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STRAW AS AN ACOUSTIC MATERIAL

Francesco D'Alessandro

University of Perugia, Department of Civil and Environmental Engineering, Perugia, Italy
email: francesco.dalessandro@unipg.it

Samuele Schiavoni and Francesco Bianchi

University of Perugia, Department of Engineering, Perugia, Italy

The use of straw bales in construction is not as old as one may suppose. The first straw bale houses date back to the invention of the baling machine at the end of the 19th century and were built in Nebraska. After a long period of abandon, this construction technique was rediscovered in the 70s and since then it has significantly evolved, gaining attention among both self-builders and professionals. The huge amount of straw available worldwide can turn this material into a very interesting resource for the building sector. Nevertheless the absence of certified or reliable technical data discourages engineers and architects to use it. This paper aims at investigating the acoustic properties of straw bale constructions. The first section reports a brief summary about straw bale constructions and their energy and environmental performance. Then the state of the art of the acoustic properties is presented in more detail. Normal incidence sound absorption coefficient of loose straw is measured using a two microphone incidence tube in accordance with ISO 10534-2. Five and seven centimetres thick samples with different water contents were investigated. A limited variation of sound absorption with water content was noticed. Lastly the results of a façade sound insulation test on a real straw bale wall are reported. The tested wall resulted to be a poor sound insulator, especially at low frequencies, because of the low mass of the structure.

Keywords: straw, sound absorption, sound insulation, sustainability, green building

1. Introduction

Straw is a residue of cultivation of several types of cereal plants. According to cereal production data released by FAOSTAT, 3.5 gigatonnes of straw are available per year, which are mainly used in agriculture and farming. Other minor applications are paper manufacturing, bioenergy production and building.

Straw, alone as an insulator of roofs or mixed with clay or mud to create bricks, just as other natural materials [1, 2], has been used since the very first buildings constructed by the mankind: thousands of years ago Egyptians, Sumerians, Babylonians and other civilizations used straw to reinforce clay bricks [3]. However the actual birth of straw constructions can be traced to the end of the 19th century, when European settlers in the Sandy Hills region of Nebraska started to build temporary shelters with the only material available in the area, i.e. straw bales. When they realized that straw shelters were comfortable enough both in winter and summer they decided to plaster the walls and temporary shelters became real houses [4]. After a long period of abandon, straw bale houses are now gaining new attention from scientists, professionals and also from a substantial number of self-builders, who are fascinated by the sustainability and environmental friendliness of this construction technique.

Straw bale houses can be built in several ways, but the most used techniques are the Nebraska style and the post and beam system. In Nebraska style constructions straw bales are the structural elements supporting the roof. This building method, being very simple, is the preferred choice for self-builders, but it is not accepted in countries with strict building codes (for instance in Italy), which do not include straw bales in the list of admissible structural materials. On the other hand in the post and beam infill system the structural function is given to a wooden or metallic frame and straw bales are used to fill the walls. Usually two-strings (size 35x40x100 cm) or three-strings (size 70x100x200 cm) bales are used in the building sector, with density in the range 80 – 180 kg/m^3 [5].

A major issue when approaching for the first time straw bale buildings is the absence of certain and reliable technical data about fire resistance, mould resistance, hygro-thermal and acoustic performance. This is caused by supply channels. While traditional building materials are bought from manufacturers or sellers and come with detailed technical data sheet, straw bales are usually purchased from local farmers, who have no idea of the technical performance of their straw. Furthermore technical characteristics of straw bales are strongly influenced by a number of variables, such as the cereal type (wheat, rice, barley, etc.), desiccation process, baling process and moisture content. So engineers and architects have to face serious problems when designing straw bale constructions in order to predict the actual performance of the building.

Analysing scientific literature and technical reports one can see how variable are data reported from the different sources. For instance thermal conductivity of straw bales can vary from 0.038 to 0.120 W/mK depending on the density, the water content and heat flux orientation [6, 7]. One of the main concerns of builders when working with straw is fire, but straw bales have proven to achieve very good values of fire resistance, since the greatest part of the combustive agent, i.e. oxygen, is removed during the compression of the bales [5]. Fires can occur during construction if loose straw, which is highly flammable, is left on the ground. So the worst enemy of straw bales is not fire, but it is water: fungi and moulds can proliferate quite easily if moisture content of the bales becomes too high. Also in this case univocal indications are missing: some scientists affirm that decomposition of straw begins with values of moisture content higher than 25% [5], other indicates 14% as a limit [8], still others have observed that degradation stops when the nutrients of moulds and fungi are reduced [9]. As far as the acoustic properties, a state of the art will be presented in the following section.

Finally, the European Energy Performance of Building Directive 2010/31/EU requests all new buildings to be NZEB (nearly zero energy buildings) by the year 2020. Considering the entire life cycle of a building, energy consumptions during the operating phase will decrease significantly and embodied energy will became a fundamental parameter for selecting construction materials [10]. Natural materials, in particular those cultivated locally as straw, can represent a valuable alternative to the traditional ones, as they limit transportation impacts: for instance, the embodied energy of straw is 0.3 MJ/kg against about 87.0 MJ/kg and 16.6 MJ/kg for polystyrene and mineral wool, respectively [11].

2. State of the art of the acoustic properties of straw

People living in straw bales houses generally affirm that straw bale walls are extremely effective in insulating noise from outside [12]. However most straw bale houses are detached buildings located in the countryside, where environmental noise is not such an issue. Actually, research aimed to evaluate the real performance of straw bale houses is quite limited.

As mentioned in the previous section, straw is commonly used pressed in bales and included in a wooden or metallic frame; then the bales are covered with a thick layer of plaster on both sides of the wall. So straw bale walls, though usually 50 cm thick or more, are very lightweight since they are made only of straw (usually 45 cm thick, density 80–180 kg/m^3) and plaster (usually earthen or lime plaster 4-8 cm thick, density 800-1500 kg/m^3).

Dance et al. collected the results of some laboratory and field tests of 45 cm straw bale walls: a comparison with the current requirements in different European countries shows that the majority of the tested walls do not meet the criteria regulating wall and façade sound insulation [12]. In addition they observed that sound insulation was particularly poor at low frequencies; this result could be expected considering the low weight of the structure.

Dalmejer [13] reported the results of a test on a plastered straw bale wall performed according to ISO 140-3: he found a weighted sound reduction index R_w of 53 dB, which is a rather good result. However the fact that the test was performed on a small sample (1.9 m^2 instead of 10 m^2 required by the standard) could have overestimated the sound reduction index.

One of the few official test reports available on line is the one released by the Building Physics Laboratory of the Municipality of Wien for Gruppe Angepasste Technologie (GrAT) of the Technische Universität Wien [14]. The test results are shown in Table **1**.

Table 1: Results included in the test report of Building Physics Laboratory of the Municipality of Wien.

Number	Configuration	R_W (C; C_{tr}) [dB]
1	• 9 cm three-layered cross-laminated spruce plates	33 (-1; -4)
2	• 9 cm three-layered cross-laminated spruce plates • 50 cm straw bale (density 120 kg/m^3)	48 (-2; -9)
3	• 9 cm three-layered cross-laminated spruce plates • 50 cm straw bale (density 120 kg/m^3) • 5 cm vertical battens • 2.2 cm spruce plates	53 (-4; -12)
4	• 9 cm three-layered cross-laminated spruce plates • 50 cm straw bale (density 120 kg/m^3) • 4 cm clay plaster with jute net	55 (-3; -10)

Tests performed by DELTA laboratories [15], Deverell et al [16] and Wall et al. [17] on several configurations of straw bale walls resulted in values of weighted sound reduction index in the range 44 – 52 dB.

Figure 1 reports the results of several tests performed on straw bale walls. It is an updated version of the plot included in [12]. Values expressed in terms of sound reduction index R were converted in standardized level difference D_{nT} according to EN 12354-1 in order to obtain comparable data. All the tested samples are plastered 45 cm straw bale walls (with density 120-130 kg/m^3), apart from the item "D_{nT} Wien" that refers to configuration n. 4 of Table 1.

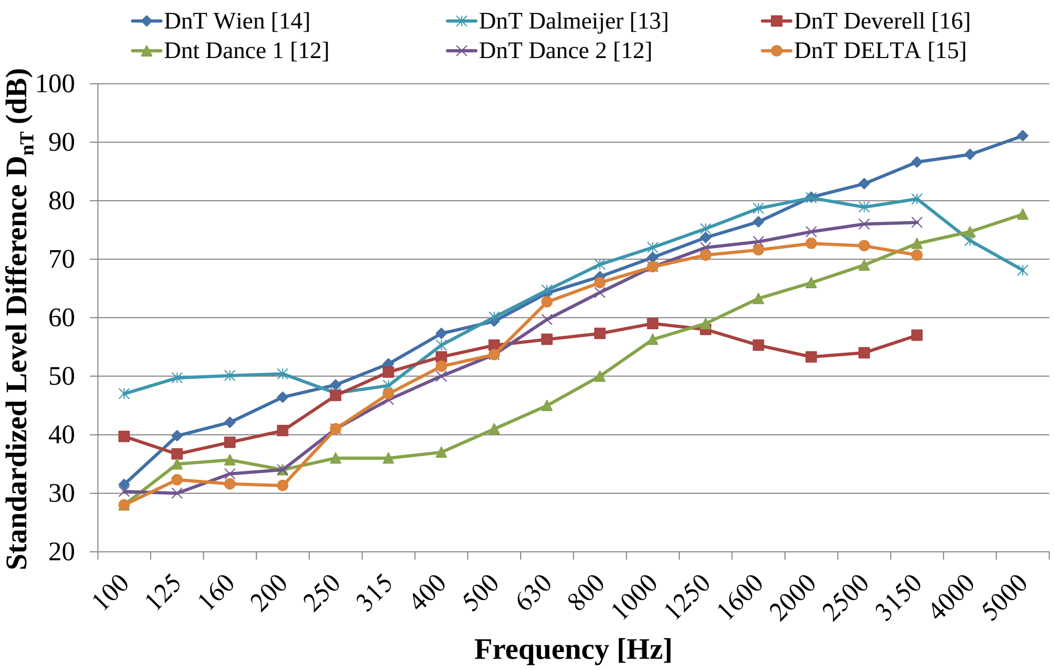

Figure 1: Collection of the results of several field and laboratory tests performed on straw bale walls.

The wall tested by Dalmejer [13] has the best performance at low frequencies, while other walls show a dip around 200 Hz and have quite low performance at low frequencies. Wall n.1 tested by Dance [12] and the one tested by Deverell [16] seems affected by constructive defects, whereas the remaining four walls follow almost the same trend from 200 to 2000 Hz.

Moving to sound absorption of straw bales or of loose straw, authors are not aware of studies that have investigated this issue, apart from a paper of the authors themselves [18].

3. Sound insulation

3.1 Description of the tested wall

A field sound insulation test was performed on the façade of a building located in central Italy, built using the post and beam infill system. The frame was made of fir and the straw bales were 45 cm thick and 80 kg/m^3 dense (Figure 2a). An earthen plaster mixed with straw was used both outdoor and indoor, and an additional layer of natural hydraulic lime was laid on the external façade. The thickness of the wall is 51 cm. The blind façade was tested (Figure 2b).

Figure 2: a) Picture shot during construction; b) tested façade in red.

3.2 Methodology

The descriptors commonly used to characterize a façade in terms of its sound insulation are the standardized level difference $D_{2m,nT}$ and the corresponding single number quantity $D_{2m,nT,w}$. Test were performed according to ISO 140-5, which was later replaced by ISO 16283-3. Further details about measurement procedures can be found in [19]. The global method prescribed by the standard was used, using a directional loudspeaker (Lookline FL01) fed with pink noise as sound source (Figure 3a). Reverberation time of the receiving room was measured with the interrupted noise method in compliance with ISO 354, using an omnidirectional loudspeaker (Lookline DL301, Figure 3b). Signals were acquired using a four channel Sinus Soundbook. Receiving room contained unused building materials which could have influenced the test.

Figure 3: a) Façade sound insulation and b) reverberation time measurements.

3.3 Results

Figure 4 reports the results of the of the façade sound insulation test; the values of the apparent sound reduction index R' calculated from the standardized level difference $D_{2m,nT}$ according to EN 12354-3 are also reported.

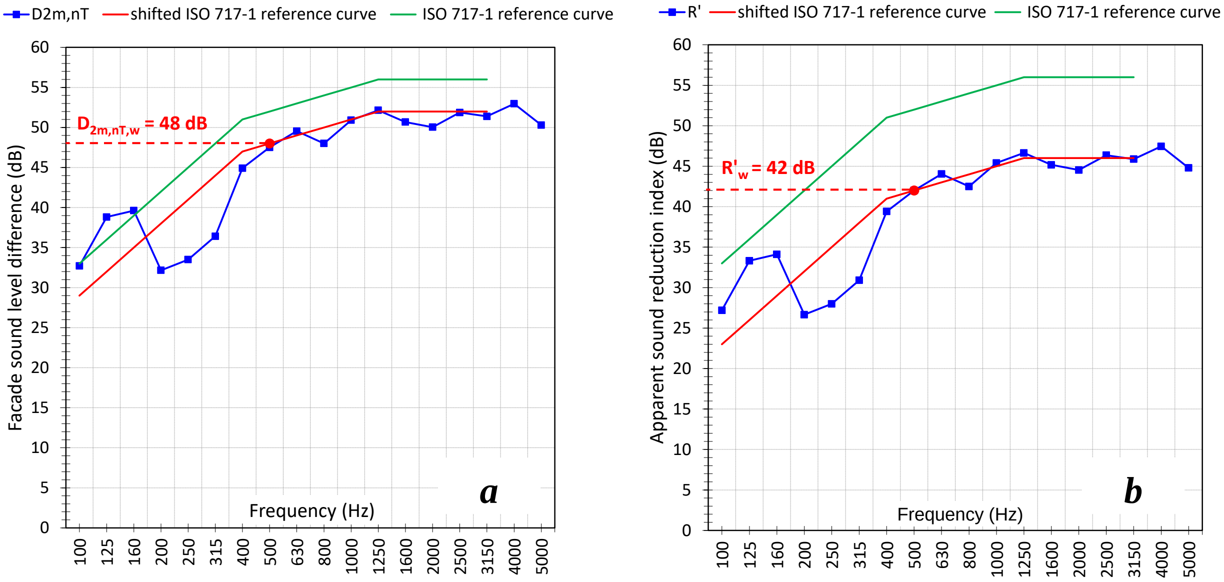

Figure 4: a) Measured façade sound level difference; b) calculated apparent sound reduction index.

The performance of the tested straw bale wall resulted to be quite poor ($D_{2m,nT,w}$ = 48 dB). This is confirmed by the calculated value of the weighted apparent sound reduction index (R'_w = 42 dB). However values reported in Figure 4 seem to underestimate the real sound insulation of the tested wall, at least at medium-high frequencies: these results may be attributable to the presence of a ventilated floor, to the presence of old and weak windows on the other facades of the room and, in general, to the poor installation quality. Nevertheless, as already observed in other straw bale walls (Figure 1), also in this case the dip at 200 Hz is clearly recognizable.

4. Sound absorption

4.1 Description of the tested samples

Given the impossibility of testing the bale with the impedance tube, loose straw was cut and poured inside the sample holder of the impedance tube; then straw was pressed in order to reach a density value of about 55 kg/m^3. Reaching higher values of density was not possible without binding the straw with wires.

4.2 Methodology

Normal incidence sound absorption coefficient was measured according to ISO 10534-2 in a two microphones Bruel & Kjaer 4260 impedance tube placed in vertical configuration. The 100 mm diameter sample holder was used, which allowed to obtain results in the frequency range 50 - 1600 Hz. The small tube configuration was not used since it would have required cutting the straw into too small pieces. Further details about impedance tube measurements and porous material characterization can be found in [20]. Before each test, samples were conditioned by means of a climatic chamber and the water content was measured with the gravimetric method using a precision scale. Further details about conditioning of the samples are reported in [18]. Each test was repeated three times by emptying and refilling again the sample holder with straw and the results were then averaged. Measurements of 5 cm and 7 cm thick samples with variable water content were performed.

4.3 Results

Figure 5 reports the results of the impedance tube tests performed on samples of loose straw. Sound absorption coefficient is expressed in one third octave bands for each value of water content.

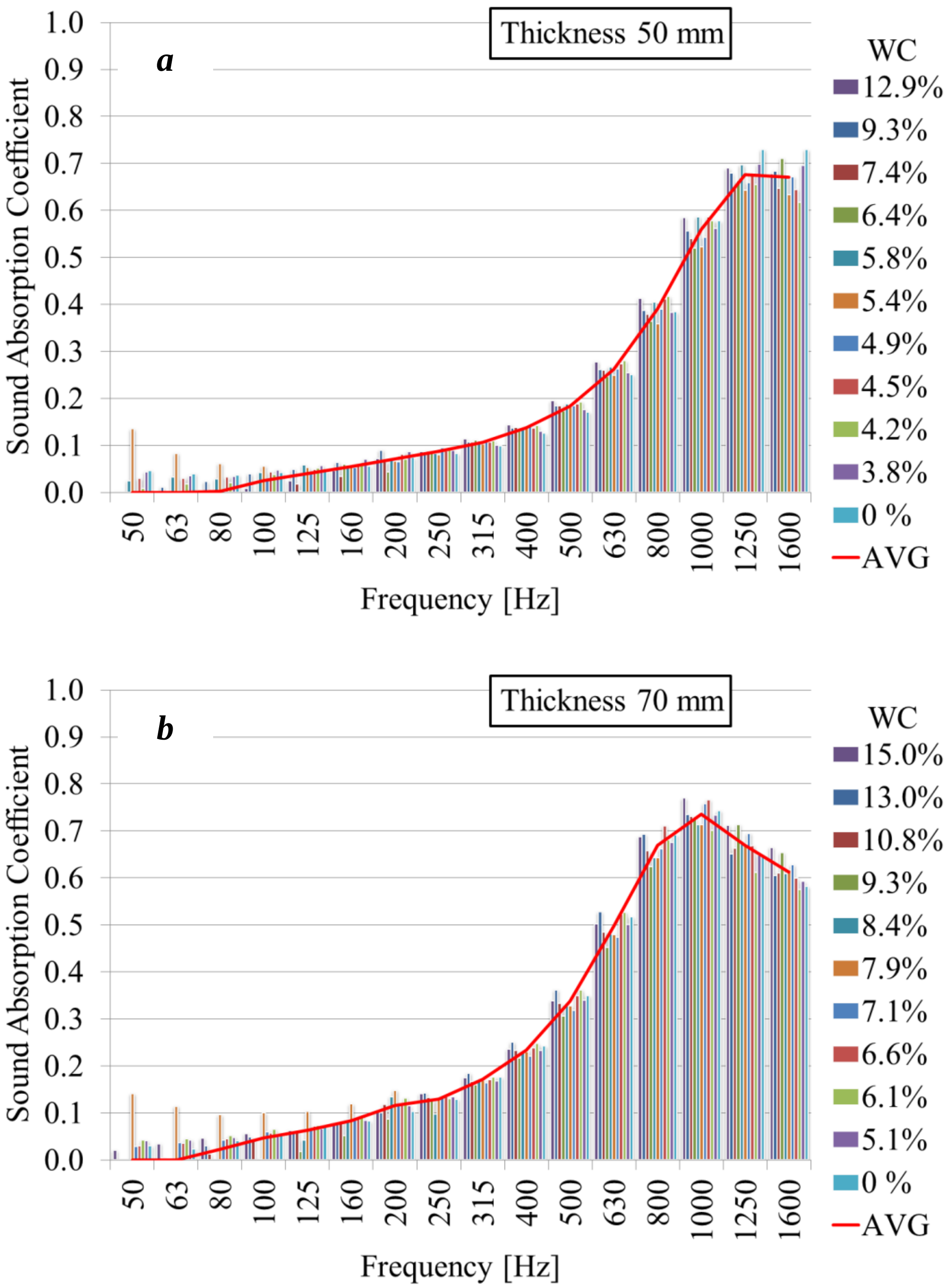

Figure 5: Normal incidence sound absorption coefficient of loose straw for various water contents: a) 50 mm thick sample; b) 70 mm thick sample.

For each test the corresponding value of the Sound Absorption Average (SAA) was evaluated. According to ASTM C423, SAA is the average of diffuse field sound absorption coefficients for the one-third octave frequency bands with nominal mid-band frequencies of 200 Hz to 2500 Hz. In this case tests were performed at normal incidence and up to 1600 HZ; nevertheless SAA values were calculated in order to make a comparison between all obtained results with a single number descriptor. Values of SAA for the tested samples are shown in Figure 6.

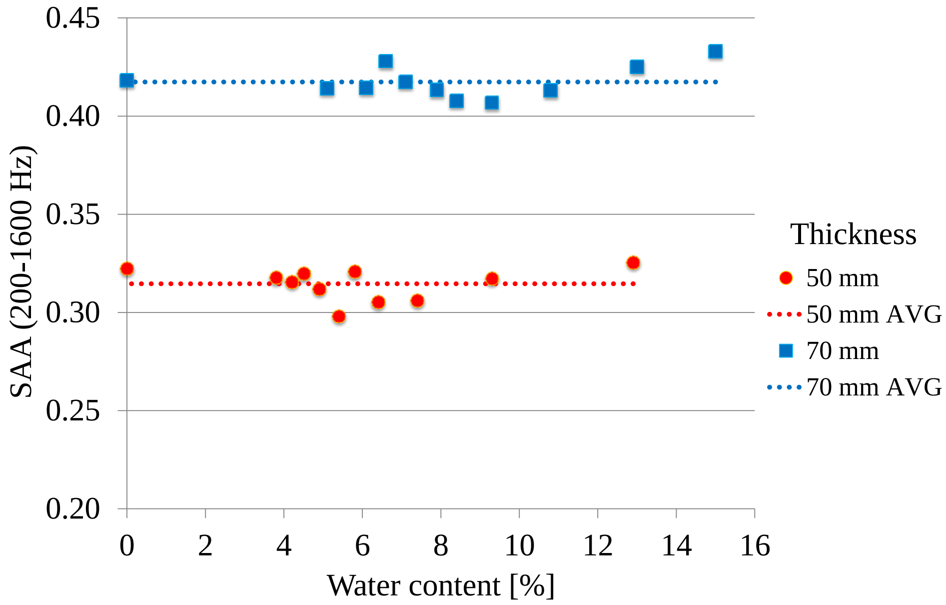

Figure 6: SAA vs water content for the tested loose straw samples.

Loose straw can be considered as a porous material. Therefore the sound absorption coefficient increases with increasing values of thickness. SAA in on average equal to 0.31 and 0.42 for 5 and 7 cm samples, respectively. As far as water content, it seems to have no significant influence on the sound absorption properties of straw: SAA values are randomly scattered in a very narrow range both for 5 cm and 7 cm samples (Figure 6).

5. Conclusions

The results of a façade sound insulation test on a plastered straw bale wall and of normal incidence sound absorption tests of loose straw with variable water content were reported in this paper.

In agreement with other studies [12], sound insulation performance of the tested wall resulted to be rather poor, especially at low frequency, with an evident dip at 200 Hz. Building defects and the presence of a ventilated floor could have affected the wall performance at medium-high frequency. Common straw bale walls (made of 45 cm straw bales plastered on both sides with 3-4 cm of lime or earth plaster) appear to be not as acoustically efficient as many self-builders or other experts in straw buildings claim: the reason of this belief may be found in the fact that the overwhelming majority of existing straw bale houses are detached buildings located in the countryside. Although they are rather thick, straw bale walls are lightweight structures if compared with traditional concrete or masonry walls; furthermore they can be hardly regarded as double walls, i.e. mass-spring-mass systems, because of the thinness of plaster layers, which should act as masses of the system. Addition of massive layers could be a possible improvement of straw bale walls. This would help to increase the sound reduction index and could be beneficial also for thermal insulation. Indeed straw bales can be considered excellent thermal insulators in the winter season, mainly because of the large thickness, while summer performance is definitely worse: the light weight of the structure results in values of the periodic thermal transmittance that do not guarantee thermal comfort and that can lead to overheating [6].

Sound absorption is less interesting for current applications. The sound absorption coefficient of loose straw resulted to be quite low in comparison to common sound absorbing materials (mineral wool, foams, etc.) and to other natural materials too [21], mainly because of the size of straw which does not allow to obtain high values of open porosity. Tests also showed that sound absorption of loose straw is almost completely independent from water content.

In conclusion, it can be affirmed that common plastered 45 cm straw bale walls are usually not sound insulating enough for fulfilling the acoustic requirements of building codes and that sound insulation performance depend greatly on how carefully the wall is built. Nevertheless straw, especially if harvested locally, has extremely low environmental impact and embodied energy, and its amount is almost infinite.

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