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AIRBORNE SOUND INSULATION OF A NOVEL ENVIRONMENTALLY FRIENDLY STRAW WALL

D. Mannina[1*] **G. Pilloni**[2] **M. Depalma** [3]
C. Scrosati [3]
[1] Acustica Mannina, Via Pietro Teuliè 20, 20136 Milano, Italy
[2] GP Project, Palazzo N3 - Strada 6, 20089 Rozzano, Italy
[3] Construction Technologies Institute of the National Research Council of Italy CNR-ITC, Italy

ABSTRACT[*]

The building demand for environmentally friendly materials has led to develop new systems such as ”Pablok”, a panel made up of a wood platform frame, insulated with compressed straw and covered with a gypsum fiber board, applied to the wall or the deck. Straw is the inedible stalks, especially of certain species of grain, chiefly wheat, rye, oats, and barley. Unlike hay, which is used as a forage, straw does not attract mice or insects and does not rot unless wetted. The sound reduction index in laboratory was measured for a wall 39.25 cm thick with a wall lining with CW profile-single layer cladding for a total thickness of 46.5 cm. The study shows the airborne sound insulation measured in laboratory and in situ and compares the results with a software prediction.

Keywords: *straw wall; environmentally friendly materials; airborne sound insulation; acoustic performance estimation.*

1. INTRODUCTION

The European Union aims to be climate-neutral by 2050 – an economy with net-zero greenhouse gas emissions. This objective is at the heart of the European Green Deal and in line with the EU’s commitment to global climate action under the Paris Agreement [1].

Globally over the next 80 years due to the population increase, the world will have to build over 2 billion new homes. This will place significant future strains on materials supply and resources in the coming decades and is likely to focus governments and public sector to amend future planning requirements to increase the density of new housing per site.

A key component of the net-zero delivery [2] is the compatibility between the future changes and improvements in energy performance of buildings and well-being of occupants [3] and the other key building regulations, such as fire resistance, sound insulation and structure. A further dimension will be carbon reduction objectives for both the selection of construction materials and the low or zero carbon heating systems adopted [4].

Therefore, the building demand for environmentally friendly materials has led to develop new systems such as ”Pablok”, a panel made up of a wood platform frame, insulated with compressed straw and covered with a gypsum fiber board, applied to the wall or the deck.

Straw is a natural, renewable and biodegradable material, which is already grown in many areas, making it easy to find, and which requires little processing from when it is harvested to when it is used. Having a low incorporated carbon content, it is a material that lends environmental impact of new building infrastructures [5].

This paper presents the preliminary evaluation of the airborne sound insulation of the straw panels “Pablok”, both in laboratory and in situ, as well as an estimation of the airborne sound insulation of the façade.

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[*] ***Corresponding author**: info@mannina.it*

2. MATERIAL AND METHOD

This study was carried out on a prefabricated wall panel “Pablok” with a wooden structure, thermo-acoustic insulation of pressed straw and cladding on one side in wooden planks and on the opposite side in fiber gypsum board.

A two-phase test was carried out in the Acoustic laboratory. The first phase to evaluate the performance of the “Pablok” panel alone. Then, the second phase to evaluate the “Pablok” panel plus a detached self-supporting wall lining.

The study continued with an estimation of the airborne sound insulation of the facade $D_{2m,nT,w}$ according to EN ISO 12534-3 - Estimation of acoustic performance of buildings from the performance of elements - Part 3: Airborne sound insulation against outdoor sound. For this evaluation the sound reduction index, R_w determined in laboratory was used.

Finally, the facade insulation on site was measured.

2.1 Platform Frame

The “Pablok system” can be considered a platform frame system.

This constructive system differs from all the previous ones in that it has the possibility of being used in prefabricated systems. The boxes used are generally covered and can be placed empty, partially or totally filled. Although equipped with a coating, this construction technology is often considered load-bearing, but does not always guarantee structural capacity. Thanks to its prefabricated structure, this system guarantees various advantages:

- Flexibility, speed and adaptation to the work: they are laid in a very short time and can be modeled on the basis of the work to be built or the lifting means available on site.
- Possibility of using completely dry systems: the coating is also generally used dry, avoiding the use of plasters which, due to the drying period, lengthen the construction site times of the system.
- Possibility of introducing insulating materials that can respond to thermal, acoustic and environmental sustainability needs.
- The particularity of the prefabrication of the caisson system reduces the ease of installation that has characterized straw systems up to now, forcing the use of special means of transport and lifting.

Once the panels arrive on site, they are assembled according to a particular technique, which is currently the most used for prefabricated wooden structures: "Platform Frame". It consists of a system in which each floor of the building serves as a platform for the subsequent floors. Since construction takes place one floor at a time, and each floor is used as a base for the construction of the walls of the next, which are fixed directly above the cladding of the same, safety during the construction phases also increases considerably. For this technology, foundations made with reinforced concrete slabs are generally used.

Figure 1. Platform construction system

2.2 Technical characteristics of the straw

Being a waste from the cereal harvest, straw is easy to find.

It can be pressed to form panels on whose surface sheets of paper treated with waterproof resin are placed. The straw is pressed and packaged in different sizes and the types used for building use are spelt, rye straw and wheat. Thanks to the fibrous composition full of cavities, straw has the density of about 120 kg/m^3.

2.2.1 Stem orientation

The properties of straw buildings are also conditioned by the different positioning of the stalks inside the bales. In particular, the thermal conductivity of these elements mainly depends on two factors: the density of the bale and the orientation of the fibers inside it. Thermal conductivity increases when the fibers have been oriented horizontally and decreases when they are oriented vertically. This happens mainly for two reasons: variation of the air volume and heat flux path. If we consider the fibers arranged horizontally, the heat flow passes parallel to them through the bale and only the air affects the resistance. If they are arranged vertically instead, not only the air, but also the straw fibers affect the resistance of the bale. During the packaging process it is therefore essential to pay particular attention to how the fibers are oriented, as this factor significantly affects the final thermal conductivity [6].

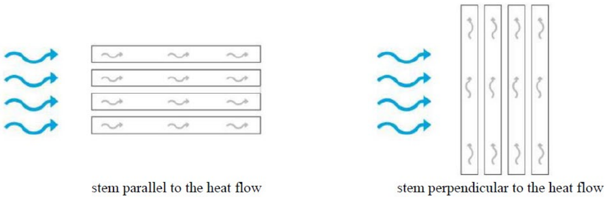

Figure 2. Stem orientation

2.3 Acoustic insulation

From the first studies conducted on a straw system, covered with a layer of plaster, some interesting results can be taken into account. Straw can be considered a good acoustic insulator thanks to the high presence of pores and micro-pores inside it and the mass it is equipped with. Generally, the layer of plaster with which it is covered internally and externally plays a fundamental role in the soundproofing power of the straw partitions. The combination of the two different materials, the plaster layer as a rigid element and the straw as a layer with a good mass, arranged alternately, create an acoustic decoupling and make the wall an excellent acoustic insulator.

Moreover, the direction of the straws within the bale can affect the sound insulation. In a test carried out on two straw partitions with different straw orientations, the first positioned perpendicular to the wall plane and in the second parallel, the result obtained with perpendicular orientation was 6 dB higher than the one obtained with the parallel orientation of the fibers. [7].

2.4 The Pablok system

Pablok is mainly based on the use of two different panels: Pablok Wall, or the panel used for vertical closures, and Pablok Roof, which completes the structure, being used for the construction of the roof. The prefabricated panels are made through the application of pre-compressed and pre-treated straw bales, inserted inside the frames of uprights and transoms in laminated wood, completed externally by fiber plaster board 12.5 mm thick. The use of biological materials, the prefabrication and the completely dry structure guarantee, in addition to the high thermal, acoustic, structural and seismic performances, extremely short construction times. The decision to use completely natural and eco-sustainable materials has also made possible to almost completely reduce CO_2 emissions and to allow energy savings of 80% less than that of traditional buildings.

This paper will focus, in particular on the system applied to the wall.

3. RESULTS

3.1 Laboratory test

The airborne sound insulation measurement tests were carried out at the CNR-ITC laboratory.

The test was carried out in two phases: in the first phase, the Pablok wall alone (base wall) was tested; in the second phase a self-supporting wall lining was installed on the receiving room (internal side), insulated with 40 mm of rock wool with a density of 70 kg/m^3 and covered with a 12.5 mm fiber gypsum board.

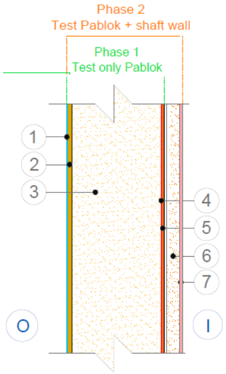

Figure 3. Stratigraphy of Pablok Wall (base wall) with the self-supporting wall lining

The stratigraphy of the wall, both phases, shown in **Figure 3**, is a follow:

1. Highly breathable membrane Rothoblaas TRASPIR 150 breathable sheet (150 g/m^2);
2. 20 mm thick fir tongued planking – 150 mm wide;
3. Filling of the frame with natural compressed straw insulation 360 mm thick;
4. Vapor barrier screen with Rothoblaas Vapor 150 membrane (150 g/m^2);
5. Plasterboard 12.5 mm, apparent specific weight 1150 ± 50 kg m^3;

6. NaturBoard Silence Knauf rock wool (density 70 Kg/m^3 thickness 40 mm);
7. Fiber gypsum board 12.5 mm, apparent specific weight 1150 ± 50 kg m^3.

3.1.1 Phase 1 – Test of Pablok wall alone

In the following figures, the layers of the Pablok base wall are shown. In **Figure 4** the straw filling of the wooden structure, in **Figure 5** the external side with wooden planking, in **Figure 6** the internal side with fiber gypsum board planking and in **Figure 7** the installation of the self-supporting wall lining insulated with 40 mm of rock wool.

Figure 4. Wooden structure with straw filling

Figure 5. External side cladding with wooden planking

In **Figure 8** the sound reduction index R of the Pablock base wall is shown (blue line). The negative peack at 3150 Hz is typical of fibre gypsum plaster board. The weigthed sound reduction index R_w is 48 (-2;-5) dB.

Figure 6. Internal side cladding with fiber gypsum board planking

Figure 7. Installation of the self-supporting wall lining on the receiving room (internal side), insulated with 40 mm of rock wool

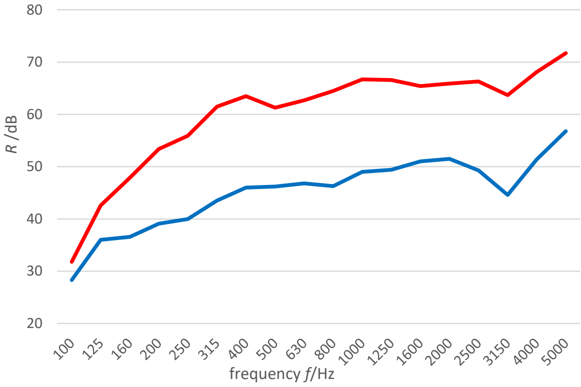

Figure 8. Sound reduction index of Pablok base wall (blue line) and Pablok base wall + self-supporting wall lining (red line).

3.1.2 Phase 2 – Test of Pablok wall with wall Lining

For the second phase, a self-supporting wall lining was installed on the receiving room (internal side), insulated with 40 mm of rock wool with a density of 70 kg/m^3 and covered with a 12.5 mm fiber gypsum board.

In **Figure 8** the sound reduction index R of the Pablock base wall with the self-supporting wall lining is shown (red line). It is noticeable here the same negative peack at 3150 Hz, as found in the case of the basic wall alone. The weigthed sound reduction index R_w is 63 (-5;-12) dB

3.1.3 Comparison with literature results

Dance and Herwin [8] found that straw walls could perform as well as, but sometimes worse than, conventional constructions, due to poor performance at low frequencies. In their study they analysed nine laboratory and field sound insulation test reports and two tests done by themselves. They found that all of the 450 mm straw bale field sound insulation tests seems to show a shared coincident dip at around 125 Hz to 200 Hz.

The same deep was found in the Pablok base wall (blue line in **Figure 8**), at 160 Hz. This deep at low frequencies is not present in the case of Pablok wall with the self-supporting wall lining. This confirms that the self-supporting wall lining is a good solution to improve the performance of the base wall also in the low frequencies range.

Another interesting study was performed in Portugal by Marques *et al.* [9] on walls made from rice straw bales. They performed tests on a bare base wall, made of only straw bales and on this wall with different coating: wall solution 1 with lime mortar on both sides, wall solution 2 with gypsum plasterboard on both sides and finally a wall solution 3 with OSB (Oriented Strand Board) on both sides.

These solutions are comparable with Pablok base wall, which is a hybrid solution: one side coated with 20 mm thick wooden planking and the other side coated with a 12.5 mm thick gypsum plaster board.

The straw bale wall solutions with gypsum plasterboard and OSB coatings show similar trends. The first drop in sound insulation at 125 Hz (160 Hz for Pablok) of the wall solution with gypsum plasterboard may be attributed to the mass–spring–mass resonance frequency. After this frequency, a significant sound insulation recovery occurs for both board coating solutions. The second significant drop in sound insulation is caused by the frequency coincidence effect of these board coating solutions. The coincidence effect occurs when the wavelength of the sound waves projected on the exterior wall panels equals the wavelength of guided waves travelling along the wall panels, which leads to increased movement of the panel and thus causes low sound insulation. The generation and propagation of these guided waves is less evident in the presence of lime plaster coatings. This coincidence effect is the same in the case of Pablok which showed the same deep at 3150 Hz, as wall solution 2 and 3 with gypsum plasterboard and OSB coatings respectively.

Table 1 Weighted sound reduction index R_w literature and present value of straw bale walls.

Type of wall	Weighted sound reduction index R_w (C;C$_{tr}$)/ dB
Wall solution 1 (lime mortar) [9]	51 (-1;-3)
Wall solution 2 (gypsum plasterboard) [9]	49 (-2;-6)
Wall solution 3 (OSB) [9]	47 (-1;-3)
Pablok	48 (-2;-5)
Pablok + self-supporting wall lining	63 (-5;-12)
Straw bale with clay plaster both sides [11]	54
Clay plaster /straw bale wall / 40mm airgap + 58 mm ekopanel [11]	57
Clay plaster /straw bale wall / 40mm airgap + 15 mm Wolf PhoneStar Tri boards [11]	57

The weigthed sound reduction index of these solution are comparable with the results found for Pablok (**Table 1**). The weithgted sound reduction index value of Pablok 48 dB is exactely in the middle between wall solution 2 (49 dB) and wall solution 3 (47 dB), confirming on the one hand that the value found in ITC laboratory are comparable with value found in other laboratories [10], on the other hand that this hybrid straw wall (wooden planking and gypsum plaster board) is a middle ground between these solutions.

Teslík et al. [11] mesured n laboratory a straw bale partition wall in different configurations. The highest values they found (R_w = 57 dB) were obtained with the straw bale wall plastered on one side and with 40mm airgap and a 58 mm Ekopanel or a 15 mm Wolf PhoneStar Tri boards on the other side.

3.2 Software prediction

Following the laboratory tests, we wanted to evaluate whether the evaluation software available on the market gave values comparable with the results obtained. For this purpose, the INSUL software version 9.0.20 was used.

INSUL predicts the transmission loss of double panel systems in 4 different frequency regions [12, 13, 14]:

In region 1 at low frequencies the transmission loss is determined primarily by the mass law. The TL increases at 6 dB/octave but INSUL can account for the inefficient radiation of low frequencies. In region 2, above the mass-air-mass resonance frequency of the partition (f_0) determined by the mass of the panels and the air gap, the TL increases at 18 dB/octave as the two sides become decoupled. In region 3, when the cavity width becomes comparable to a wavelength at frequency fl the cavity modes couple the panels together and the TL increases at 12 dB/octave. And finally, in region 4, solid connections act as sound bridges between the two panels and the TL is limited to a constant amount above the mass law, and increases at only 6 dB/octave.

In **Figure 9** the laboratory values have been compared with the calculated data

It can be seen that the predicted curve for the Pablok panel has a trend similar to that measured in the laboratory. Moreover, in both cases it is noticeable the same negative peak at 3150 Hz. The software underestimates the laboratory values at low-medium frequencies, while overestimates them at higher frequencies.

The values obtained with the prediction software INSUL for Pablok base wall plus the self-supporting wall lining shown an overestimation too high to be considered reliable, respect to the measured data, starting from medium frequencies up.

It is then possible to say that this software cannot be used in this case because it gives an overestimation that cannot be justified.

The single number quantities obtained with the prediction software is comparable with the results obtained in laboratory. The prediction software recommends to subtract 3 dB from the value obtained to take into account the onsite installation. As we are comparing the values obtained with the laboratory values, this cautionary subtraction was not taken into account.

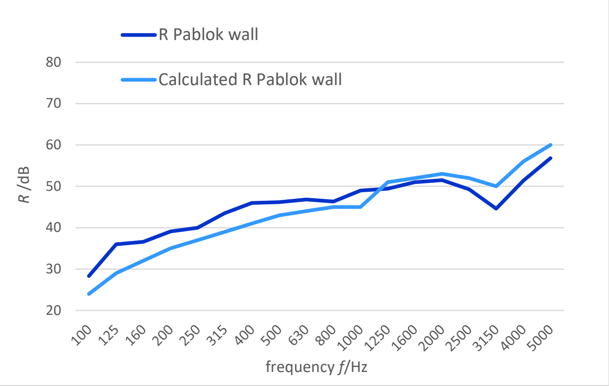

Figure 9. Pablok base wall comparison of the sound reduction index in laboratory (blue) and calculated with the prediction software INSUL (light blue).

The software values are $R_w = 46$ (-2;-6) for the base wall and $R_w = 67$ (-6;-14) for the base with the wall lining. The former is 2 dB lower that the value measured in laboratory while the latter is 4 dB higher, confirming that the software overestimates this second case.

3.3 On-site measurements and comparison with the evaluation method

The last analysis was carried out in order to compare the laboratory data with the system with a similar stratigraphy installed on site.

Before carrying out the on-site measurements, according to standard ISO 16283-3, the evaluation calculation of the façade sound insulation was carried out according to standard ISO 12354-3, in a room used as a warehouse without windows. The room has a volume of 51 m^3 and a facade area of 7.2 m^2.

The wall tested on-site is similar to the wall tested in laboratory: the Pablok base wall + self supporting wall but installed on the other side respect to the one tested in laboratory. The thickness of the Pablok base wall is higher: 40 cm on-site instead of 36 cm in laboratory. The self supporting wall has an additional 3.5cm air gap.

The standard EN ISO 12354-3 provides an equation that correlates the standardized level difference $D_{2m,nT}$ and the apparent sound reduction index R':

$$D_{2m,nT} = R' + \Delta L_{fs} + 10\log\frac{V}{6T_0 S} \qquad (1)$$

where ΔL_{fs} is a corrective term that takes into account the façade shape, V is the volume of the receiving room,

T_0 is the reference value of the reverberation time and S is the surface of the test element. For a plain façade ΔL_{fs} is equal to 0 dB, while for dwellings T_0 is equal to 0.5 s. R' is obtained from the laboratory measurement by the following formula:

$$R' = \left(-10\lg\left(\sum_{i=1}^{n} \tau_{e,i} + \sum_{f=1}^{m} \tau_{f} \right) \right) \mathrm{dB} \qquad (2)$$

Where the direct transmission is given from:

$$\tau_{e,i} = \frac{S_i}{S} 10^{-R_i/10} \qquad (3)$$

Where R_i is the sound reduction index of element i, in decibels and S_i is the area of element i, in square metres. Considering the small differences of the on-site wall, and to stay on the safe side (taking into account the measurement uncertainty [10]) for the calculation we used the sound reduction index obtained in laboratory.

The sound power ratio τ_f for flanking transmission by element f follows from the summation of the flanking transmission factors for all flanking transmission paths to that element. In most case, it is not necessary to calculate the contribution of flanking transmission. To be on the safe side, it would be sufficient in the cases with rigid elements to incorporate flanking transmission in a global way by reducing the sound reduction index for this type of rigid, heavy façade elements; subtracting 2 dB is normally sufficient. Therefore, for the present calculation we subtracted 2 dB to take into account the onsite flanking transmission.

The evaluated single number quantity of the façade sound insulation of this wall is $D_{2m,nT,w} = 64$ dB.

Measurements of façade sound insulation were performed according to Standard ISO 16283-3. In particular, the global method prescribed by the Standard was followed, using a directional loudspeaker as sound source. The standard defines the level difference D_{2m} as following:

$$D_{2m} = L_{1,2m} - L_2 \qquad (4)$$

where $L_{1,2}$m is the sound pressure level measured 2 m in front of the façade and L_2 is the average sound pressure level measured inside the receiving room. Then, the level difference is “standardized” by introducing a correction term that considers the reverberation time measured in the receiving room T, and a reference reverberation time T_0, which is equal to 0.5 s for dwellings:

$$D_{2m,nT} = D_{2m} + 10\lg\frac{T}{T_0} \qquad (5)$$

The reverberation time T of the receiving room was measured according to Standard ISO 3382-2. Measurements were performed in one third octave bands in the range 100 – 5000 Hz.

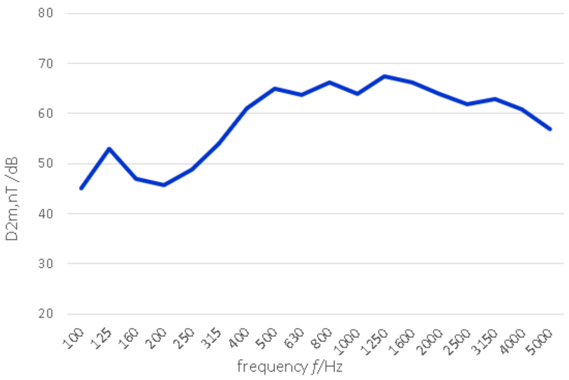

Figure 10. Façade level difference $D_{2m,nT}$ of Pablok + self-supporting wall lining + 1.25 cm fibre gypsum panel.

The result of the on-site measurements (**Figure 10**) presents the same dip at 200Hz as in other studies: like in [15], where a 45 cm straw bale wall plastered on both sides façade was measured; and in the already analyzed [8]. This confirms the behavior of the straw walls, despite the presence of the self-supporting wall lining. In the higher frequency region it is evident the presence of flanking transmission by the decrease of sound insulation.

Considering the single number quantity, the measured $D_{2m,nT,w}$ was 63 (-2; -6) dB. This value is perfectly comparable with the so far estimated value $D_{2m,nT,w} = 64$ dB. Indeed, on the one hand the measurement uncertainty of about 0.7-0.8 dB for the in-situ standard deviation [16,17] shall be taken into account, on the other hand the uncertainty of the evaluation method (± 2dB) shall be taken into account as well, leading to a perfect agreement between the estimated and the measured façade sound insulation.

4. CONCLUSIONS

The Pablok construction system was developed as the demand to build energy-efficient buildings while using eco-sustainable materials has grown. A laboratory measurement campaign was carried out to determine the sound reduction index of the Pablok wall and of the wall treated with a self-supporting wall lining. Other researches [9, 11] found values of the weighted sound reduction index R_w of different configurations of straw bale walls ranging from 47 to 57 dB. Almost all results were affected by dips due to significant resonance and coincidence effects. The Pablok wall behavior is therefore comparable with this literature results, and is a very good solution obtaining an R_w = 63 dB with the self-supporting wall lining, comparable also with the traditional concrete or masonry walls that can easily exceed the value of 60 dB, but with smaller thickness.

Starting from the results obtained, it was verified whether the prediction software can be used for prediction calculations of such kind of wall. It was found that the prediction software INSUL well estimates the Pablok wall alone, but led to a very high overestimation of the sound insulation in the case of the Pablok wall with the self-supporting wall.

Finally, an on-site measurement campaign was carried out, showing a good agreement with the measured data ($D_{2m,nT,w}$ = 63 (-2; -6) dB) and the evaluation method as per ISO 12354-3 ($D_{2m,nT,w}$ = 64 dB).

Further evaluation and on-site measurements will be carried out where the installation of the Pablok system is envisaged.

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