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Use of clay and olive pruning waste for building materials with high hygrothermal performances

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Abstract

Several clayey materials incorporating different percentages of leaves and small branches derived from the pruning of olive trees were prepared and tested in Thermophysical Laboratory of Polytechnic University of Bari. Hygrothermal properties were measured according to technical standards. In order to consider the potential of earthen materials to improve indoor comfort, the software WUFI®Plus was used to simulate the hygrothermal behavior of a Test Building, placed in a Mediterranean climate. The analysis was carried out considering the internal surface of the walls of the building covered by two different plasters i.e. gypsum plaster and clayey plaster with 6% of olive waste. Results demonstrated that when considering an unconditioned scenario (without HVAC system) the clayey plaster lead up to a greater improvement of the hygric performances, unlike traditional coverings as gypsum plaster. However, in presence of HVAC system any significant variations occurs in terms of energy saving.

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Keywords: clayey plaster, olive waste, test building, hygrothermal behavior, energy saving.

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1. Introduction

In the last decades, eco-friendly materials are playing an increasing role in the building industry. The natural resources can contribute to the creation of bio-based building materials reducing the energy consumption and the

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gases emissions. For this purpose, in recent years there has been a revival of interest in earthen construction materials.

This study investigates hygric and thermal properties of the clay-based plasters incorporating leaves and branches derived from the pruning of olive trees. Meli et al. [1] state that earth plasters outperform conventional industrial plasters because they allow to create comfortable and healthy spaces with a minimal impact on the environment.

Many studies deal with the use of natural fibers as replacement to synthetic fibers in reinforced composites. Several aggregates derived from plants such as coconut fibers [2], hemp [3], straw [4], flax fibers [5], date palm trees fibers[6], or bamboo [7] have already been studied due to their attractive features, such as good mechanical properties, low cost, low density, low thermal conductivity, durability and recyclability. Palumbo et al. [8] evaluated the thermal conductivity, the thermal diffusivity, the water vapour permeability and the moisture buffering of plasters incorporating two types of vegetable materials such as barley straw and corn pith. It was observed that the thermal conductivity of the clay materials decreased with the addition of the vegetable materials that had a limited effect on the hygric properties. Ashour et al. [9] measured the thermal conductivity. They studied three different types of fibers as a reinforcement for natural plaster. Wheat straw, barley straw and wood shavings were used. As expected, the thermal conductivity of all materials decreased with increasing the fiber content and increased with the addition of sand.

The aim of this paper is to better understand and quantify how the application of a clayey plaster can improve the indoor environmental conditions, reducing energy consumption for climatization. For this purpose, this study focuses on the hygrothermal behavior of a test-building with two different materials as interior wall coatings. PC software tool WUFI®Plus was chosen for the analysis. This software has been developed and extensively validated by the Fraunhofer Institute for Building Physics in Germany, for "the calculation of transient internal climatic conditions and heat losses by combination of energetic whole building simulation with hygrothermal component calculation" [10, 11].

Nomenclature

A	specimen area (m^2)
c	specific heat capacity (J/kgK)
d	specimen thickness (m)
m	mass (kg)
n	bulk porosity (-)
R_A	water vapour diffusion resistance in the gap in the plastic cup (m^{2}sPa/kg)
RH	relative humidity (%)
t	time (s)
V	volume (m^3)
w	moisture content (kg/m^3)
α	thermal diffusivity (m^2/s)
δ_p	water vapour permeability (kg/msPa)
$\Delta G/\Delta\tau$	flow of water vapour over time (kg/s)
Δp	difference of the water vapour pressure between the saline solution and the air of environment (Pa)
λ	thermal conductivity (W/mK)
Λ	vapour permeance (kg/m^{2}sPa)
μ	water vapour diffusion resistance factor (-)
ρ	density (kg/m^3)
φ	relative humidity (-)

2. Experimental procedure

2.1. Materials

Four different clayey plasters with olive fibers were studied. Different percentages of clay, sand, gravel and fibers were used. Clay, sand and gravel were mixed with leaves and branches derived from the pruning of olive trees. According to Laborel-Préneron et al. [12], the aggregates were sized to obtain a homogeneous mixture that would be easy to apply to the wall. The average size of the fibers was about 3 cm.

The composition of the cohesive soil was as follows: quarry fines, quartzite grit sand (<2 mm), quartzite grit gravel (2-4 mm), hydrated lime and water.

The clay used had sandy fraction (1%), 28% silt and 71% clay. Carbonates were equal to 22%.

2.2. Sample preparation

The blends were prepared using a forced-action rotary paddle mixer before adding the required water content for dynamic compaction. Different weight percentages of clay, sand, gravel and olive pruning waste were used according to the proportions reported in Table 1. The specimens were cured for 28 days at environmental conditions.

Table 1. Composition of the olive-clay plasters (%b.w.).

Mixture code	Clay (%)	Sand (%)	Gravel (%)	Fibers (%)
4	38	56	2	4
6	38	54	2	6
8	37	53	2	8
12	35	51	2	12

3. Experimental tests

3.1. Thermal performances

The thermal properties (thermal conductivity, thermal diffusivity and specific heat capacity) were experimentally evaluated. Prior to testing, all specimens were oven dried at 105 °C until they achieved constant mass before cooling to ambient temperature in desiccators containing silica gel. The dry-state thermal conductivity and thermal diffusivity were measured using ISOMET 2104, a transient plane source device.

Table 2 gives the average values of the density and the measured thermal properties.

Table 2. Thermal properties.

Mixture code	Bulk density ρ_{bulk} (kg/m^3)	Thermal conductivity λ (W/mK)	Thermal diffusivity α (m^2/s)	Specific heat capacity c (J/kgK)
4	1669	0.593	0.387×10^{-6}	849.6
6	1599	0.532	0.365×10^{-6}	869.7
8	1497	0.458	0.320×10^{-6}	908.6
12	1409	0.428	0.295×10^{-6}	958.9

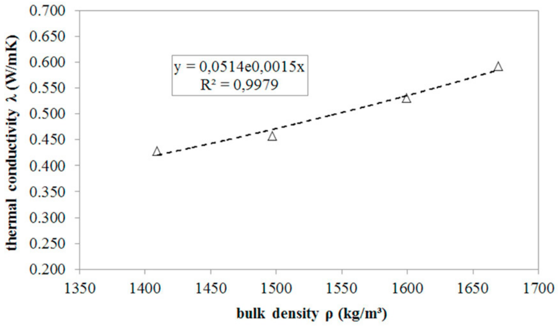

Fig. 1. Dry thermal conductivity versus dry density.

Thermal conductivity versus density analysis is presented in Fig.1. The curve shows a decrease of thermal conductivity when the density decreases. Plasters with a higher content of fibers have a lower thermal conductivity, i.e. a greater thermal insulation capacity.

3.2. Water vapour permeability

Water vapour permeability was measured according to UNI EN 1015-19 [13] using dry cup method. Saturated salt solutions of Potassium Nitrate (KNO_3) were used for wet-cup test (93.2% RH) and Lithium Chloride (LiCl) saturated solutions for dry-cup test (12.4% RH). Each cylindrical specimens was wax sealed on the top of a PVC vessel containing salt solution with 1 cm thickness air layer between the water surface and internal sample surface.

The assembly was then placed in the Perani AC520 climate chamber set to 20±2 °C and 50±5% RH. The assemblies weight was recorded by a Mettler Toledo PB3002 balance (±0.01 g accuracy) until constant mass was achieved. The vapour pressure gradient between the air in the climatic chamber and that in the cup was estimated.

For each specimen, the vapour permeance was calculated as follows:

$$\Lambda = \frac{1}{\frac{A\,\Delta p}{\frac{\Delta G}{\Delta \tau}} - R_A} \tag{1}$$

The water vapour permeability was achieved from the following equation:

$$\delta_p = \Lambda \cdot d \tag{2}$$

The water vapour resistance factor was:

$$\mu = \frac{1.94 \cdot 10^{-10}}{\delta_p} \tag{3}$$

where $1.94 \cdot 10^{-10}$ was the air permeability at 20 ± 2 °C.

Hygric properties are reported in Table 3 in terms of water vapour diffusion resistance factor measured by the cup method (dry and wet).

Table 3. Hygric properties.

Mixture code	Water vapour diffusion resistance factor μ (-)	
	Wet cup test	Dry cup test
4	12.5	20.8
6	15.1	25.2
8	14.1	23.5
12	13.4	22.3

3.3. Porosity

ULTRAPYC 1200-e Quantachrome Helium gas Pycnometer was used to determine bulk porosity:

$$n = \frac{V_{tot} - V_{true}}{V_{true}} \tag{4}$$

Table 4 gives the average values of the total open porosity for each mixture.

Table 4. Average values of the bulk density, true density and total open porosity.

Mixture code	Bulk density ρ_{bulk} (kg/m^3)	True density ρ_{true} (kg/m^3)	Porosity n (-)
4	1669	2721	0.38
6	1599	2683	0.39
8	1497	2724	0.42
12	1409	2601	0.44

3.4. Hygrothermal sorption properties

The hygroscopic sorption properties of porous building materials can be measured by the salt solutions in desiccators or in climatic chamber [14]. In this study, there was used a Perani AC520 climatic chamber at 20±2 °C and 50±5% RH. Three representative samples were tested after oven drying at 105 °C for 48 hours. The specimens were placed in the climatic chamber at 20 °C and 30% RH. Their weight was recorded daily, until constant mass was achieved. According to UNI EN 12571 [14], a specimen was considered to be in steady-state when the weight loss between two successive measurements, with a time interval of at least 24 h, remained less than 0.1%. Values at 30%, 50%, 65%, 80%, 93% RH were performed. The moisture content at 97% RH was measured according by salt solution in the desiccator [14]. The specimens were placed in a desiccator containing a Potassium Sulphate (K_2SO_4) saturated solution on the bottom.

The water content (w) was calculated as the amount of absorbed water per dry volume (kg/m^3) with an experimental error of 3%:

$$w = \frac{m - m_0}{V} \tag{5}$$

The sorption isotherms (w(φ)) describes the equilibrium moisture content and it is a function of relative humidity (φ). It was represented by the following relation:

$$w = \exp\left(a \cdot \varphi^b + c \cdot \varphi^d\right) \tag{6}$$

where a, b, c, d were constant to be determined with a multiple regression on the experimental data.

Fig 2 shows the sorption isotherms obtained from adsorption-desorption test. It can be observed that the sorption isotherms of the four materials display a similar slope up to 80% RH. As the relative humidity increases above 80%, the moisture content adsorbed increases especially for the specimens with higher content of fibers (C08- CO12). This is due to the highest porosity of these materials.

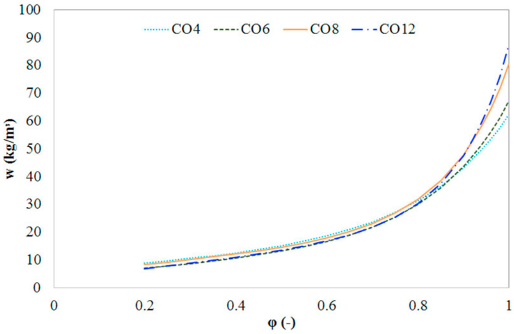

Fig. 2. Sorption curves of different earthen plasters.

4. Hygrothermal simulation

4.1. Calculation

The subject of this analysis was the energy upgrading of an existing building, using two different types of plaster i.e. gypsum plaster and clayey plaster with 6% of olive fibers. A duplex terraced house, placed in a Mediterranean climatic context (climate station of Bari-Palese, Fig. 3), was modeled.

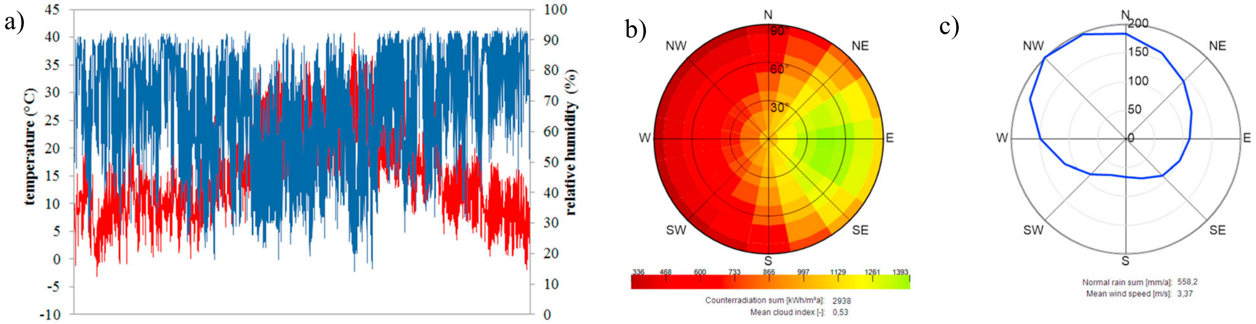

Fig. 3. (a) Temperature and relative humidity of external air; (b) sun radiation; (c) driving rain.

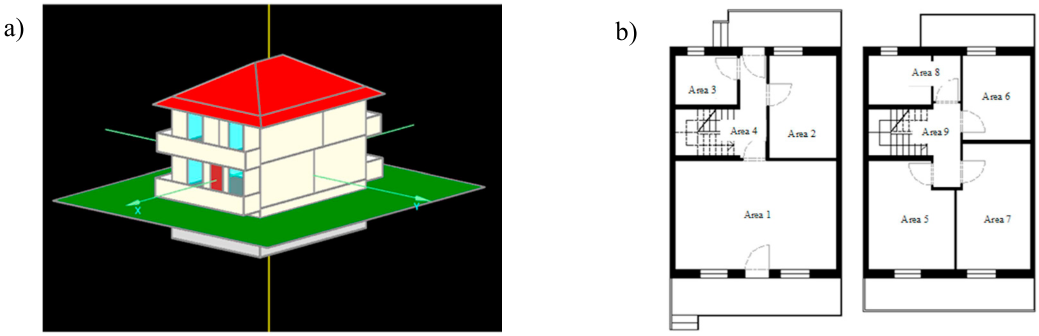

Fig. 4. (a) Test Building; (b) floor plan of the Test Building.

The Test Building (Fig. 4 (a)) was supposed with two levels of about 70 m^2 and height 2.7 m. Nine thermal zones were identified depending on their end use (Fig. 4 (b)). The hygrothermal simulation involved only the two most significant heated zones: the area 1 (living room) and the area 5 (double bedroom).

The external walls consisted of hollow bricks of 25 cm thickness, covered by an external cement-sand plaster of 2 cm thickness. On the internal side there were supposed two different coatings of 1.5 cm thickness:

- Gypsum plaster (GY)
- Clay-olive plaster (CO)

The same cover was applied on both sides of the internal walls and on the internal side of the upper horizontal slab.

Hygrothermal data of clay-olive plaster were reported in Table 2-3-4. Hygrothermal properties of the gypsum plaster, taken from WUFI's database, are: $\rho_{bulk} = 1800$ kg/m^3, $\lambda = 0.9$ W/mK, $c = 837$ J/kgK and $\mu = 20$.

The building was supposed to be occupied 7 days a week by three adults and two children. The internal gain schedule was supposed for each attached zone. Table 5 gives the internal daily schedule for the living room and the bed room.

The analysis were performed supposing two different scenarios: without HVAC (*Unconditioned scenario*) and with an air conditioning system (*Conditioned scenario*).

Table 5. Internal daily schedule.

	Hour	Occupants	Heat convection (W)	Heat radiant (W)	Moisture (g/h)	Human activity (met)	Air velocity (m/s)	Clothing (clo)
Living room	6 a.m.-7 a.m.	5	364	182	216	1.2	0.1	0.7
	1 p.m.-3 p.m.	4	280	140	166	1.2	0.1	0.7
	9 p.m.-11 p.m.	5	364	182	216	1.2	0.1	0.7
Double bed room	11 p.m.-6 a.m.	2	96	48	68	0.7	0.1	0.7

4.2. Unconditioned scenario

The building was simulated in free running conditions without HVAC. Fig. 5 provides results in terms of relative humidity of the indoor air from 1st January to 31st December. It can be appreciated a greater damping capacity of the clay-olive plaster in both areas, especially during the winter. This demonstrates the buffering performance of these olive-clay plaster materials.

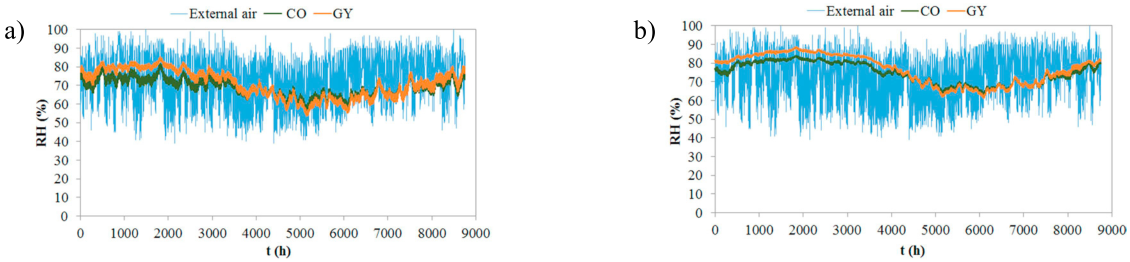

Fig. 5. (a) relative humidity of external air, of indoor air with clay-olive plaster and of indoor air with gypsum plaster of living room; (b) relative humidity of external air, of indoor air with clay-olive plaster and of indoor air with gypsum plaster of bedroom.

The comfort analyses on the basis of the adaptive model, according to UNI EN 15251 [15], shows that the clay-olive plaster allows a reduction in the hours of discomfort during the summer from 33% for gypsum plaster to 23% for clay-olive plaster. In order to reduce such discomfort percentage an HVAC system was considered.

4.3. Conditioned scenario

With the aim to improve the thermal comfort of the occupants it was considered a second scenario. In order to estimate the real energy demand of the building an oversized HVAC plant for heating, cooling, humidification and dehumidification was supposed. The model were re-run according to new design conditions: 20 °C and 50% relative humidity in winter (i.e. from 15th November to 31st March); 26 °C and 50% relative humidity in the rest of the year (i.e. from 1st April to 14th November).

The cooling energy demand in summer is showed in Fig. 6 for the living room and the double bedroom.

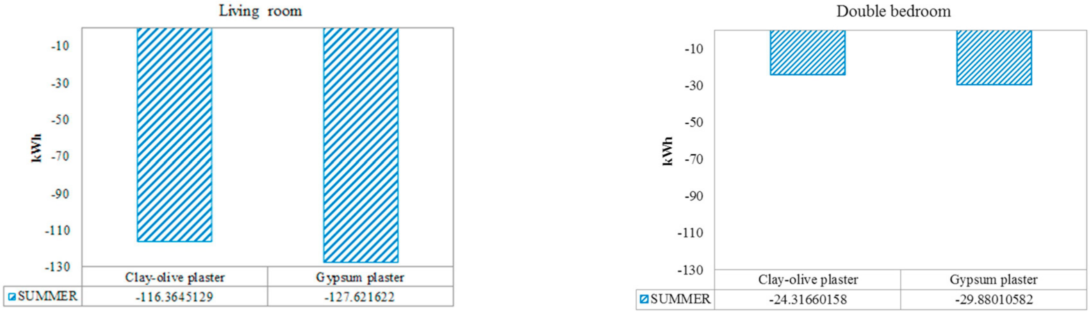

Fig. 6. Total energy demand in summer

Some reduction in the energy demand can be appreciated for the clay-olive plaster, it can be due to its better hygrothermal properties in comparison to the gypsum plaster ones.

The heating energy demand in winter is the same for the two types of plasters. Perhaps the latent load in winter is not very significant, so the interaction between plasters and internal air is negligible.

5. Conclusions

The results achieved from the test measurements and the hygrothermal simulation show that the addition of the vegetable fibers in clayey mixtures have a great impact on the density and the thermal conductivity. When increasing the olive fiber percentage, the thermal insulation capacity enhances.

The dynamic simulations by WUFI®Plus underline a moderate enhancement of the buffering performance with the addition of the vegetable fibers. Considering a first scenario without HVAC system, the numerical simulations showed that the clay-olive plaster dumps the amplitude of relative humidity fluctuations especially during winter in comparison with traditional plaster. The use of such plaster resulted in a reduction in the hours of discomfort in summer under free running conditions. Considering an HVAC system, the energy demand for humidification/dehumidification and cooling/heating was studied. A reduction of energy demand can be noted in summer when using clay-olive plaster.

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