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An innovative multilayer wall composed of natural materials: experimental characterization of the thermal properties and comparison with other solutions

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Abstract

In order to reduce the carbon emissions resulting from buildings construction, some non-conventional materials are emerging, especially the ones of natural origin. In this scenario new building components have been developed as thermal insulating panels such as the ones made of wood, straw, and cork. In the present paper a multi-sheet wall was investigated by analyzing the thermal properties of each layer by means of a new experimental apparatus named Small Hot-Box. The wall is composed from the outside towards the inside by a 'cocciopesto' mortar, a thick layer of straw, a wooden planking, an air interspace of about 5 cm, and a final raw earth plaster, for a total thickness of about 50 cm. Results showed thermal conductivities in accordance to Literature values both for the wood (0.089 W/mK) and for the straw (0.065 W/mK). For the 'cocciopesto' and the earth-based plasters no many Literature data are available: the thermal conductivities are equal to 0.92 and 0.98 W/mK respectively. The total thermal transmittance of the wall was estimated by combining the results and considering the real scale thickness of each layer; it is about 0.15 W/m^{2}K.

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1. Introduction

The concept of sustainability [1] has been primarily applied on economy conjugating profit with environmental and social aspects. When applied to building construction, it must be considered from the very earliest stages because it implies a very significant commitment to consume resources; designers may be able to limit this consumption since they can influence decisions [2], while most of a building's overall impact is related to its operation [3]. Natural materials, such as straw bale and earth, have substantially less embodied energy than processed materials, so that their choice for building construction can give a valuable contribution to sustainability. Straw is a waste material from cereal harvest, made up of dead stalks of cereal plants. The use of straw bales in constructions was strictly connected to the invention of the baling machine at the end of the 19th century. The modern construction technique started in Nebraska, USA around 1880 [5]. Some of the first straw bale houses still exist, such as the Burke house built in 1903 in Alliance, Nebraska [6]. In Europe, France can be considered the pioneer of straw bale construction, indeed in 1921 ing. Émile Feuillette built the first European straw bale building in Montargis. This construction technique was almost abandoned during 40s, due to the spread of cement, and was rediscovered in the 70s due to the energy crisis [7]. Since the 80s many straw bale constructions spread in the country, especially in Northern Europe and United Kingdom. In Italy the diffusion of straw bales for building construction is relatively recent and now it is gaining considerable attention among "self-builders", technicians, and scientists. To improve the spread of this material it is fundamental to know its mechanical and thermal properties. In general, straw bales have shown good mechanical properties and also excellent thermal insulation [8-11]. However thermal characteristics, such as thermal conductivity, are not defined univocally due to material heterogeneity and porosity (the stalk arrangement and density in the bale can influence its general properties [8,9]). Most of the studies present measurements made on small size samples, since the high thickness of the bale prevents the correct positioning of the sample in the test-bed. During the resizing process, it is difficult to preserve the original physical characteristics of the material, such as its density and stalk orientation [12]. In this paper a multi-sheet wall containing straw and innovative plasters was investigated by analyzing the thermal properties of each layer, in order to estimate the thermal transmittance of the entire package. The thermal conductivity of the single layer was investigated in a Small Hot Box and the total thermal transmittance of the wall was estimated by combining the results and considering the real scale thickness of each layer.

Nomenclature

CP	'cocciopesto'
H	thermal transmittance
λ	thermal conductivity
P	polystyrene
pW	plywood
q	heat flux
R	thermal resistance
RE	raw-earth
s	thickness
S	straw
T	temperature
U	uncertainty
W	wooden planking

2. Materials and methods

2.1. Description of the multilayer wall composed of natural materials

Straw-bale construction is a method that uses bales of straw (commonly wheat, rice, rye and oats straw) as building insulation systems. The advantages of these walls are the low cost, easy availability, naturally fire-retardant and high insulation value. The wall considered for this study is completely composed by natural and renewable construction materials. The section, with a total thickness of 52.3 cm, is composed of an outer layer of 'cocciopesto' plaster, a core made of straw bales contained within continuous fir boards, an interspace bounded by uninterrupted planks of fir wood; finally, the plaster in raw earth is applied on the fir wood. The external plaster of 'cocciopesto' is about 3cm thick, designed to resist external atmospheric agents and to guarantee good breathability of the wall, essential also for keeping the straw in good conditions and reducing the humidity level. The "Guglielmino" 'cocciopesto' plaster, based on natural hydraulic lime and 'cocciopesto', consists of three cohesive layers. The adhesion is guaranteed through the application of a layer of wicker, anchored to the wooden plank with metal staples. The straw bales are positioned with the fibers in vertical direction and are contained within two layers of solid 2 cm thick fir wood. In order to guarantee the bracing function, this boarding is fixed to the wooden supporting structure in an oblique position with nails. A third layer of internal board creates an air gap, through which the services are passed. Finally, the internal finishing layer is made of a plaster about 3 cm thick, also fixed to the planks using wicker. The "Guglielmino" raw clay plaster consists of two layers: the "plaster body" made of selected raw earth and sand, with controlled granule sizes and dosage, and addition of vegetable fibers, and the finishing made of raw earth and fine sand. The clay quickly absorbs moisture from the air and releases it as quickly as necessary. This regulates indoor air and makes the climate healthier. Moreover, the raw earth, thanks to the high thermal inertia, heats up very slowly and just as slowly cools. In winter it has the ability to accumulate heat, in summer it manages to keep a cool temperature. The layers of the walls are shown in Fig.1. The final stratigraphy originates from surveys and evaluations that take into account the sustainability of the wall and its energy and mechanical efficiency.

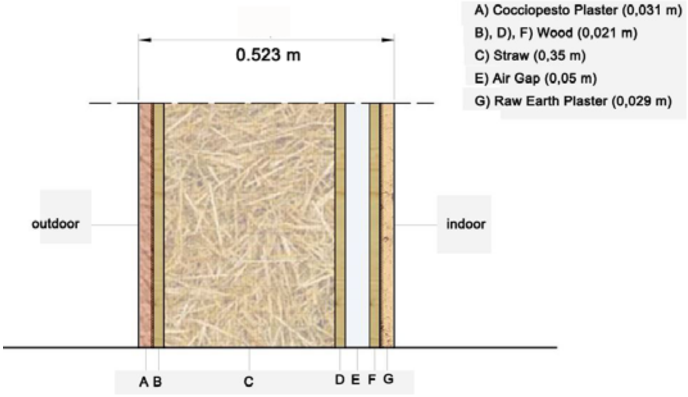

Fig.1. Stratigraphy description of the studied wall.

2.2. Samples characteristics

Square samples were assembled with external dimensions 300 × 300 mm, for a total area of 0.09 m^2, due to the dimensions of the thermal measurements experimental apparatus. The description of the specimens (from 1) to 5)) and their total thickness are reported in table 1.

At first a specimen composed by a plywood panel (0.01 m thick) with a polystyrene panel characterized by a known thermal conductivity ($s = 0.054$ m and $\lambda = 0.038$ W/(mK)) (specimen pW+P) was tested in order to evaluate the thermal conductivity of the plywood (pW), that is the support panel of the samples type 2), 3) and 4). A support panel is necessary for the straw that, is a loose material: the box is necessary to give the straw an adeguate compression for construction purposes, that has to be higher than 80 kg/m^3. In order to estimate density value, the assembled sample and only plywood were weighed separately, obtaining the straw density by difference (p = 105.69 kg/m^3). During the test, the straw stalks were oriented in vertical position (Fig.2 a)).

Samples types 3) and 4) need the plywood support because they are fragile (see Fig.2). In particular the 'cocciopesto' and natural lime sample is composed of (Type 3): plywood (1 cm) as support, red wattle (0.5 cm), body plaster made of hydraulic lime NHL 3.5 and cocciopesto (2 cm), finishing layer made of hydraulic lime NHL 3.5 and 'cocciopesto' (0.6 cm), for a total thickness of 4.1 cm. Moreover a final panel of polystyrene (s = 1 cm) is used in order to close the package. Similarly to n. 3, Sample 4) is composed of: plywood (1 cm) as support, red wattle (0.5 cm), body plaster made of unfired clay, lava sand and straw (2 cm), finishing plaster made of unfired clay (0.4 cm), a polystyrene panel (1 cm), for a total thickness of 4.9 cm. Samples 3) and 4) thickness corresponds to the real one in the wall package. Therefore, the sandwich structures of samples 2), 3) and 4) were specifically composed for the evaluation of the thermal properties of Straw (S), 'cocciopesto' Plaster (CP), and Earth-based Plaster (RE) respectively.

The last one (5) is a sample with a single layer: it is composed by two fir wooden planking elements joined by nails, with a total thickness of about 2 cm; it reproduces the real implementation of the wood in the multilayer package.

Fig.2. a) Construction of the plywood box filled with Straw (Sample type 2); b) Sample type 3: 'Cocciopesto' plaster with plywood panel and polystyrene; c) Sample type 4: Raw Earth plaster with plywood panel and polystyrene.

Table 1. Description of the tested samples.

	Sample Name	Description	s_{TOT} (m)	Layer to be analysed
1)	**pW**+P	plywood panel (0.010 m) + polystyrene panel (0.054 m)	0.064	plywood panel (**pW**)
2)	pW+**S**+pW	A box composed by plywood panels (0.010 m) with straw inside (0.08 m thick) (fibers with parallel disposition)	0.10	Straw (**S**)
3)	pW+**CPplaster**+P	plywood panel (0.010 m) + 'cocciopesto' plaster layer (0.031 m) + polystyrene panel (0.010 m)	0.051	'cocciopesto' plaster layer (**CPplaster**)
4)	pW+**REplaster**+P	plywood panel (0.010 m) + earth-based plaster layer (0.029m) + polystyrene panel (0.010 m)	0.049	Raw Earth plaster layer (**REplaster**)
5)	**W**	two fir wooden planking elements joined by nails in order to obtain a panel 30 x 30 cm	0.021	Wooden planking (**W**)

2.3. Small Hot Box apparatus for thermal flux meter measurements

The thermal properties of the samples listed in tab. 1 were evaluated with an experimental apparatus, named Small Hot Box (Fig. 3) [13-15], designed and built at the Department of Engineering (University of Perugia). The experimental facility is composed of a very insulated hot chamber heated by a wire (maximum power 50 W) keeping the room at constant temperature. A sandwich insulated panel closes the system and a square opening (0.3 x 0.3 m dimensions, for a total area of 0.09 m^2) is present in the central part for the sample location. The cold side of the system is the Laboratory room, kept at constant temperature thanks to the HVAC system. The temperature difference between hot and cold side was maintained at least equal to 20 °C. The heat flux (q) is measured through a thermal flux meter installed in the central part of the sample; 4 thermal resistance probes are installed on each side of the sample for the measurements of the surface temperatures. The value of thermal conductivity is obtained as shown in Eq. (1):

$$\lambda = \frac{q}{(T_{sH} - T_{sC})} \cdot s \tag{1}$$

where T_{sH} and T_{sC} are the mean surface sample temperatures in the Hot and Cold sides during the tests, s is the total thickness of the sample.

Considering the composition of the studied panels described in 2.2, in many cases it was necessary to evaluate the contribution of only one layer of a sandwich panel; it was calculated from the total thermal resistance of the composed samples, as shown in Eq. (2):

$$R_{tot} = R_1 + R_2 = \frac{s_1}{\lambda_1} + \frac{s_2}{\lambda_2} \tag{2}$$

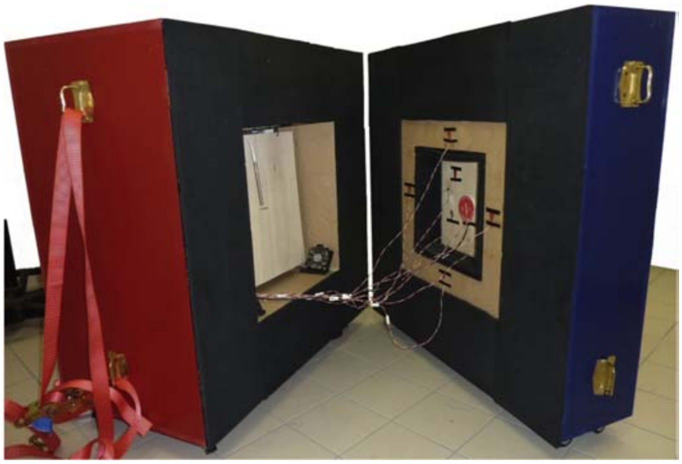

Fig. 3. The Small Hot Box apparatus with a sample inserted inside.

Finally the relative uncertainties (type B) were calculated in compliance with JCGM 100:2008 [16]. Not enough data are available in order to hypothesize a statistical distribution and the considered probability distribution is rectangular. From the maximum and minimum values of the surface temperatures of both the hot and cold side and the heat flux measured in each test, it is possible to calculate the mean value ($\bar{x}_i$), following the hypothesized distribution and the uncertainty $u(x_i)$ for each measured quantity (T_{sH}, T_{sC}, q). The absolute uncertainty of the thermal conductivity u (λ), obtained by considering the partial derivatives of λ with respect to the quantities taken into consideration, is given by Eq. (3) and the relative value of the uncertainty is shown in Eq. (4):

$$u(y) = \sqrt{\sum_{i=1}^{n} \left[\left(\frac{\partial y}{\partial x_i} \right)^2 * u^2(\bar{x}_i) \right]} \tag{3}$$

$$\dot{u}(y) = \frac{u(y)}{y} \tag{4}$$

where the variable y is equal to λ in this study.

3. Results and discussion

3.1. Thermal conductivity values and uncertainties estimation

Thermal properties of the described samples are reported in Table 2. Several tests were carried out for each sample, considering two set point air temperatures in hot chamber, 45°C and 50°C, but the most significant results are related to the first condition (45°C) for almost all the samples.

Also the type B uncertainties are reported in the table, in order to highlight the best results: the final considered tests are written in bold. Generally the uncertainty u – values vary in 4.5 – 7.8 % range: only for one test a value of about 10% is obtained and the correspondent result was discarded.

In order to evaluate the thermal conductivity of the only investigated materials, the contribution of the other layers are deducted: Table 3 shows the thermal conductivity values of the only investigated materials that would be used in order to evaluate the total thermal transmittance of the composed wall, in the next paragraph.

The plywood panel is used in the packages in order to have a support for other materials and its conductivity can be calculated from the first test, in order to obtain a value that could be used in the subsequent tests for the conductivity extrapolation of the only interested layer. It is obtained a λ that is consistent with Literature values (about 0.15 W/mK). Also the polystyrene used in some tests has a known value of λ, that is also the same value certified by the producer: 0.038 W/mK. Both the plywood and the polystyrene are not present in the final composition of the wall.

Table 2. Thermal results of the investigated samples: thermal flux meter methodology (Small Hot Box).

	Samples	**Hot Side Test Condition (°C)**	**s_{TOT} (m)**	**ΔT_s (°C)**	**q (W/m^{2}K)**	**λ_{TOT} (W/mK)**	**$\dot{u}(\lambda)$(%)**
1a)	pW+P	45	0.064	20.06	13.49	**0.043**	4.53
1b)	pW+P	50		24.18	16.63	0.044	5.16
2a)	pW+S+pW	45	0.10	19.66	14.37	**0.073**	6.26
2b)	pW+S+pW	50		23.57	17.62	0.075	5.37
3a)	pW+CPplaster+P	45	0.051	17.03	46.85	**0.140**	4.66
3b)	pW+CPplaster+P	50		21.76	43.94	0.103	9.61
4a)	pW+REplaster+P	45	0.049	15.12	42.08	**0.136**	5.50
4b)	pW+REplaster+P	50		18.54	51.45	0.136	5.42
5a)	W	45	0.021	13.07	55.37	**0.089**	7.67
5b)	W	50		15.53	65.73	0.089	7.81

For the straw, it can be observed that the measured conductivity is 0.065 W/mK, aligned to the values present in the Literature [8,12], with comparable densities (about 100 kg/m^3); it corresponds to the thermal conductivities obtained for straw layers that have a parallel disposition of the fibers. Considering a perpendicular orientation, the λ-values are slightly lower. For the 'cocciopesto' plaster the λ-value that can be considered significant is the first test (0.98 W/mK); the second one should be discarded because of the too high uncertainty obtained (about 10%). The Raw Earth plaster layer has a value included in the 0.95 – 0.98 W/mK range: it is consistent with the value approximate provided by the manufacturer (about 0.91 W/mK). Anyway the λ obtained from the first test (45°C) is the most significant (0.98 W/mK). Finally the wooden planking (W) tested at the end (total thickness of 0.021 m) has a thermal conductivity equal to 0.089 W/mK, the same for both the tests; also this value is aligned to the Literature. For this last test the uncertainty values are higher than the ones obtained for the other materials (about 8%); this is due to the total thickness of this sample that, is very low (about 2 cm): the heat flux were not very steady during the test.

Table 3. Thermal results of the only investigated materials that composed the wall.

	Samples	Hot Side Test Condition (°C)	s (m)	λ (W/mK)
1a)	**plywood (pW)**	**45**	**0.010**	**0.152**
1b)	plywood (pW)	50		0.144
2a)	**Straw (S)**	**45**	**0.080**	**0.065**
2b)	Straw (S)	50		0.066
3a)	**'cocciopesto' Plaster (CPplaster)**	**45**	**0.031**	**0.920**
3b)	'cocciopesto' Plaster (CPplaster)	50		*0.187*
4a)	**Raw Earth plaster (REplaster)**	**45**	**0.029**	**0.982**
4b)	Raw Earth plaster (REplaster)	50		0.951
5a)	**Wood (W)**	**45**	**0.021**	**0.089**
5b)	Wood (W)	50		0.089

3.2. Evaluation of the total transmittance of the designed wall

For the evaluation of the total thermal transmittance of the wall, the λ-values were used in order to calculate the thermal resistances of each layer R_i (Tab.4), considering the in real thickness. For the air gap inside the wall, a thermal resistance of 0.18 m^2K/W was assumed, in compliance with UNI 10351 [17] related to an air gap of about 5 cm with a horizontal thermal flux. The total thermal transmittance was evaluated considering also the thermal resistance of the internal and external surfaces (about 0.17 m^2K/W, in compliance with EN 6946 [18]).

Table 4. Thermal resistances of the layers that compose the sandwich wall.

	Layer	s (m)	λ (W/mK)	R_i (m^2K/W)
A)	'cocciopesto' Plaster (CPplaster)	0.031	0.920	0.033
B)	Wood (W)	0.021	0.089	0.23
C)	Straw (S)	0.350	0.065	5.38
D)	Wood (W)	0.021	0.089	0.23
E)	Air gap	0.050	-	0.18
F)	Wood (W)	0.021	0.089	0.23
G)	Raw Earth plaster (REplaster)	0.029	0.982	0.029
	s_{tot} (m)	**0.523**	**R_{tot} (m^2K/W)**	**6.312**

A value of H equal to 0.154 W/(m^2K) is calculated for the investigated wall: it is much lower than all the limited values of the thermal transmittances fixed from the DM 26/06/2015 [19] for all the climate zones (from A to F) and it also complies the limits imposed for the years 2019-2021 (0.43 – 0.24 W/(m^2K) passing from climate zone A to F).

4. Conclusion

New techniques aiming at reducing the environmental impact of the construction systems have become important, particularly concerning the building materials. In this scenario, the use of natural materials as building components can be very important, considering that they are good thermal insulating solutions. In the present paper an external wall system about 50 cm thick, completely composed by natural layers, was investigated. In order to evaluate the thermal transmittance of the wall, all layers were preliminary tested in a new experimental apparatus named Small Hot-Box: thermal flux meter measurements were carried out in order to find the thermal conductivity of each material. All the measurements have a relative uncertainty included in 4.5-7.8% range and they were considered reliable, also to their agreement with Literature. The straw has a thermal conductivity of about 0.065 W/mK: it is not very low, but a thickness of about 35 cm of straw was considered in the final composition of the wall and the total thermal resistance of this layer is 5.38 m^2K/W. Also the plasters have a thermal conductivity aligned with the values assumed from the manufacturers (0.92 – 0.98 W/(mK)). The total thermal transmittance of the investigated package is very low (0.154 $W/(m^2K)$ for a total thickness of 52.3 cm), also considering the restrictive limits of the Laws. Among the advantages of these natural structures it must be considered the renewable nature of straw, earth, wood, and 'cocciopesto', the easy availability of the materials, the naturally fire-retardant effects and the high insulation value. Nevertheless, the disadvantages include susceptibility to rot, difficulty for obtaining insurance coverage, and high thickness necessary for the straw: these kind of walls have always high thickness and it is necessary to control the moisture inside the layers, that should be less than 20%, in order to avoid the breakdown and the decaying of the straw. In the future the environmental analysis (Life Cycle Assessment) would be also necessary, in order to highlight the added value of these natural solutions.

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