have been conducted to study the acoustic properties of straw bale wall. Untreated and treated straw fibres are considered. The straw treatment is made with immersing straw in the cement slurry.

Through experiments at frequency ranges between 250 Hz and 4000 Hz, absorption coefficient and insulation index are determined. Experiences show that the acoustic behaviour of straw walls is similar to the known behaviour of vegetable fibres described in the literature.

We also find good acoustic proprieties with an absorption coefficient which reaches 0.8 and a value of insulation index which reaches 58 dB. So, the observed acoustic characteristics for the straw walls are much better than those of the considered reference walls.

Finally, we can see that the treatment of straw has a minimal effect on sound properties. Thus, treated or not, the bale straw walls absorb most of the sound and transmit only a small part of the absorbed sound.

All these properties can make straw walls, a good choice for as an acoustic barrier, essentially for its low cost, low environmental impact and acoustic performance.

References

[1] A. Lacasta, A. Penaranda, I. Cantalapiedra, C. Auguet, S. Bures and M. Urrestarazu, Acoustic evaluation of modular greenery noise barriers, *Urban Forestry & Urban Greening,* 20, 2016.

[2] W. Schwanen, In-situ testing of acoustical properties of noise barriers, *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, Institute of Noise Control Engineering, 2016.

[3] F. Koussa, J. Defrance, P. Jean and P. Blanc-Benon, Acoustic performance of gabions noise barriers: numerical and experimental approaches, *Applied acoustics*, 74, 2013.

[4] G. Watts, Acoustic performance of parallel traffic noise barriers, *Applied Acoustics*, 47, 1996.

[5] M. H. Fouladi, S. Y. Peng, S. Y. Wen, P. Z. Xin, M. J. M. Nor, M. A. M. Saleh and T. C. Seng, Replacement of synthetic acoustic absorbers with natural fibers, *ASME 2012 International Mechanical Engineering Congress and Exposition*, American Society of Mechanical Engineers, 2012.

[6] J. P. Arenas and M. J. Crocker, Recent trends in porous sound-absorbing materials, *Sound & vibration,* 44, 2010.

[7] X. Zhu, B.-J. Kim, Q. Wang and Q. Wu, Recent advances in the sound insulation properties of bio-based materials, *BioResources,* 9, 2013.

[8] X. Tang and X. Yan, Acoustic energy absorption properties of fibrous materials: A review, Composites Part A: *Applied Science and Manufacturing,* 101, 2017.

[9] N. Zunaidi, W. Tan, M. Majid and E. Lim, Effect of physical properties of natural fibre on the sound absorption coefficient, *Journal of Physics : Conference Series*, IOP Publishing, 2017.

[10] U. Berardi and G. Iannace, Predicting the sound absorption of natural materials: Best-fit inverse laws for the acoustic impedance and the propagation constant, *Applied Acoustics,* 115, 2017.

[11] U. Berardi and G. Iannace, Determination through an inverse method of the acoustic impedance and the propagation constant for some natural fibers, *INTER-NOISE and NOISE-CON Congress*

and Conference Proceedings, Institute of Noise Control Engineering, 2015.

[12] C. M. Helepciuc, Utilization possibilities of some cereal plant wastes in the constructions domain, in the context of available crops in romania-a review, *Buletinul Institutului Politehnic din lasi. Sectia Constructii, Arhitectura* 62, 2016.

[13] U. Berardi and G. Iannace, Acoustic characterization of natural fibers for sound absorption applications, *Building and Environment*, 2015.

[14] E. Milutiene, K. Jürmann and L. Keller, Straw bale building - reaching energy efficiency and sustainability in northern latitudes, *Proceedings of the 11th international conference on solar energy at high latitudes "North Sun*", 2007.

[15] S. Dance and P. Herwin, Straw bale sound insulation: Blowing away the chaff, *Proceedings of Meetings on Acoustics ICA2013, ASA,* 2013.

[16] C. J. Whitman and D. F. Holloway, Improving energy efficiency and thermal comfort of rural housing in chile using straw bale construction, *Second International Conference on Sustainable Construction Materials and Technologies*, Universitá Politecnica della Marche, Ancona, Italy, 2010.

[17] D. M. CANTOR (ANDRES) and M. Daniela Lucia, Using wheat straw in construction, *ProEnvironment Promediu,* 8, 2015.

[18] K. Bäcklund, Bamboo and wheat straw as a green building composite material, *Master's thesis,* Chalmers University of Technology, Göteborg,Sweden, 2011.

[19] A. Mansour, J. Srebric, B. Burley, Development of straw-cement composite sustainable building material for low-cost housing in egypt, *Journal of Applied Sciences Research,* 3, 2007.

[20] Y. S. Tjahjono, J. J. Sudjati, F. Binarti and C. E. Mediastika, Acoustic wall panels constructed from paddy-straws, *Jurnal Arsitektur KOMPOSISI*, 9, 2011.

[21] M. Saadatnia, G. Ebrahimi and M. Tajvidi, Comparing sound absorption characteristic of acoustic boards made of aspen particles and different percentage of wheat and barely straws, *17th World Conference on Nondestructive Testing*, 2008.

[22] B. Zahra, G. Morten, I. Nigel and W. Sam, Agricultural by-products for the production of building insulation in new zealand, *51st International Conference of the Architectural Science Association*, Architectural Science Association, 2017.

[23] D. B. Dittenber and H. V. GangaRao, Critical review of recent publications on use of natural composites in infrastructure, Composites Part A : *Applied Science and Manufacturing,* 43, 2012.

[24] G. Muller and M. Moser, Handbook of engineering acoustics, Springer Science & Business Media, 2012.

[25] C. H. Hansen, Fundamentals of acoustics, Occupational Exposure to Noise: Evaluation, Prevention and Control. World Health Organization, 2001.

[26] F. Asdrubali, S. Schiavoni and K. Horoshenkov, A review of sustainable materials for acoustic applications, *Building Acoustics,* 19, 2012.

[27] F. Asdrubali, S. Schiavoni and K. Horoshenkov, A review of sustainable materials for acoustic applications, *Building Acoustics,* 19, 2012.

[28] I. Ekici and H. Bougdah, A review of research on environmental noise barriers, *Building Acoustics,* 10, 2003.

[29] J. M. N. Mohd, J. Nordin and M. T. Fadzlita, A preliminary study of sound absorption using multi-layer coconut coir fibers, *Technical Acoustics,* 4, 2004.

[30] M. N. Yahya, M. Sambu, H. A. Latif and T. M. Junaid, A study of acoustics performance on natural fibre composite, *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 2017.

[31] Y. Zhong, U. Kureemun, T. L. Q. Ngoc and H. P. Lee, Natural plant fiber composites-constituent properties and challenges in numerical modelling and simulations, *International Journal of Applied Mechanics,* 9, 2017.

[32] F. D'Alessandro, S. Schiavoni and F. Bianchi, Straw as an acoustic material, *24th International congress on sound and vibration ICSV24*, London, 2017.

[33] F. D'alessandro, F. Bianchi, G. Baldinelli, A. Rotili and S. Schiavoni, Straw bale constructions: Laboratory, in field and numerical assessment of energy and environmental performance, *Journal of Building Engineering,* 11, 2017.