IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

Thermo-hygrometric behavior of hempcrete walls for sustainable building construction in the Mediterranean area

To cite this article: P Aversa *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **296** 012020

Thermo-hygrometric behavior of hempcrete walls for sustainable building construction in the Mediterranean area

P Aversa[1], B Daniotti[2], G Dotelli[3], A Marzo[4], C Tripepi[4], S Sabbadini[5], P Lauriola[1,6] and V A M Luprano[1,]*

[1] ENEA C.R. Brindisi, Department for Sustainability, SS 7 km 706, Brindisi, 72100, Italy
[2]Politecnico di Milano, Department of Architecture, Built environment and Construction engineering, Via G. Ponzio 31, Milano, 20133, Italy
[3]Politecnico di Milano, Department of Chemistry, Materials and Chemical Engineering "G.Natta", p.zza L. da Vinci 32, Milano, 20133, Italy
[4]ENEA C.R. Bologna, Department for Sustainability, Via Martiri Monte Sole 4, Bologna, 40129, Italy
[5] Politecnico di Milano, Department of Architecture and Urban Studies, p.zza L. da Vinci 32, Milano, 20133, Italy
[6] University of Camerino SAAD, Viale delle Rimembranza, Ascoli Piceno, 63100, Italy

* vincenza.luprano@enea.it

Abstract. Recent studies have demonstrated that the use of natural materials represents one of the pathways to achieve energy efficiency and environmental sustainability in buildings. In the framework of Circular Economy policies aimed at reducing the consumption of raw materials, shives, as an agricultural by-product of hemp cultivation, have gained a renovated life in the construction sector. Among all the building products made of hemp, hempcrete blocks are the most innovative, because they represent the solution to the needs of new and traditional buildings, offering a high energy saving, combined with the sustainability of materials and products, while remaining, in terms of shape and size, very close to the culture and the construction systems best known by professionals. In order to assess the potential benefits of hempcrete in the construction sector, its environmental performances were evaluated using the LCA methodology, following the international standard ISO 14044:2006+A1:2018 and in compliance with the European standard EN 15804:2012+A1:2013. To this purpose, four non-loadbearing walls were compared in the "cradle-to-gate" scenario, one made with hempcrete blocks and the others with more "traditional" materials. This research aims to be a basis for the development of future guidelines at national and international level in order to guarantee the maximum diffusion of this type of product also in the Mediterranean area. For this reason, it is important to identify the performance characteristics essential for hempcrete products studying their behavior not only as defined in the UNI EN ISO 12571, 2013 standard, but also in the Mediterranean climate. To achieve these objectives, some tests have been carried out to verify the thermo-hygrometric behavior. A 1 m2 of hempcrete wall was submitted to tests in a climatic chamber which simulated the environmental conditions typical of the south of Italy, in terms of temperature and moisture, in order to evaluate thermo-hygrometric behavior of hempcrete. Sensors and thermo-flowmeters for parameter analysis were applied on the wall. On the same material was carried out hygroscopic sorption tests as defined in the UNI_EN_ISO12571,2013 standard. The behavior detected by the experimental measurements on the masonry was compared with the simulated numerical behavior using WUFI software.

1. Introduction

The reactivation of hemp's production chain generated new usage scenery for this material, even in the construction field, often, starting from the by-products of the seeds processing (not eatable oils), of the stem (short fibers unusable in textile field) and the hard hemp. Fibers are used both to produce insulating mats and as reinforcing fibers for plasters or other prefabricated materials in bio-construction. In terms of energy performance for the Mediterranean areas, the fibers are a good solution for thermal insulation as much as construction with high thermal inertia since they can grant good performances for all climatic zones. In the construction field, hard hemp is especially used for its characteristics of porosity and lightness for technologies and productions used for thermal insulation. The mix-design of this material, like aerial lime, hydraulic binders, earth, silicates does not generate very high insulation performances, especially if compared to insulation materials of petrochemical origin like EPS, but the need of higher thickness to obtain the requested transmittance values and its natural and intrinsic properties confer to the wall other qualities in terms of health of the environment (walls breathability, thermal leg, hygrometric regulation). Hard hemp, in its different sizes can be used as bulk insulation to fill closed double walls. The durability and sanitation of hemp straw could be solved with mineralization processes. To confer dimensional stability to the fills and at the same time avoiding constipation, in the last years several mix designs and technologies were developed to solve this problem by using mixtures developed directly on the worksite or with industrial products. The critical point of the mixtures realized and laid in the worksite is the drying time. The porosity of the hemp hurd absorb and hold water for long time and the conditions of the worksite have to enable a quick and good drying process in order to avoid any alteration of the vegetable material duration. While the products realized on-site, can adapt to every need and specificity, even if they require professional rules for the laying process and tests to value the effective performances, the industrialized products increase the environmental impacts, but they can grant consistency and certified quality of the product. The mix design based on vegetable aggregate such as hemp hurd led to a vastness of products with different typologies and grain sizes of the hemp hurd, dosages, binder typologies (aerial, hydraulic, natural like the earth), as well as to the use of additives and of pozzolanic materials, not to mention the wide range of application techniques. The choice of the hemp hurd and its performance standards, nowadays is not exhaustively solved. Indeed, hemp straw, unlike mineral aggregates, because of its organic nature can induce chemical reactions between the binder and sugars, lignine and other substances contained in the hemp stem. Furthermore, the choice of a variety of hemp plants can result in the presence of different percentage of several substances contained in it causing different reactions with the chosen binder. For this reason, identifying not only the physical characteristics of the product (grain size, density, moisture content, powder content...), but also the vegetable origin of the material, i.e. the variety of the plants and their chemical characteristics, becomes extremely important.

The blocks production is centered mainly on products for self-supporting walls or surfaces with vibrocompression production chain. In Spain it exists even a production chain for loadbearing blocks in hempcrete and *terracanapulo* (hemp hurd and earth). Even if the thermal insulation capacity of the blocks is lower than that of other hemp-based products created on the worksite, maturing and drying in the factory guarantee product homogeneity making them particularly suitable for their use on site; indeed, this strategy solvesall the problems concerning timing, drying process and quality/reproducibility of the product. For this research on the hygro-thermal behavior of hempcrete, it has been decided to use mature and ready to use hempcrete blocks, for both speeding up the testing time and for having standardized products. Furthermore, since these blocks are products certified with laboratory tests, it was possible have access to more data to compare the results of the performed tests.

For the same reason, also plaster and bedding mortar mixtures were chosen among industrialized products. Hempcrete mixtures in Italy started approximately ten years ago, which means around twenty years since their first creation in the neighboring countries of France, Switzerland and England. Again, ten years ago the first company to develop industrialized products was born (Equilibrium) and since then the growing interest for the hemp in every sector has led to the creation of other industries and new construction products. The development of construction techniques was possible thanks to the contribution of green building associations and university researches. Nowadays, on the Italian territory, there are some companies of first transformation. Despite this presence, a lot of hemp hurd for the industrial production is imported from abroad because of the warranty of constant quantity and quality. The production companies are mostly focused on the production of the blocks. Even in this case, despite the many national production centers, there are importers of products from other European countries, even if there is not a big variation of the quality of the product. Nowadays the block production companies have completely different mix designs (especially in the use of different binders: aerial lime, hydraulic lime, concrete, hydraulicized lime, lime mix...) for this reason it is hard to find a harmonized standard to be used for all the products [1].

This research aims to be a basis for the development of future guidelines at national and international level in order to guarantee the maximum diffusion of this type of products also in the Mediterranean area. For this reason, it is important to identify the performance characteristics essential for hempcrete products studying their behavior not only as defined in the UNI EN ISO 12571:2013 standard, but also in the Mediterranean climate. To achieve these objectives, some tests have been carried out to verify the thermo-hygrometric behavior. Before, a preliminary analysis of its environmental performances as measured by LCA was carried out.

2. LCA of hempcrete blocks

Life Cycle Assessment (LCA) is a largely accepted methodology used to evaluate environmental performances of building products, among others. Moreover, there are well established international ISO standards (ISO 14040:2006 [2] and 14044:2006+A1:2018 [3]) and European standards as well (for instance, EN 15804:2012+A1:2013 [4]) that regulate the application of this methodology, in particular in the construction sector.

As many other new building materials, hempcrete has attracted the interests of researchers and many studies have focused on its physical and mechanical properties; for a detailed account see the recent review by Ingrao et al. [5]. However, few studies have investigated hempcrete environmental performances and even less have analyzed hempcrete blocks [6][7], to the best of our knowledge.

To give a preliminary account of the environmental sustainability of hempcrete blocks, a comparative assessment of 4 different non-loadbearing walls is performed. In this case, the function expressed by the walls is the ability of self-standing as a wall, but no other properties are accounted for. Normally, in this type of studies the wall thermal performances are considered and thermal transmittance as measured by U is the most common functional unit adopted. However, in the present study we have only thermal transmittance as measured in our experimental set-up, while for the other possible walls we have not performed any experiment. For this reason, in this preliminary LCA evaluation we have just considered as functional unit (FU) 1 m^2 of non-loadbearing wall finished on both sides. Detailed description of the four wall assemblies is given in Table 1.

Table 1. Detailed stratigraphy of the four wall assemblies analyzed with the LCA methodology.

Assembly	Thickness [cm]	Layer
Hempcrete wall system	0.5	External finishing
	1.5	external plaster
	30	hempcrete blocks
	0.6	mortar
	1.5	internal plaster
	0.5	internal finishing
	34.6	
AAC wall system	0.5	External finishing
	1.5	external plaster
	33	AAC blocks
	0.4	mortar
	1.5	internal plaster
	0.5	internal finishing
	37.4	
Expanded clay wall system	0.2	External covering
	1.3	external finishing
	9	thermal insulation (EPS)
	0.2	adhesive glue
	0.6	mortar
	30	Expanded clay blocks
	1.5	internal plaster
	0.5	internal finishing
	43.3	
Masonry bricks wall system	0.3	External covering
	0.5	external finishing
	4	thermal insulation
	0.2	adhesive glue
	0.4	mortar
	30	Masonry bricks
	1.5	internal plaster
	0.5	internal finishing
	35.4	

The materials selected for comparison have been certified with an environmental label of type III (ISO 14025) [8]; accordingly, their environmental performances were taken from their Environmental Product Declarations (EPD):

- Leca Universalblock made on lightweight concrete and expanded clay (EPD was approved by the “Norwegian EPD Foundation” in 2014): Expanded clay wall system;
- Wienerberger bricks (EPD approved by the “IBU - Institut Bauen und Umwelt” in 2014): masonry brick wall system;
- Xella Ytong blocks made on cellular concrete (EPD approved by the “IBU - Institut Bauen und Umwelt” in 2016): AAC wall system;

The hempcrete block, instead, has not yet been certified and the data source is private communication and previous studies [6,7]. To be consistent with the EPD of these materials, the impact categories adopted are those required by the standard EN 15804:2012+A1:2013 [4]:

- Global warming potential (GWP) measured in kg CO2 eq.;

- Depletion potential of the stratospheric ozone layer (ODP) measured in kg CFC11 eq.;
- Formation potential of tropospheric ozone photochemical oxidants (POCP) measured in kg ethylene eq.;
- Acidification potential of land and water (AP) measured in kg SO2 eq.;
- Eutrophication potential (EP) measured in kg PO43- eq.;
- Abiotic depletion potential for non-fossil resources (ADP) measured in kg Sb eq.
- Abiotic depletion potential for fossil resources (ADPE) measured in MJ.

The scenario adopted is from-cradle-to-gate, which according to [3] include the following stages: A1-A3, where the gate is the product manufacturer gate. Transport to construction site and construction phase at this preliminary level have been neglected, considering also the uncertainty about data.

Life Cycle Impact Assessment (LCIA) results are summarized in Figure 1. Masonry bricks wall system is the most impacting assembly in 5 out of seven categories, and the expanded clay wall system is the second most impacting in 4 out of seven categories. The best performances are given by the hempcrete and ACC wall systems. In AP, GWP, and ADP Fossil Fuels hempcrete wall is outperforming ACC wall, while in POCP and ADP there is practically no sensible difference between the two. Only in ODP hempcrete wall performs lower than others; the result is not very clear and further investigation is ongoing.

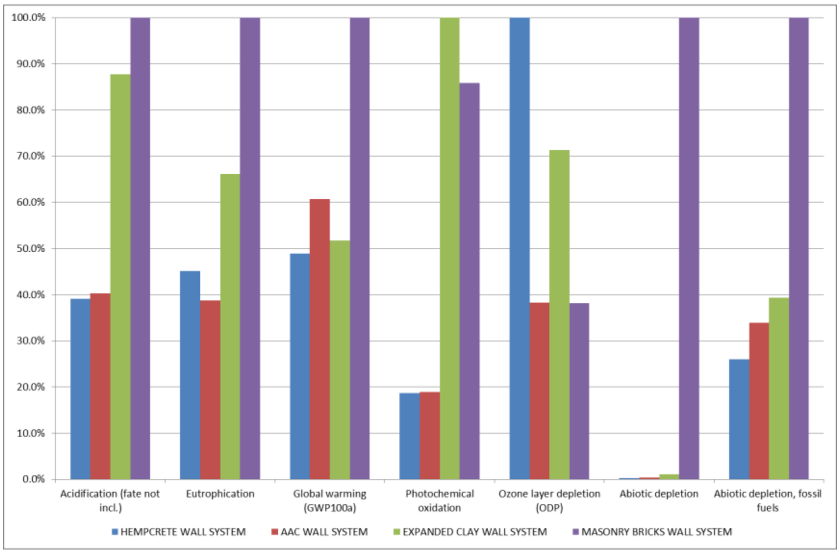

Figure 1. Comparison of the 4 walls assemblies in the seven impact categories considered.

3. Experimental details

Samples coming from 3 different companies were received in the laboratory, after having made the request to all Italian manufacturers of hempcrete blocks. For privacy reasons it is not possible to share the name of these companies, but we will use the codes A3, A4, A5 (Figure 2).

For transmittance tests, on the other hand, a specially designed wooden framework, with inside blocks from the A4 company were requested.

As can be seen from Figure 2, even at purely aesthetic levels, the products differ a lot in shape and color. Also to the touch, some differences were observed.

Figure 2. Hempcrete samples of three different companies (A3, A4, A5)

3.1. Hygroscopic sorption on the hempcrete samples

On the samples were carried out hygroscopic sorption tests as defined in the UNI_EN_ISO12571,2013 standard. The objective of the method is the definition of the moisture content of a material that is in equilibrium with the environment in which is laid.

In the standard there are two alternative methods for determining this characteristic:

- Desiccator method: using a desiccator and a weighing cup
- Climatic chamber method: using a climatic chamber

According to the equipment available in the laboratory, the test methodology that we selected is the second one, the climatic chamber method.

The standard does not indicate specific dimensions for the test specimens. It indicates only that they must have a mass of at least 10 g. Another indication reported in the document declares that, for materials with a dry density less than 300 kg/m3, the minimum area must be 100 mm x 100 mm.

Our products have a declared dry density that is higher than 300 kg/m^3 but we can define that the specimens have a cubic shape with the following dimensions:

Thickness: 100 ± 1 mm; Length: 100 ± 1 mm; Width: 100 ± 1 mm.

The testing results are reported in Table 2 and in Figure 3 the graphs of the moisture contents.
The type A4 blocks were chosen for the following activities as they are better representing the average Italian production as for the moisture behavior.

Table 2. Samples' weights for different relative humidities [g]

Relative Humidity (%)	0%	30%	50%	70%	80%	85%
A3	279	283	285	288	290	292
A4	366	370	374	378	381	384
A5 (26/04/18)	383	389	392	396	399	402
A5 (17/05/18)	375	379	381	387	389	391

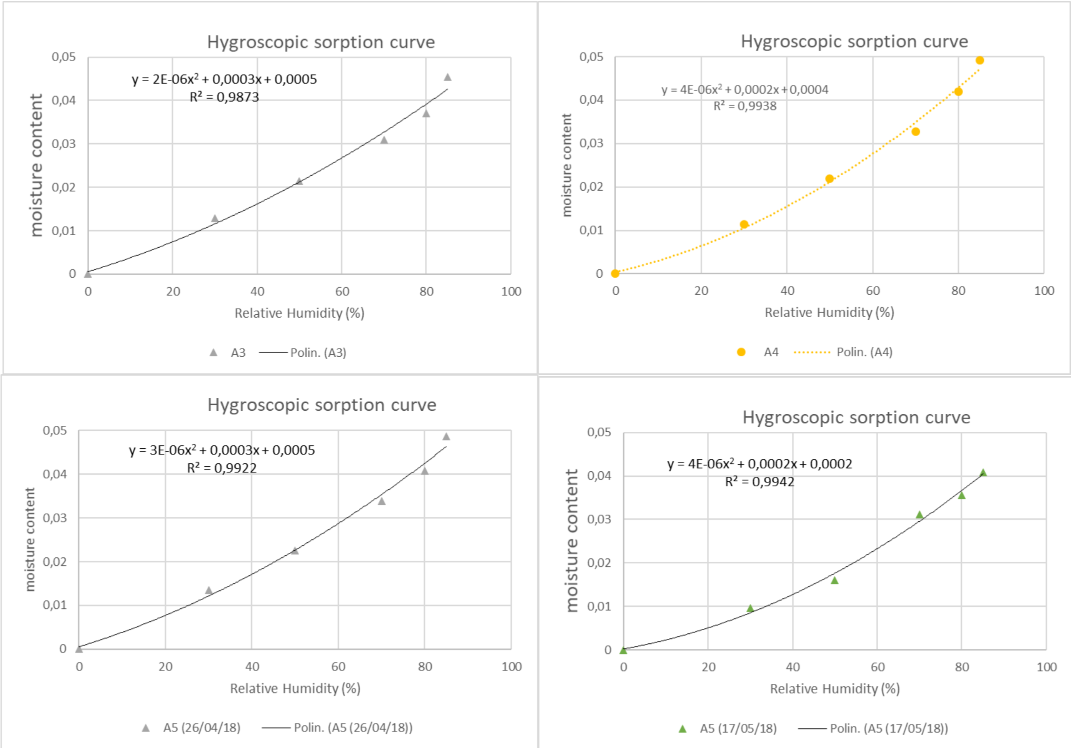

Figure 3. Moisture contents of samples A3, A4 and A5

3.2. Weathering test

In order to evaluate thermo-hygrometric behavior of hempcrete, 1 m^2 wall was submitted to tests in a climatic chamber. It was necessary to make a project of a framework to support the wall of hempcrete blocks plastered on both sides (Figure 4). Two cycles at constant temperatures, 23°C and 35°C respectively, and time-varying level of humidity (Table 3) have been performed. The second one simulates the environmental conditions typical of the south Italy weather.

Table 3. Time-varying levels of humidity

Relative Humidity (%)	Time (min)
30%	180
50%	180
30%	180
70%	180
30%	180
80%	180

The dimensions of the blocks are Length 50 cm, Height 20 cm, Thickness 30 cm. The plaster chosen is a premix based on NHL 5 hydraulic lime.

Figure 4. Hempcrete blocks' wall in the framework

The hempcrete wall has been applied on the climatic chamber in order to simulate outdoor conditions on the external surface and to keep controlled indoor conditions in lab (Figure 5).

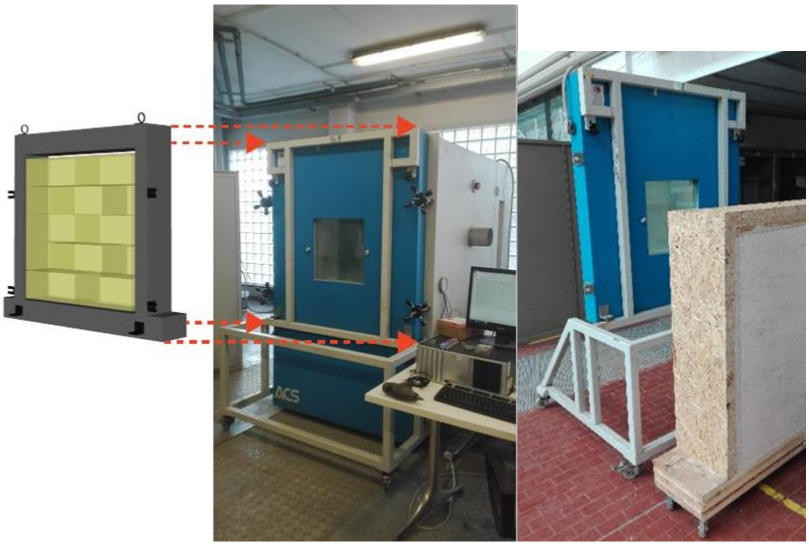

Figure 5. Hempcrete blocks' wall application on the climatic chamber

The sensors and thermo-flowmeters devices were applied on both sides of the wall, as depicted in Figure 6 (a,b), in order to measure its hygrothermal behavior according to the UNI ISO 9869-1:2014 [9,10]. Since the chamber simulates the external climate, hereinafter the location of the sensors will be referred to as *internal side* (for the laboratory side) and *external side* (for the chamber side).
The experimental measures have been performed by using the equipment shown in Table 4.

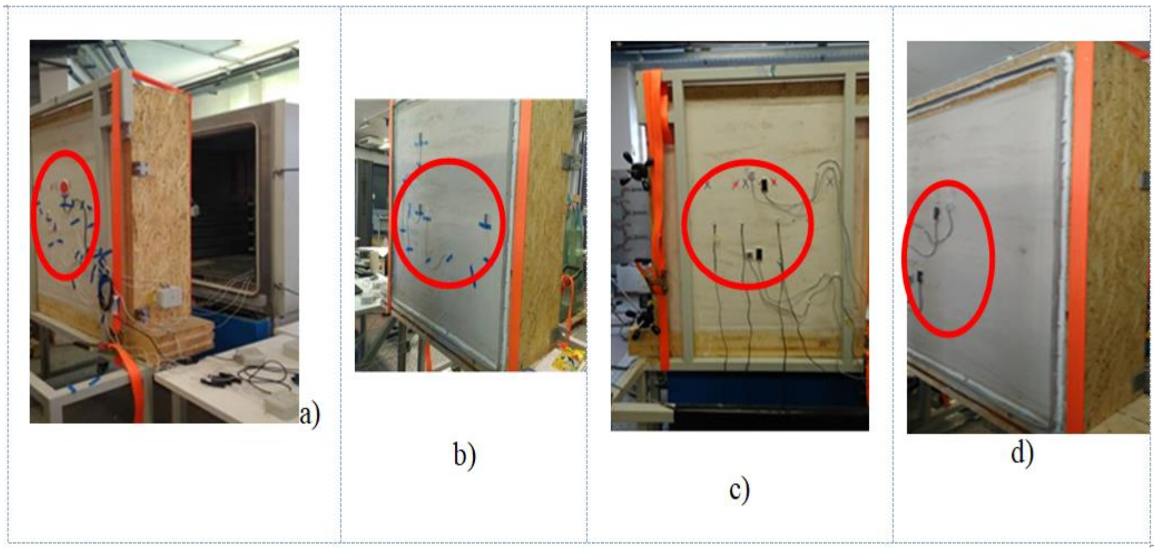

Figure 6. Location of devices on the hempcrete wall at both laboratory and chamber sides: a,b) thermo-flowmeters sensors; c,d) temperature and humidity sensors.

Table 4. Experimental equipment

DEVICE	FEATURES
Angelantoni CH 1200 Environmental Chamber	- Temperature range: -40/+180°C - Accuracy of temperature: ±0,25°C..±0,3°C - Temperature variation velocity (IEC 60068-3-5): 4°C/min upward and downward - Relative humidity range: 10% - 98% within the range +5/+95°C - Dew point temperatures: +2/+94°C continuous testing ; -20/+2°C random testing - Accuracy of humidity: ±1% - ±3%
Thermo-flowmeters kit Capetti (ISO 9869) - Figure 6 (a,b)	diameter 50 mm, Thickness 5 mm, sensibility 50 µV/m2, precision ± 5%(@T=20°C), range of temepratture between -30°C e +70°C, sensor thermal resistance lower than 6.25·10-3 m2K/W, range between -2000 e +2000 W/m2
Environmental temperature and humidity sensors type PT1000 class A	- Alloy plates - Temperature range: 10°C ÷ 60°C - Humidity range: 10% ÷ 90% - Resolution: 0,01°C - Accuracy: 0,1 °C
Contact temperature sensors type T1000 - Figure 6 (c,d)	- Alloy plates - Temperature range: -20°C ÷ +40°C - Humidity range: 10% ÷ 90% - Resolution: 0,01°C - Accuracy: 0,1 °C

4. Results and discussion

4.1. Thermal transmittance measurement

The hygrothermal behavior of the hempcrete wall described in the above paragraphs has been analyzed according to the rules UNI EN 15026:2008 [11], UNI EN ISO 13788: 2013 [12] and UNI EN ISO 13786: 2018 [13].
The thermal transmittance, experimentally valuated considering a time range of seven days, was 0,21 W/m^{2}K, in line with the value 0,22 W/m^{2}K calculated according to the UNI EN ISO 6946:2007 [14].

4.2 Thermo-hygrometric experimental measurements

The hempcrete wall, equipped as described in the paragraph 3.2, was connected on one side (*external side*) to the climatic chamber, which simulates the external environment, and on the other side (*internal side*) exposed to the laboratory internal environment. Then, in order to simulate the south of Italy environmental conditions, the wall was undergone on the external side to two different cycles at constant temperatures (23°C and 35°C respectively) by varying, at the same time, the humidity as summarized in Table 3.

As a result, the time-variation of temperature and humidity contents on both sides of the wall have been measured and plotted in terms of time-humidity and time-temperature curves (Figure 7 and 8). In particular, resulting curves are referred to a month of measures (from 17/07/2018 to 17/08/2018).

The experimental results related to the 23°C-cycle, plotted in the Figure 7, show that the humidity content on the *internal side* is about 57-58% against a value that oscillates and reaches 60%, as the maximum, on the *external side* and a maximum value of 80% set up within the chamber (see Table 3). With regard to the temperature, a value of 31-32°C is recorded on the *internal side*, for in the face of a quite constant value of 23°C on the *external side*.
The environmental temperature of the laboratory (*internal side*) was 32 ° C.

As far as the experimental results related to the 35°C-cycle, plotted in the Figure 8, an almost constant content of humidity of about 58-60% is recorder on the *internal side* although on the *external side* it oscillates and reaches about 65%, as the maximum. Please note that the maximum value of humidity applied to the chamber was always 80%. As far as the temperature is concerned, on the *external side* this is about 32-33°C against a value of 34°C measured on the *internal side*. The environmental temperature of the laboratory (internal side) was 32 ° C.

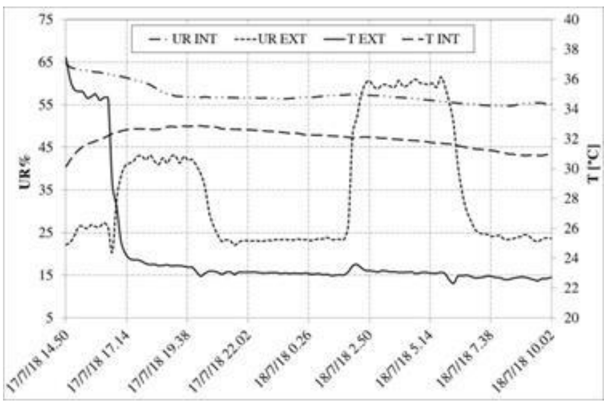

Figure 7. Experimental time-variation of temperatures and humidity at both side of the wall: Cycle at 23°C

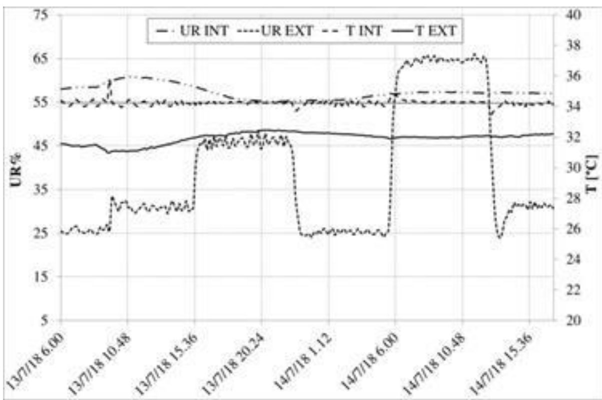

Figure 8. Experimental time-variation of temperatures and humidity at both side of the wall: Cycle at 35°C

It is worth noting that, whereas the external humidity varies over time reaching a maximum value of about 80% within the chamber, on the *external side* of the wall does not reach more than 60% and on

IOP Conf. Series: Earth and Environmental Science **296** (2019) 012020 doi:10.1088/1755-1315/296/1/012020

the *internal side* has a steady value of about 58% at 23°C. Instead at 35°C, on the *external side* of the wall does not reach more than 65% and on the *internal side* has a steady value of about 55%.

4.3. Numerical simulations

One of the purposes of this research activity was to set up a numerical model of the experimental system, so as to carry out also parametric analyses. The exterior and interior environmental loading, and the description of the output results from the heat and moisture transfer models demonstrate how moisture problems may be investigated and how better design alternatives can become possible using hygrothermal analysis [15]. Therefore, through the software WUFI® [16], a model replicating the features of the wall described in Table 1(hempcrete wall system) was implemented and the cycles, applied to the climatic chamber, numerically simulated. Then, the dynamic hygrothermal behavior was investigated, according to UNI EN 15026 [11] and UNI EN 13790 [17] for the two cycles at 23°C and 35°C respectively. A good agreement between experimental and numerical results has been obtained in terms of the wall thermal behavior. Comparing the experimental and numerical results from point of view of the vatiation of humidity (Figure 9 and 10), it is worth noting that, in both cases, the time-variation of humidity recorded on the *external side* it is not observed on the *internal side*. This means that the external humidity is not transferred to the internal part, demonstrating the efficiency of the insulating behavior of the hempcrete wall, but, for both temperatures, the experimental value of the humidity detected on the internal side is higher of about 10% then the numerical one.

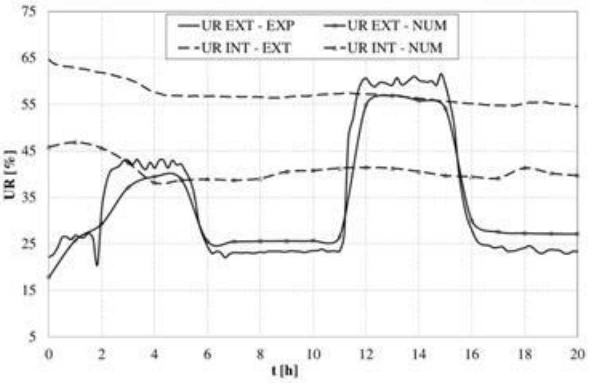

Figure 9. Comparison between experimental and numerical results: Humidity variation at T=23°C

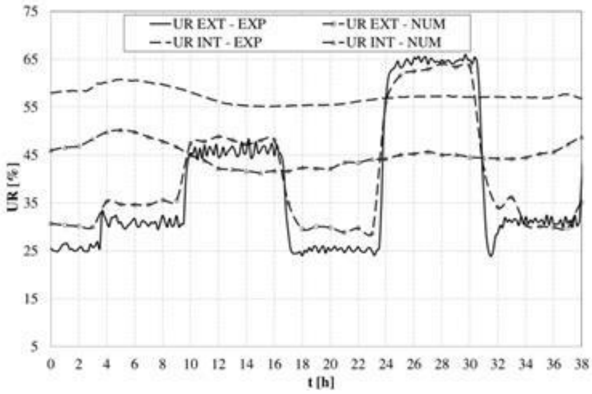

Figure 10. Comparison between experimental and numerical results: Humidity variation at T=35°C

5. Conclusions

Hempcrete blocks represent a solution to the needs of new and traditional buildings, offering a high energy saving, combined with the sustainability of materials and products, while remaining, in terms of shape and size, very close to the culture and the construction systems best known by professionals. Different kind of Italian production of hempcrete blocks are studied in this paper. Even if the thermal insulation capacity of the blocks is lower than that of other hemp-based products created on the worksite, maturing and drying in the factory guarantee product homogeneity making them particularly suitable for their use on site; indeed, this strategy solvesall the problems concerning timing, drying process and quality/reproducibility of the product.

Preliminary environmental assessment by LCA seems to indicate a good performance of hempcrete blocks walls with respect to other conventional materials. Further investigation is needed both in terms of primary data collection and wider scenario, i.e. considering also post-construction stages.

In order to evaluate thermo-hygrometric behavior of the hempcrete blocks, one square meter of wall was submitted to tests in a climatic chamber simulating the environmental conditions typical also of the south of Italy weather.

So as to reproduce and predict the hygrothermal behavior of the wall, a numerical model of the experimental system was set up through the software WUFI® and the cycles, applied to the climatic chamber, numerically simulated. A good agreement between experimental and numerical results has been obtained in terms of the wall thermal behavior.

In both cases, the time-variation of humidity recorded on the *external side* was not observed on the *internal side* demonstrating the efficiency of the insulating behavior of the hempcrete wall, but for both temperatures, the experimental values of the humidity detected on the internal side are higher of about 10% then the numerical one.

Acknowledgments
This work was supported by PAR2017 Project (D.2 Nearly zero energy buildings (nZEB)) funded by Italian Ministry of Economic Development.

References
[1] Aquari L 2017 The “hempcrete” blocks: definition of guidelines for prototyping, designing and maintenance to ensure material durability *Degree thesis* (Politecnico di Milano)
[2] ISO 14040:2006 Environmental management-Life cycle assessment–Principles and framework
[3] ISO 14044:2006+A1:2018 Environmental management-Life cycle assessment-Requirements and guidelines
[4] EN 15804:2012+A1:2013 Sustainability of construction works-Environmental product declarations-Core rules for the product category of construction products.
[5] Ingrao C, Lo Giudice A, Bacenetti J, Tricase C, Dotelli G, Fiala M, Siracusa V and Mbohwa C 2015 *Renewable & Sustainable Energy Reviews* **51** 29-42
[6] Arrigoni A, Pelosato R and Dotelli G 2016 *SBE16 Hamburg: Strategies – Stakeholders – Success factors Conference Proceedings* ed ZEBAU – Centre for Energy, Construction, Architecture and the Environment GmbH (Hamburg, Germany), 650-659
[7] Arrigoni A, Pelosato R, Melià P, Ruggieri G, Sabbadini S and Dotelli G 2017 *Journal of Cleaner Production* **149** 1051-1061
[8] ISO 14025:2006 Environmental labels and declarations - Type III environmental declarations - Principles and procedures
[9] UNI ISO 9869-1:2014 Thermal insulation - Building elements – In situ measurement of thermal resistance and thermal transmittance - Heat flow meter method
[10] Aversa P, Donatelli A, Piccoli G, Luprano VAM 2016 *SSP-Journal of Civil Engineering* **11**(**2**) 39-52
[11] UNI EN 15026:2008 Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation
[12] UNI EN ISO 13788:2013 Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation
[13] UNI EN ISO 13786: 2018 Thermal performance of building components - Dynamic thermal characteristics - Calculation methods
[14] UNI EN ISO 6946:2007 Building components and building elements-Thermal resistance and thermal transmittance-Calculation method
[15] Künzel H M, Achille N Karagiozis 2010 *Materials for Energy Efficiency and Thermal Comfort in Buildings* ed Matthew hall. DOI: 10.1533/9781845699277.1.54
[16] Cascione V 2016 Valutazione igrotermica di soluzioni tecniche d'isolamento dell'involucro edilizio per il recupero energetico in Italia per mezzo di simulazioni dinamiche. *Degree thesis* (Politecnico di Bari, Bari), p. 154 (In Italian)
[17] UNI EN ISO 13790:2008 Energy performance of buildings-Calculation of energy use for space heating and cooling