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Performance comparison between building insulating materials made of straw bales and EPS for timber walls

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Abstract. Abstract. This paper studies the thermal and acoustic performance of straw bale walls used in timber-frame semi-detached houses recently built in Sicily (Southern Italy), and compares them to similar walls where expanded polystyrene (EPS) is adopted in place of the straw bales. In-situ measurements were carried out to analyse the acoustic performance of both wall typologies. The weighted Apparent Sound Reduction Index for the partition wall between two houses, as well as the weighted Standardized Level Difference for the façades were assessed based on the ISO Standards 16283. Moreover, the two insulating solutions were compared in relation to their steady and dynamic thermal performance. The results underline that the acoustic performance of the straw bale walls is far better than the walls adopting traditional EPS insulation. However, slight improvements are suggested to further increase the sound insulation properties of straw bales. On the other hand, EPS is a more effective thermal insulation even if straw bale walls comply with Italian standards. Finally, the dynamic performance of straw bales should be improved by increasing their density. Overall, the proposed straw bales used can be conveniently used in low-energy and n-ZEB buildings in warm and mild countries.

1. Introduction

Synthetic products and mineral wools constitute more than 90% of the insulating material market, because of their excellent performance and cost effectiveness [1]. Nevertheless, their manufacture consumes high quantities of non-renewable resources and causes greenhouse gas emissions. Hence, the requirement for low carbon buildings has acted as a driver for the success of innovative environmentally friendly and energy-efficient building materials [2].

Straw is a by-product of agricultural grain and it is currently produced in surplus to necessities; thus, straw is cheap and easily available in several areas of the world. It can be used as a building material when arranged in bales, with a thickness usually ranging from 200 to 500 mm. in In the last ten years, the benefits of straw as a building material have been widely documented [3]. Indeed, straw acts as a carbon sink and it has significantly lower embodied energy and carbon than traditional materials [4]. Furthermore, straw provides high-quality physical properties including low thermal transmittance, typically between 0.13 and 0.19 W/(m^2·K) [5]. While the thermal and acoustic properties of commercial insulating materials are already reliable [6], scientific literature information for straw bales varies within a large range of values. Given the usual variations within straw, it is needed to know the exact properties of the local straw used to correctly evaluate the thermal and acoustic properties of a building.

This paper addresses the thermal and acoustic performance of 20-cm thick straw bale walls and compares it to expanded polystyrene (EPS) performance. These solutions were adopted in timber-frame semi-detached houses recently built in Sicily (Southern Italy). Based on the thermal conductivity derived from laboratory tests, the two insulating materials were compared by looking at the steady-state and dynamic thermal parameters. Moreover, the acoustic performance was addressed by in-situ measurements based on the ISO Standards 16283, providing promising results for straw bales. The outcomes of the paper show that the proposed straw bales can be conveniently used in low energy buildings in warm countries. Some improvement can be necessary in cold climates.

2. Materials and methods

2.1. Design of the experimental building

The buildings examined belong to a recently constructed housing complex placed in Pedara, a minor town about 13 km North of Catania, in Southern Italy. The city is at about 650 m above sea level. Average minimum temperatures vary from 1 °C in January and February to 16 °C in August, while average maximum temperatures oscillate between 12 °C in January and February and 28 °C in July and August. The number of Heating Degree Days is HDD = 1568 °C·day, which places the town in the climate zone D, according to Italian climatic classification. These data suggest that the winter season is quite cold, at least if compared to other regions of Southern Italy; on the other hand, in the summer the outdoor temperature is moderate, but the solar irradiation is intense.

Two couples of semi-detached houses have been selected for this study (Fig. 1), with floor area between 50 and 100 m^2. The bearing structure is made of wood with reinforced concrete foundation beams. The floors and the roof (30% slope) are made up of wooden beams and boards. The external walls and internal partitions are realized by means of drywall systems. The windows are made with wooden frame and double glass. Fig. 2 shows the stratigraphy of the external walls.

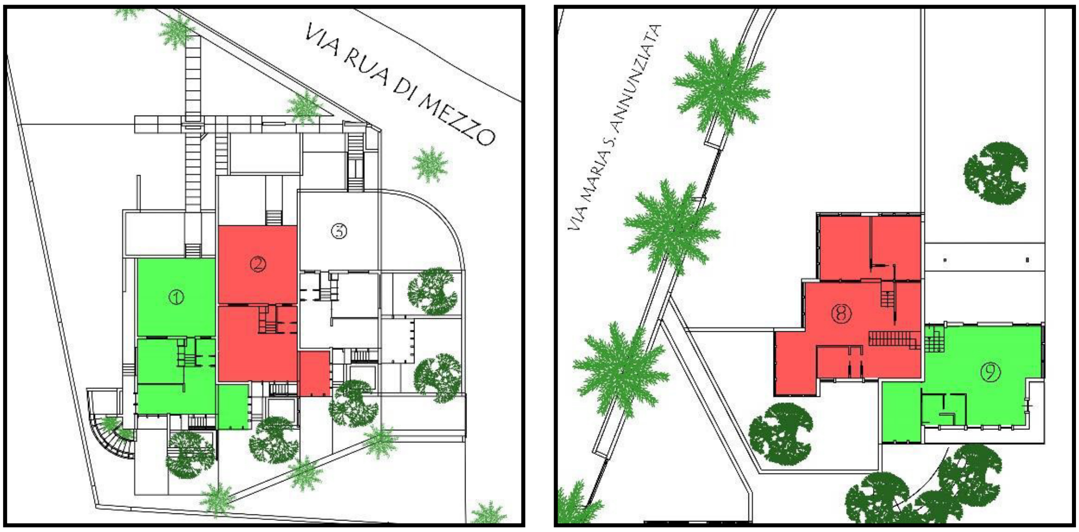

Figure 1. Ground floor of the single-family dwellings considered in this study.

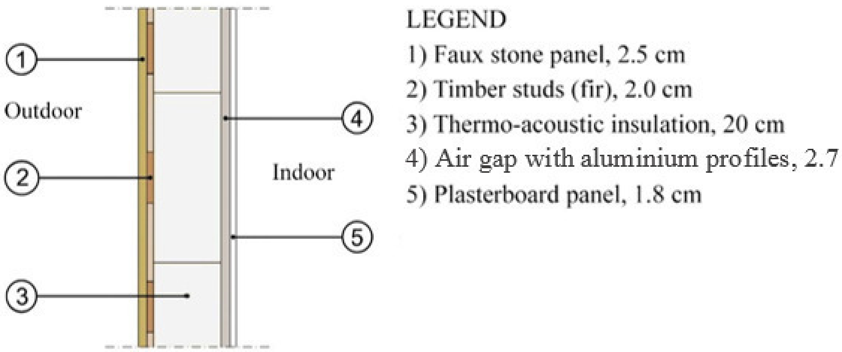

Figure 2. Section of the exterior walls (from outdoors to indoors)

In the first phase, the insulation of the building envelope was realized with a 20-cm thick layer of expanded polystyrene (EPS). Then, in some other buildings, the straw bales were used in place of the EPS, especially packaged for this research and patented as "ECOPA® Straw Bricks". The straw used to package these bales derives from wheat plantations placed in the Plain of Catania.
The packaging of the bales (45 x 50 x 20 cm) was possible because of a new packing machine (patented by Eng. Marco Riccioli) that makes straw bales with a width of 45 cm, variable length and thickness between 15 and 25 cm (on average 20 cm), tied with wire or nylon thread. These dimensions are significantly lower than the bales produced with traditional machines (width 45 cm, height 35 cm, length from 95 to 115 cm). During the packaging of ECOPA® bales, it was not possible to control the direction of the fibers, which are consequently arranged arbitrarily, and they were not treated with additives.

2.2. Steady and dynamic thermal performance of the walls

In order to describe the thermal performance of a wall, several parameters can be introduced, based on steady-state or dynamic calculation methods. In particular, the most common parameter used to measure the attitude of a wall to transfer heat under steady conditions is the *thermal transmittance*, also identified as U-value. The U-value of a wall is the inverse value of its overall thermal resistance; therefore, it should be kept as low as possible – especially for outside walls – to reduce the conductive heat losses to the outdoors. On the other hand, under dynamic conditions it is possible to introduce a *periodic thermal transmittance* (Y): its calculation is quite demanding and implies the use of algorithms reported in the ISO Standard 13786 [7], based on complex numbers. In relation to the periodic thermal transmittance, a recent national regulation states that it must be $Y < 0.10$ W/(m^2·K) for outside walls in new buildings. Similarly, the ISO Standard 13786 introduces a further dynamic parameter called *phase shift* (φ): this is the time lag between the peak outside temperature and the peak heat flux transferred indoors, and is measured in hours. A wall with good dynamic thermal performance has high phase shift ($\varphi > 10$ h), while poor performance occurs when $\varphi < 6$ h.
One more parameter to be recalled is the *internal areal heat capacity* (κ_i). A wall with high internal areal heat capacity has a high potential for heat storage, which helps to counteract indoor overheating and to improve indoor thermal comfort in summer. According to some studies available in the literature, $\kappa_i >$ 50 kJ/(m^2·K) can be regarded as good performance [8]; a recent Italian regulation also states that all new public buildings must show $\kappa_i > 40$ kJ/(m^2·K).
Finally, the capacity of a wall to accumulate heat can be judged by looking at its *surface mass* (SM). This is of course just a simplified approach: however, Italian regulations consider this approach, and state that in new buildings the outside opaque walls should have SM > 230 kg/m^2, with the only exception of those walls facing north.

Table 1. Composition of the outside walls and corresponding thermal properties

	Thickness [cm]	**Thermal conductivity** [W·m^{-1}·K^{-1}]	**Density** [kg·m^{-3}]	**Specific heat** [J·kg^{-1}·K^{-1}]
Plasterboard	1.3	0.21	730	1000
Air gap	2.7	(R = 0.18 m^{2}K/W)	1.2	1000
Insulating material	20.0	-	-	-
Air gap	2.0	(R = 0.18 m^{2}K/W)	1.2	1000
Faux stone panels	2.5	0.44	1370	850
Properties of the insulating materials				
EPS	**-**	0.041	20	1400
ECOPA®	**-**	0.069	75	1250

Table 1 lists the thermal properties of the materials included in the stratigraphy shown in Fig. 2, needed to calculate the steady and dynamic thermal parameters introduced above. Here, a non-ventilated air gap is considered in place of the timber or the aluminium studs used to support the finishing layers: actually, the studs are not a continuous layer and their contribution in terms of thermal resistance and thermal capacity can be neglected. The thermal conductivity of ECOPA® has been increased by 20 % starting from laboratory value, thus taking into account the effects of humidity and aging occurring to the material when used in a real application. This is the value suggested by UNI Standard 10351 for building materials made of wood fibres and wood boards.

2.3. Acoustic measurements
The measurement of the apparent sound reduction index for the partition walls between two adjacent residential units was performed in compliance with the procedures described in the ISO Standards (16283 series). As a sound source a directional loudspeaker was used, fed with pink noise; a condenser microphone was connected to a sound level meter Solo 01-dB to measure the sound pressure levels.
Two positions were selected for the loudspeaker in the source room, close to the corners furthest from the partition under investigation. On the other hand, five fixed positions were selected for the microphone in both the source and the receiving room. In all cases, the height of the microphone above the ground was 1.5 m; the calibration of the microphone was verified through the calibrator 01-dB Cal 21 at the beginning and at the end of the measurement campaign.
The evaluation of the apparent sound reduction index also implies the measurement of the reverberation time in the receiving room. This was done through the interrupted noise method, by keeping a fixed position for the loudspeaker while changing the position of the microphone, on a total of six measurements that are eventually averaged out. All the parameters were measured in octave bands from 125 Hz to 2000 Hz. Since the volume of the receiving room is in both cases higher than 25 m^3, it was not necessary to extend the measures to the low frequencies (below 100 Hz), as reported by the Standard. Furthermore, a preliminary check of the background noise level in both rooms showed that this is significantly lower than the sound pressure levels generated by the sound source.
The measurement of the sound level difference for the blind façades of the two buildings was performed in compliance with the global method described in the ISO Standard (16283 series). In particular, the sound source was the same directional loudspeaker as above, fed with pink noise. In this case, the loudspeaker was placed outdoors at the distance of 5 m from the façade. The sound pressure level generated by the loudspeaker outdoors was measured twice in only one position, placed at a distance of 2 m from the façade. On the other hand, five fixed positions of the microphone were used to measure the sound pressure level indoors.

3. Results
3.1. Steady and dynamic thermal performance of the walls
The values of the parameters describing the steady and dynamic thermal performance of the walls are reported in Table 2. The results refer to both the solutions adopted to insulate the buildings under investigation (ECOPA® and EPS), according to the thermal properties reported in Table 1.
In Table 2 it is possible to observe that both the insulating solutions lead to good steady thermal performance, as suggested by the low U-value. Indeed, national regulations on energy performance of buildings suggests U = 0.29 W/(m^2·K) as a reference value for the vertical walls of new buildings in climate zone D; hence, the ECOPA® insulation just slightly improves on this target, while EPS cuts the U-value by more than 30 %.

Table 2. Steady and dynamic thermal parameters for EPS and ECOPA® walls

	U-value [$W·m^{-2}·K^{-1}$]	Y_{IE} [$W·m^{-2}·K^{-1}$]	SM [$kg·m^{-2}$]	φ [hr]	κ_i [$kJ·m^{-2}·K^{-1}$]
ECOPA®	0.281	0.239	58.7	4.0	16.9
EPS	0.181	0.172	46.5	2.4	11.8

On the contrary, the ECOPA® solution shows more performing dynamic parameters. Indeed, it shows higher time shift (φ) and higher internal areal heat capacity (κ_i) than the walls insulated with EPS. However, even with the ECOPA® insulation the dynamic thermal performance is far from being good. As an example, φ = 4 h can be regarded as “poor”, while κ_i = 16.9 kJ/(m^2·K) is much lower than the reference value reported in the literature, i.e. κ_i = 50 kJ/(m^2·K). Finally, even the surface mass (SM =

58.7 kg/m^2) is too low if compared with the threshold value for new buildings, and the periodic thermal transmittance Y = 0.239 W/(m^2·K) is more than twice as high as the maximum value allowed for new buildings, i.e. Y = 0.10 W/(m^2·K).

These results suggest that the ECOPA® straw bales provide excellent insulation to the wall, but they are not sufficient to ensure good thermal capacity. Consequently, summer overheating is likely to occur, especially in hot and sunny regions. However, the thermal performance of the wall insulated with the ECOPA® straw bales is better than the equivalent wall insulated with EPS. According to these outcomes, the proposed straw bales can be conveniently used in low energy buildings (and n-ZEBS) located in countries with mild climate. In cold climates, higher insulation levels might be necessary; in hot climates – such in the coasts of Southern European countries – further improvement could be achieved by adding a massive layer on the inner side of the wall, or by adopting suitable solutions to remove the heat absorbed by the wall, such as green or ventilated façades

3.2. Acoustic performance

The weighted apparent sound reduction index of the partition walls can be read from Fig. 3, and correspond to the value of the shifted reference curve at 500 Hz. The partition wall insulated with ECOPA® has R'_w = 49 dB, whereas it is R'_w = 39 dB in the wall insulated with EPS. According to the certification scheme introduced by UNI Standard 11367 the acoustic performance of the ECOPA® partition walls can be classified as "Poor", while the performance becomes "Bad" with EPS.

However, the blame for such a deceiving result has to be put on the adoption of a too lightweight finishing layer. In fact, it would be possible to improve the weighted sound reduction index of the partition wall by applying two layers of plasterboard on both sides of the ECOPA® bales, on a total of 25 mm per side, instead of a single layer. This would allow doubling the effective mass of lining, to increase the sound reduction index by around 5 dB and to shift the acoustic performance to Class II (good). On the contrary, even by applying two layers of plasterboard on both sides of the EPS partition wall, the acoustic performance would not get better than "poor" (R'_w < 50 dB). As concerns the weighted standardized sound level difference of the façade, $D_{nt,w}$ = 43 dB for ECOPA® and $D_{nt,w}$ = 42 dB for EPS (see Fig. 4). Accordingly, the acoustic performance of the ECOPA® façades can be classified as "Excellent". This value is just 1 dB lower than for the ECOPA® façade; however, according to UNI Standard 11367 this is enough to downgrade the acoustic performance to Class II.

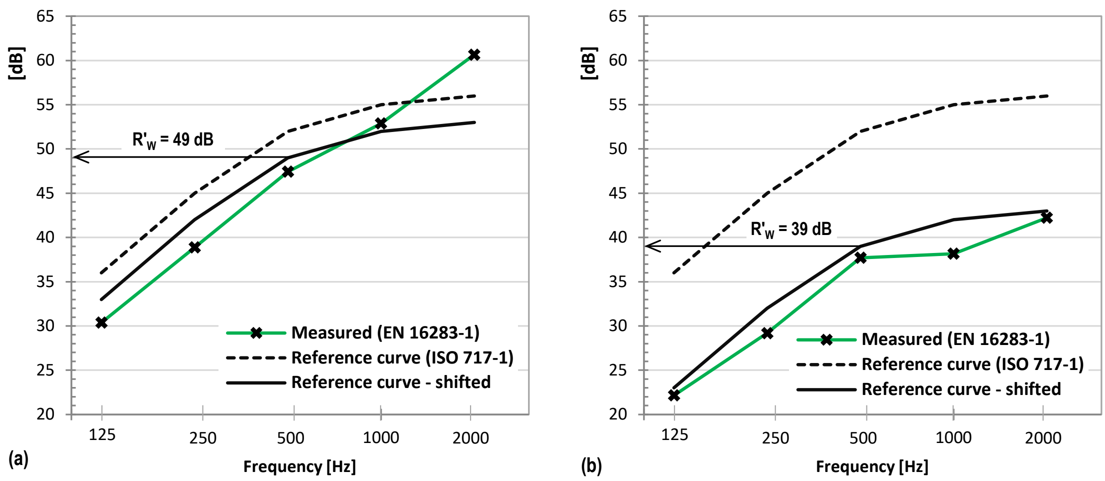

Figure 3. Weighted apparent sound reduction index of the partition wall. (a) ECOPA®; (b) EPS

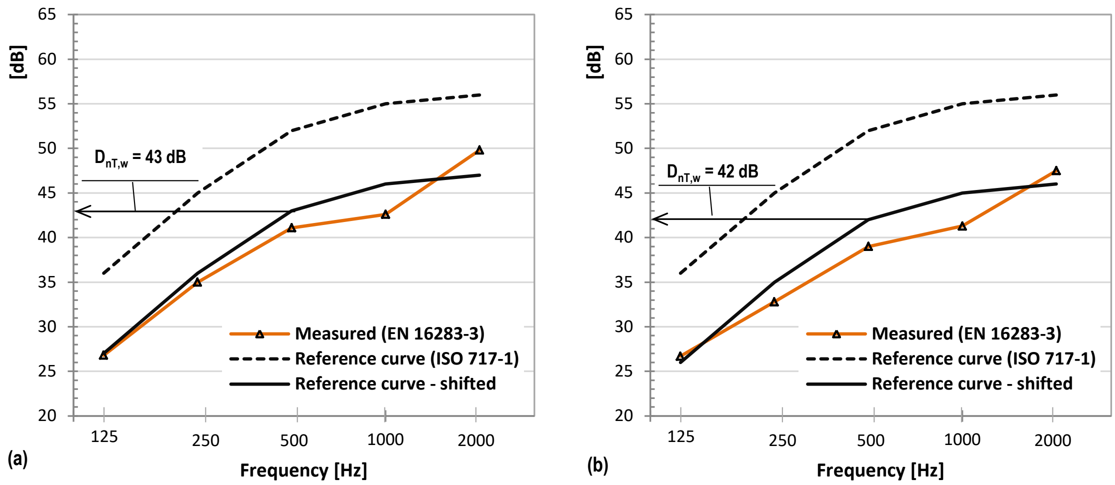

Figure 4. Weighted façade sound level difference. (a) ECOPA®; (b) EPS

4. Conclusions

According to the outcomes of the present study, based on field measurements and numerical calculations, timber frame infill walls insulated with 20-cm straw bales show good performance in terms of façade sound insulation and apparent sound reduction index of the partition walls. The corresponding single rating numbers are far better than for an equivalent wall using EPS in place of the straw bales; moreover, the acoustic performance might further improve by increasing the mass of the finishing layers, e.g. by installing two 1.25-cm layers of plasterboard on both sides of the walls.
On the other hand, contrasting results emerge when looking at thermal performance: if the U-value provided by the straw bales is sufficiently low, the calculation of the dynamic thermal parameters suggests that ECOPA® walls have low thermal capacity. Consequently, summer indoor overheating is likely to occur, especially in hot and sunny regions. This situation can be improved by increasing the density of the straw bales, by adding a massive material on the inner side of the wall, or by adopting suitable solutions to limit the heat absorbed by the walls, such as green or ventilated façades.

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