



Case Report

Historic Building Energy Audit and Retrofit Simulation with Hemp-Lime Plaster—A Case Study

Rosa Agliata , Alfonso Marino, Luigi Mollo and Paolo Pariso * 

Department of Engineering, University of Campania “L. Vanvitelli”, 81031 Aversa (CE), Italy;

rosa.agliata@unicampania.it (R.A.); alfonso.marino@unicampania.it (A.M.); luigi.mollo@unicampania.it (L.M.)

* Correspondence: paolo.pariso@unicampania.it; Tel.: +39-0815010332

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Abstract: Hemp-lime composite is a natural material, which is being increasingly used and studied in the construction sector, thanks to its recyclability, hygrothermal comfort and healthiness features. The aim of this paper is to test the benefits in terms of energy efficiency achieved through the use of hemp-lime composite as insulation in a possible refurbishment intervention. With the aim of extending the knowledge about the benefits achieved through from the integration of this natural material into construction production process, a real building in south of Italy was selected and a substitution of the standard gypsum-lime plaster with a hemp-lime one was simulated by means of a specific software (Termus[®] by Acca Sotware, Bagnoli Irpino, Italy), serving for the assessment of the energy performance. Case study analysis highlighted the good thermal insulation properties of hemp-based plaster, allowing thermal dispersion to decrease in the winter season and improve the summer performance of the walls by approximately 20% compared to traditional plaster. This results in a one-level improvement of the building in energy classification according to Italian regulation.

Keywords: sustainability; sustainable materials; energy audit; energy simulation; energy retrofit; built heritage; hemp-lime

1. Introduction

The transition from the linear economy towards the circular economy implies a deep transformation of the productive systems and has significant implications for the economy, society and the environment. [1]. In particular, environmental impact is a pivotal theme that is being increasingly implemented in the economic development of all sectors [2], particularly those with high pollution rates, such as the AEC (architecture, engineering and construction) industry [3]. Buildings and other structures entail many environmental issues during construction, operation, maintenance and destruction phases, such as large waste production, huge energy demand and high consumption of raw materials and natural resources [4]. As the use of non-renewable resources is universally considered unsustainable and likely to damage the environment [5], it is necessary to develop alternative strategies to meet human needs from a long-term perspective while safeguarding both people and the planet, considering the life cycle assessment (LCA) of buildings in both new edifications and refurbishment interventions [6]. Over the past years, building sustainability and LCA have become crucial topics [7], increasing interest in low- and zero-emission buildings and construction methods that can facilitate the reduction of CO₂ emissions [8], fossil fuel consumption and energy intake [9], according to the latest European regulations [10,11]. However, up until recently, eco-building has mainly focused on energy efficiency during service life, making use of high-performance insulation [12], renewable energy and rainwater collection, yet continuing to build structures from petrochemical-based synthetic materials. Concrete, steel and plastic are among the most used materials in the AEC industry; they have high energy demand, toxic production processes, do not biodegrade easily and are not suitable to

be disposed of in a landfill [13]. Also, many building components and insulation products make use of noxious additives like glues, binders and flame-retardants (e.g., brominated artefacts).

Only lately have the nature of the materials and methods started to be considered as equally important [14], making eco-friendly materials assume a fundamental role in the concept of sustainable development in the AEC sector. Thus, society has begun to look for sustainable materials that are renewable (i.e., materials that can be replaced, regenerated and reused without damaging the environment), less pollutant, consume minimal fossil fuel energy and have low level of greenhouse gas emission and health risk [15]. In Europe, in the last few years, a lot of effort has been allocated in this direction, taking and implementing many operative actions. For example, a number of EU research project on these topics have been funded, such as the “Energy Efficiency for EU Historic Districts Sustainability” (EFFESUS) [16] and the “Robust Internal Thermal Insulation of Historic Buildings” (RiBuild) [17]. In these projects, themes linked to energy efficiency are widely developed and experimental, operative and methodological outcomes are shared, especially regarding the thermal retrofit of historic built heritage by means of innovative insulation materials (e.g., aerogel) [18,19], relating energy benefits to economic ones by using the “Cost Optimality” methodology [20] and evaluating the proposed thermal insulations in a life cycle perspective [21]. Results of these studies are interesting and promising, but the tested products, tools and experimental procedures are not based on the use of “natural based solutions”. The demand for natural and non-toxic construction materials as an alternative to synthetic products, ensuring at the same time a high level of performance, is growing rapidly as public awareness of green issues has grown [22]. Moreover, the use of natural based materials in the AEC sector and in particular for historical building is considered as optimal by many recent studies [23–28]. Despite this ever more growing interest and the fact that a large part of eco-friendly building materials is already natural based, only a few operational and experimental data are available on their application to historical built heritage. This work tries to create an accumulation of knowledge on this issue, providing information to researchers and designers on the use of a natural-based material as insulations in a historical building. The chosen material is hemp-lime, a composite construction material that can be used in many forms (bricks, panels, paste, etc.) and for many scopes (e.g., insulation for walls, roofs and floors or as a part of timber-framed construction). Thanks to their insulation, health and recyclability features, hemp-based materials for building applications are increasingly catching researchers’ attention [29]. The aim of this paper is to test the benefits in terms of energy efficiency by means of energy performance indexes (i.e., thermal dispersions, hygrometric behaviour, energy consumption, CO₂ emissions and EU energy efficiency rating) deriving from the use of hemp-lime composite as insulation.

This paper, after an evaluation of critical and beneficial points of hemp products, presents the analysis of a case study. The hemp was also chosen because it is produced and processed in the area where the historic building is located, therefore hemp can be supplied at zero kilometre. For this aim, a real building in chosen and its thermal behaviour is calculated, by means of a specific software (Termus[®] by Acca Software), in both present condition and simulating a building refurbishment operation in which hemp-lime plaster is used to replace the standard one.

2. Challenges and Benefits of Hemp Use in AEC Sector

Challenges that AEC is nowadays facing to reduce its environmental impact are summarized in Table 1. In the left-hand column, the primary role of the AEC sector is displayed, highlighting its global importance that transversally produces significant effects in different contexts; the right-hand column displays the objectives that the sector should reach in terms of sustainability are shown. As an example, one of the primary issues in the AEC industry is the fact that it entails a large consumption of raw materials generating both high energy consumption (see Table 1, Challenge 1) and high level of wastes (see Table 1, Challenge 3). Thus, considering the life cycle assessment of the buildings and their network infrastructures (i.e., water and waste water systems), choosing sustainable construction materials, to be regenerated and reused, with low level of greenhouse gas emission and ensuring high level of

performance, can increase the sustainability of the sector [30] (see Table 1, Challenge 2). As society has begun looking for natural materials that are renewable (i.e., materials that can be replaced without damaging the environment), consume minimal fossil fuel energy, and have minimal pollution and health risk (see Table 1, Challenge 4), a large part of building eco-friendly materials have started being natural fibre based [31].

Moreover, the concept of sustainability should also be seen as a financial resource. In particular, considering the economic primary role of the AEC sector, activities such as the assessment of end of life and maintenance costs (see Table 1, Challenge 5) could be strategic to improve the use of financial resources. Economic sustainability should focus on keeping the economic gains of industry within the local community. Promoting locally run businesses and employing locals can help local communities in profiting within AEC sector [32,33] and in creating a sustainable design focused on reducing at minimum the distances between producers and consumers.

In order to pick up the five challenges shown in Table 1, it is necessary to address all the barriers hampering the establishment of the use of hemp, creating enough balance between efficiency and resilience. A summary of initial barriers for Italian hemp building industry is reported in Table 2. The six pillars (technical, commercial, knowledge, regulatory, psychological and invisible), designed as complex chains involving a great number of actors and consumers, are not always able to identify the producers of raw materials [34,35]. For example, it would also be strategic to consider the hemp certification process as an important aspect for the creation of a sustainable pattern, able to guarantee credibility of the products related to the hemp sector [36].

Table 1. Sustainability challenges in architecture, engineering and construction (AEC) sector. Source: our elaboration from [37–41].

Challenges	Primary Role of the AEC Sector	Sustainable AEC Sector Objectives
1. Savings in the supply of power	<ul style="list-style-type: none"> 40% of the total energy consumption comes from 160 million buildings. 2/3 of energy consumption in buildings are used for heating and air conditioning. 3.3 million barrels of oil could be saved every year in Europe if the buildings were made more efficiently from the energy viewpoint. 	Supply of raw materials: <ul style="list-style-type: none"> Production of manufactured products Reduce energy consumption Lower CO₂ emissions Reduce impact on air, soil, water Reduce production waste Improve transport on site
2. Mitigation of climatic change	<ul style="list-style-type: none"> 460 million tons of CO₂ could be saved every year in Europe by energy-efficient measures from an energy point of view in buildings. Buildings are primarily responsible for greenhouse gas emissions and represent 36% of the CO₂ emissions in Europe 	Use of resources: <ul style="list-style-type: none"> Improve quality of the building (estate air) Reduce waste production Improve energy efficiency Make more efficient the use of water Reduce CO₂ emissions Make more effective maintenance and replacement Improve impact on the built environment
3. Waste management and protection of resources	<ul style="list-style-type: none"> Construction in the Organisation for Economic Co-operation and Development (OECD) countries is responsible from 30 to 40% of solid waste creation, 30% of use of raw materials and 10% of land cultivated. 	Dismantling, demolition in situ, recovery, disposal and transport: <ul style="list-style-type: none"> Reduce impact of waste from demolition Improve the sustainability in construction and assessment skills in time
4. Health and wellness economic growth	<ul style="list-style-type: none"> In Europe alone, 8 billion euros could be saved every year in health and economic costs related to air pollution, simply by improving insulation. 	Improve workers' health and safety on construction sites: <ul style="list-style-type: none"> Reduce disorders of the neighbourhood (noise, dust, congested traffic) Improve performance in place compared to project performance Solutions for thermal and acoustic comfort: Improve safety (fire protection) Preserve health (indoor air quality)

Table 1. Cont.

Challenges	Primary Role of the AEC Sector	Sustainable AEC Sector Objectives
5. Financial resources availability	<ul style="list-style-type: none"> Between 10 and 28% of European family income is for home maintenance and repair, water supply, electricity, gas and other fuels for domestic use. Up to 530,000 jobs could be created in Europe through a strategy ambitious aimed at improving efficiency energy in buildings [35] A strong increase in regulations energy in construction in Europe could lead to an increase of 700,000 additional jobs in AEC sector 	End-of-life costs: <ul style="list-style-type: none"> Improve processes of dismantling, demolition and recovery/ disposal Maintenance costs Reduce external costs: heating, air conditioning, water, electricity Reduce purchase and construction costs

Table 2. Initials barriers for hemp building industry mainstreaming.

Technical	Commercial	Knowledge	Regulatory	Psychological	Invisible
<ul style="list-style-type: none"> Lack of expertise in production and use Initial capital Processing plants 	<ul style="list-style-type: none"> Difficult to source hemp seed Winter storage Transportation costs Farmers' profitability Weakness of start up in hemp industry 	<ul style="list-style-type: none"> Builders' lack of knowledge Weakness of R&D Consumers' knowledge 	<ul style="list-style-type: none"> Legislation lack by government Difficulty for farmers to get clearance for hemp cultivation Quality certification. 	<ul style="list-style-type: none"> Hemp association with marijuana Misconception that traditional products are better built. 	<ul style="list-style-type: none"> Synthetic fibre and vested product interests Cement industry vested interests for hemp and lime

2.1. Technical Standpoint

In the last decade, following the growing interest generated by hemp, a number of hemp-based materials have been developed in the AEC industry [42,43], such as hemp-concrete [44–46] and various types of insulations for use both internally and externally [47]. Among these natural based composites, some result from the combination of a mineral binder matrix with shives aggregate [48] and can be used for envelopes as well as internal partitions. Among the hemp-based composites, hemp-lime plays a main role, since it can be used as premixed mortar (e.g., simply sprinkled) plus it is the main component to produce all hemp-based composites in different forms, like bricks and panels [49].

Several studies focused on the hemp-lime properties, among which one of the most interesting is the ability to sequester CO₂ during manufacturing, both in the hemp plant growing phase and in the lime production process, so that this composite can be considered as a carbon negative material [50]. Moreover, the composite is breathable and healthy [51] and a bad thermal conductor, thus ensuring good insulation [52–54], good soundproofing [55] and fire resistance properties [56]. Its load bearing capacity is quite poor, so it is not made for structural purposes, however it can be used as infill wall for wooden frames [57,58]. Lastly, hemp-lime also ensures protection against infestations with very little toxicity [59]. Thanks to the described features, hemp-lime is being increasingly studied and used as thermal insulation for buildings energetic retrofit operations as well as new constructions [44]. It is interesting to note, despite these potentialities, that technical barriers are linked to the lack of expertise in both production, with few businesses having yet achieved significant industrial dimensions, and use, with the presence of 94% of micro enterprises (1 to 9 employees) in the Italian AEC sector (ISTAT, 2018).

2.2. Commercial Standpoint

Despite the production of industrial hemp being developed in more than 35 countries in the world, only in the last 15 years has there been an increase of such cultivation. In fact, in 2004 the hemp cultivation area expressed in ha within European countries was 14,932 [60], and in 2016 was 33,300 [61]. This trend, 2004–2016, is the result of several factors; on one hand, the increase of the demand for natural products, the growth of awareness about environment sustainability and the rise of raw material and petrol costs; on the other hand, the improving of techniques, cultivation practices and industrial equipment. In line with this assumption, industrial hemp production should be profitable from an economic standpoint, since it should be competitive not only with other fibres, but with other

production alternatives as well. Some of the barriers limiting hemp commercial development and causing potential profitability issues for the farmers is the lengthy storage period required during the winter season before being further processed and the transportation costs, which could have a negative implication on hemp economic and environmental feasibility. In fact, this material has a low bulk density [62], and in turn, its value per ton is fairly low for transportation while high for storage [63].

2.3. Knowledge Standpoint

Among the stakeholders, a general lack of knowledge on lime-hemp exists [64]. Usually, they ignore the potential advantages of its application and the overcoming of this barrier starts first of all by the stakeholders of the AEC sector that could realize it thanks to the increase in its use, creating a higher visibility and consequently more consciousness in the general context.

2.4. Regulatory Standpoint

Orienting adequate government actions to a favourable legislation means recognizing a positive identity to hemp linked both to the crop, with quality certification ensuring national quality standards, and to hemp-lime as a construction material, in that way affecting the AEC sector. In line with this, thanks to its features of being easily cultivable, hemp cultivation could be a profitable alternative.

2.5. Psychological Standpoint

Despite there being a great difference between hemp and marijuana, public opinion seems to be confused associating hemp to recreational drug uses [65]. Naturally, it could be beneficial to counteract the lack of knowledge with an increase of awareness about this product. In addition, environmentally friendly solutions are generally associated only with reduced heating costs in AEC sector, belittling materials such as hemp-lime that also offers other well-established benefits.

2.6. Invisible Standpoint

The growing of hemp-lime industry inevitably creates, in the AEC sector, a competitive market that could harm the niche market of materials that do not have a consolidated and strong market position. This initial invisible barrier is linked to the competitiveness of other similar products that are used in the AEC sector such as synthetic fibres.

3. Materials and Methods

For its characteristics, hemp-lime is considered as a suitable material for energy retrofit of historic buildings [66]. Many historic buildings have been studied at full-scale, to evaluate the effects of hemp-lime use on their energetic performance [67]. In this work, the effective increase in the energy performance of a historic-monumental building generated by use of lime-hemp at full scale was evaluated. The chosen case study was “Palazzo Jadiccico”, a historical courtyard building built in the second half of 17th century in Frattamaggiore, a town located in the suburban belt of Naples that was an important site for hemp production until the Second World War [68]. In 1780 Michele Niglio Jadiccico, poet and officer of king’s personal guard, decided to restore the palace following the late Baroque style, an expression of the refined and aristocratic spirit of the Kingdom of Naples. The palace has a smooth ashlar ground floor façade, separated by a fluted band from the upper part, where windows alternate with balconies. The main entrance is a large arch in Vesuvian stone leading to a wide courtyard where in past times garages for carriages, stables and cellars faced. Rooms on the ground floor facing the street have a total area of 255 m² with a height of 5 m and are used for commercial purposes; upper rooms are all intended for homes and most of them still preserve the original 18th century style, with frescoes, stuccoes and floorings. Figures 1 and 2 show plans, elevation and an axonometric of the case study.

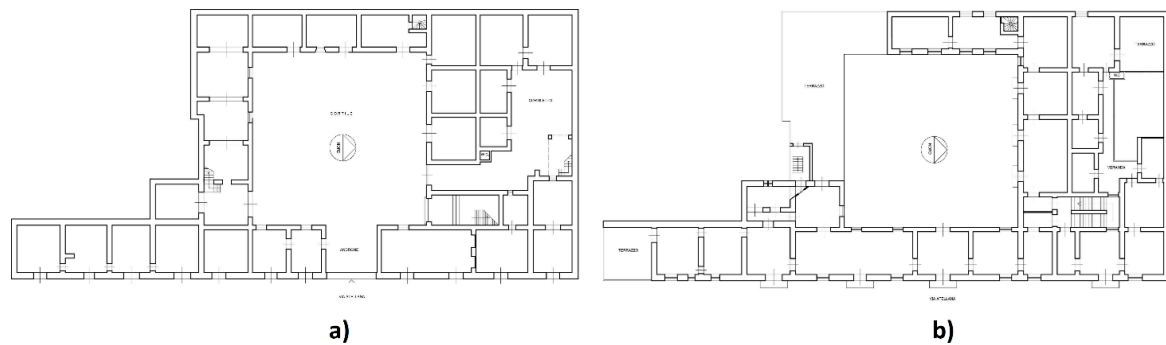


Figure 1. Floorplans of the case study: (a) ground floor; (b) first floor.

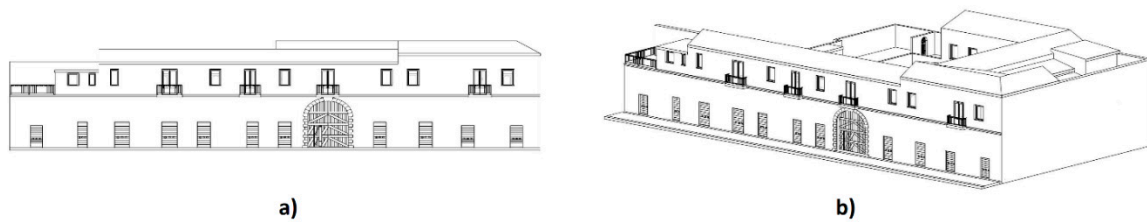


Figure 2. Case study: (a) street façade elevation; (b) axonometric projection.

The building has a load-bearing masonry structure made with Yellow Neapolitan Tuff (YNT), a volcanic material very widespread in South Italy, used for centuries to build vertical barriers of any kind of construction in Campania Region. The external walls facing the street have a granite coating on the external façade and gypsum lime plaster (GL-P) on the internal one, while the other walls are coated on both sides with plaster. Some other partitions are made with hollow bricks (HB), also coated with plaster on both sides. The characteristics of all existing materials, alongside hemp-lime plaster (HL-P) are reported in Table 3. The software calculated thermal resistance and thermal admittance.

Table 3. Characteristics of all materials.

Material	Thermal Conductivity λ [W/mK]	Surface Mass Density * s.m.d. [kg/m ²]	Steam Permeab. (RH \leq 50%) P [kg/msPa]	Specific Heat Cap. c [J/kgK]
Yellow Neapolitan Tuff	1.70	23	0.02	1380
Hollow bricks	0.25	6	36.00	840
Gypsum lime plaster	0.70	14	18.00	1000
Hemp-lime plaster	0.12	5	43.00	1200

Characteristics marked with * refer to a 10 mm thickness layer.

Different wall layouts are distinguished, depending on the wall position (layouts with one side facing the outside and the other the inside are called “envelope”, while layouts with both sides facing indoor areas are called “partition”), materials and thickness, nine in total, whose features are reported in Table 4.

Table 4. Wall layouts.

LAYOUT A1			LAYOUT A2			LAYOUT A3		
Layer n°	Material	Thickness [mm]	Layer n°	Material	Thickness [mm]	Layer n°	Material	Thickness [mm]
1	GL-P	20	1	GL-P	20	1	GL-P	20
2	YNT	660	2	YNT	660	2	YNT	560
3	GL-P	20	3	GL-P	20	3	GL-P	20
Total		700	Total		700	Total		600
envelope			partition			envelope		
LAYOUT A4			LAYOUT A5			LAYOUT A6		
1	GL-P	20	1	GL-P	20	1	GL-P	20
2	YNT	560	2	YNT	510	2	YNT	460
3	GL-P	20	3	GL-P	20	3	GL-P	20
Total		600	Total		550	Total		500
partition			partition			envelope		
LAYOUT A7			LAYOUT A8			LAYOUT A9		
1	GL-P	20	1	GL-P	20	1	GL-P	10
2	YNT	460	2	YNT	360	2	HB	80
3	GL-P	20	3	GL-P	20	3	GL-P	10
Total		500	Total		400	Total		100
partition			partition			envelope		

GL-P = gypsum-lime plaster; YNT = yellow Neapolitan tuff; HB = hollow bricks.

It is worth noting that the study excludes the external wall facing the street covered with granite stone since no render substitution was possible for those walls. All identified envelopes belong to the external barrier facing the internal court, where there is no granite cover. Details about other elements, such as slabs, windows, MEP (mechanical, electrical and plumbing) systems, etc., are not described here because they are not significant for the purpose of this study, since they are kept constant in the simulation of the refurbishment intervention. In fact, the latter concerns only the substitution of renders and plasters not covered by frescos, in the perspective of protecting the aesthetic characteristics of the building. For the same reason, the substitution of ceiling plasters is not considered either, since most of the ceilings are decorated with frescoes dating back to the construction.

For the evaluation of the building energy performance, two conditions are considered: a) as it is, and b) replacement of the standard internal plaster and external render with a hemp-lime one, from 4 to 7 cm thick [69], depending on the wall side (internal or external) and type (tuff or bricks masonry). To achieve such thickness, hemp-lime plaster should be laid in three steps, each corresponding to a layer: the first layer, called “scratch coat”, is rich in lime and has to be applied with a trowel, so as to obtain a perfect adhesion to the wall and a rough surface for a better grip of the next layer. The second layer is the crinkle and is applied with a smooth trowel or an American spatula with a thickness between 2 and 5 cm. The finishing layer has to be lime-based, especially on the external walls, to protect the hemp-lime from atmospheric agents; for this layer, a smaller size of the shives can be selected if a finer appearance is desired. All layers can also be applied as a spray.

Comparing the two situations, it is possible to assess the benefits deriving from this type of refurbishment intervention. Table 5 reports the resulting layouts after the simulated installation of the hemp-lime plaster. Layers are listed from inside to outside.

Table 5. Wall layouts after hemp-lime lying simulation.

LAYOUT B1			LAYOUT B2			LAYOUT B3		
Layer n°	Material	Thickness [mm]	Layer n°	Material	Thickness [mm]	Layer n°	Material	Thickness [mm]
1	HL-P	50	1	HL-P	50	1	HL-P	50
2	YNT	660	2	YNT	660	2	YNT	560
3	HL-P	70	3	HL-P	70	3	HL-P	70
Total		780	Total		780	Total		680
envelope			partition			envelope		
LAYOUT B4			LAYOUT B5			LAYOUT B6		
1	HL-P	50	1	HL-P	50	1	HL-P	50
2	YNT	560	2	YNT	510	2	YNT	460
3	HL-P	70	3	HL-P	70	3	HL-P	70
Total		680	Total		630	Total		580
partition			partition			envelope		
LAYOUT B7			LAYOUT B8			LAYOUT B9		
1	HL-P	50	1	HL-P	50	1	HL-P	40
2	YNT	460	2	YNT	360	2	HB	80
3	HL-P	70	3	HL-P	70	3	HL-P	40
Total		580	Total		480	Total		160
partition			partition			envelope		

The software used for the scope was TerMus[®] by ACCA software, which supports building design with verification of thermal dispersion. This software, working in steady state, is one of the most popular among professionals in South Italy so it was chosen to make the simulation easily referable to the professional sphere. The use of steady state conditions introduces some simplifications in the model, which may lead to different results than using a dynamic simulation. However, the use of this model is in accordance with the law in force (EN ISO 13788/2012) and to recent similar researches [18].

Thermal analysis was conducted setting the coordinates of the settlement area, from which TerMus[®] retrieved the outdoor air temperatures. The indoor design parameter was fixed at 20 °C and 26 °C, in winter and summer respectively, with constant 50% relative humidity.

The walls energy performance, both before and after plaster substitution, was evaluated by means of the parameters and limitations reported in Table 6.

Table 6. Parameters and limitation used for the evaluation of walls energy performance.

Parameter		Legislation		Reference Value
Thermal admittance	U [W/m ² K]	D.M. 26.06.2015	$U < 0.36 \text{ W/m}^2\text{K}$ —climate zone C (a warm Italian zone)—refurbishment interventions	
Dynamic thermal admittance	Y_{ie} [W/m ² K]	D.M. 26.06.2015	$Y_{min} < 0.10 \text{ W/m}^2\text{K}$ (vertical and inclined walls, excluding those facing north)	
Attenuation coefficient	F_a $ Y_{ie} /U$	D.M. 26.06.2009	$F_a > 0.60$ inadequate $F_a < 0.15$ excellent	

The *Dynamic thermal admittance* Y_{ie} estimates the ability of an opaque wall to phase out and attenuate the heat flow passing through it over 24 h. The *Attenuation coefficient* F_a expresses the ratio between the amplitudes of the outgoing and incoming heat flows through the wall. Both parameters are a measure of the summer behaviour of the wall, contrary to *Thermal admittance*, which assesses instead the winter performance.

The overall energy performance of the whole building for both conditions, before and after plaster substitution, was evaluated by using the following performance indexes, according to Italian regulation (D.M. 26.06.2015 [70]):

- *Winter and summer performances* are qualitative indexes of the energy requirement needed to meet the indoor comfort, regardless the type and performance of the MEP system. They give an indication of the building (or housing unit) thermal insulation capacity in summer and winter, on a qualitative assessment scale, “high” (☺), “medium” (☹), “low” (☹). In particular, $EP_{H,nd}$ is a general requirement on the building envelope measuring the heating thermal performance and depending on the thermal insulation of the envelope (opaque and transparent), on the performance of a possible ventilation system and on the internal and solar intake. Y_{IE} is the *Dynamic thermal admittance* averaged on the whole building.
- $EP_{gl,nren}$ is the “non-renewable energy performance index”, indicating the amount of energy consumed for the building to reach the comfort conditions. It takes into account the need for non-renewable primary energy for (a) winter and summer air conditioning, (b) production of domestic hot water and (c) ventilation. It is calculated on the basis of the ratio between the energy required to bring an environment to the comfort temperature and its net walkable area. It directly determines the building energy class. The smaller, the better.
- $EP_{gl,ren}$ is the “renewable energy performance index”, same as the previous index but applying only to energy produced from renewable sources. The higher, the better.
- $CO_2\ emiss$ is a measure of the building impact on the environment in terms of estimated carbon dioxide (CO_2) emissions per year. The lower the value, the less the impact.
- *Energy efficiency rating* is a score, ranging from G to A4, directly deriving from the “non-renewable energy performance index” ($EP_{gl,nren}$) by comparing the latter to a predefined scale, in which each step is an energy performance level. The efficiency class scale is based on the value of the “non-renewable energy performance index” of a reference building ($EP_{gl,nren,standard}$), corresponding to the threshold between classes A1 and B. All other performance levels are obtained by multiplying the asset value ($EP_{gl,nren,standard}$) by reduction (classes from B to G) or increase (classes from A1 to A4) coefficients.

4. Results and Discussion

The design external air temperatures, calculated by the software inputting geographical coordinates of the site, were 1.82 °C and 32.2 °C, in winter and summer respectively. Figure 3 reports the calculated thermal characteristics of the wall layouts before (A-layouts) and after (B-layouts) the simulated plaster substitution, where “e” stands for envelope wall and “p” for partition wall.

LAYOUT		U [W/m ² K]		Y _{ie} [W/m ² K]		F _a [-]	
		A-layout	B-layout	A-layout	B-layout	A-layout	B-layout
1	YNT 660mm e	1.52	0.64	0.02	0.00	0.01	0.00
2	YNT 660mm p	1.42	0.61	0.01	0.00	0.01	0.00
3	YNT 560mm e	1.80	0.67	0.04	0.00	0.02	0.00
4	YNT 560mm p	1.55	0.63	0.02	0.00	0.02	0.00
5	YNT 510mm p	1.62	0.64	0.04	0.00	0.02	0.00
6	YNT 460mm e	2.01	0.69	0.10	0.01	0.05	0.01
7	YNT 460mm p	1.70	0.65	0.05	0.00	0.03	0.01
8	YNT 360mm p	1.89	0.68	0.12	0.01	0.07	0.02
9	HB e	1.92	0.86	1.83	0.60	0.96	0.70

Figure 3. Thermal characteristics before (A-layouts) and after (B-layouts) hemp-lime substitution simulation. Red colour means that the property does not meet the regulation limitations; green colour stands for the fulfilment of the requirement.

Results show that layout thermal properties change according to whether or not the wall outlines the outside. Thermal admittance is always more than halved going from A-layouts to B-layouts, denoting an improved thermal inertia of the walls, in turn indicating fewer thermal dispersions. However, the decrease in thermal admittance is not sufficient, in any case, to meet the regulation requirements, meaning a poor winter performance of the walls.

The dynamic thermal admittance and attenuation coefficient went to zero in most of the B-configurations (100% reduction). In particular the attained value of the dynamic thermal admittance allowed the results to go from “unacceptable” to “satisfactory” status in two cases, layouts 6 (90% reduction) and 8 (92% reduction); conversely for layout 9 (hollow bricks) the value remained above the regulation threshold (67% reduction). The same happened for the attenuation coefficient, which was fine in all A-layouts (80%, 67% and 71% reduction for layouts 6, 7 and 8, respectively) but not 9; although this value decreased 27% in B-configuration, it was not sufficient to fulfil the standard. Overall, the summer performance of the walls turned out to be improved.

Figure 4 reports the results of the hygrometric test, conducted in steady state, according to EN ISO 13788/2012 [71], where the “yes symbol” (✓) indicates that the test gave positive results and the wall was verified against the applied condition. In particular, for the interstitial test, it means that the structure was not subject to interstitial condensation phenomena; for the mould test, it means that the structure was not subject to mould formation. However, in this second test, for both YES and NO outcomes, the software indicated the most critical month, which is also reported in Figure 4.

LAYOUT		INTERSTITIAL TEST		MOULD TEST		
		A-layout	B-layout	A-layout	B-layout	Most critical month
1	YNT 660mm e	✓	✓	✗	✓	February
2	YNT 660mm p	✓	✓	✓	✓	October
3	YNT 560mm e	✓	✓	✗	✓	February
4	YNT 560mm p	✓	✓	✓	✓	October
5	YNT 510mm p	✓	✓	✓	✓	October
6	YNT 460mm e	✓	✓	✗	✓	February
7	YNT 460mm p	✓	✓	✓	✓	October
8	YNT 360mm p	✓	✓	✗	✓	February
9	HB e	✓	✓	✗	✓	February

Figure 4. Results of the hygrometric tests.

Results show that the interstitial test was always verified, both before and after the simulation. The mould test was not-verified four times out of nine in the “as it is” condition and always verified in the “hemp-lime plaster” condition. This result is consistent with previous studies conducted by other authors [72]. All “not-verified” outcomes corresponded to envelope layouts; conversely, all partitions gave positive results. The mould test critical month was October for partitions and February for envelopes, for both A and B layouts.

5. Discussion

The overall energy performance in both conditions, before and after plaster substitution, is summarized in Figure 5.

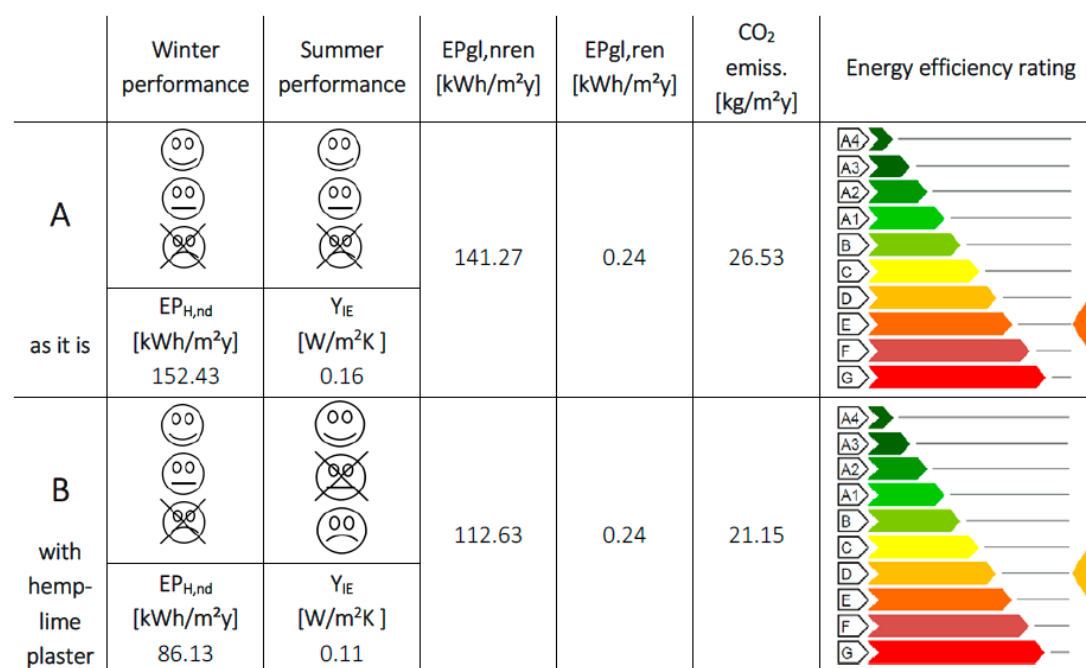


Figure 5. Overall energetic performance.

Although the winter performance index (Figure 5, column 2) after the simulated intervention remained in the “low quality class”, the insulation capacity was almost doubled (−43%). In fact, the amount of energy required to reach the indoor comfort during winter went from 152.43 kWh/m² per year to only 86.13. The increase in thermal insulation power was also registered in summer condition (Figure 5, column 3), where the Y_{IE} index decreased 30%, yielding to an improvement of “quality class”, from “low” to “medium”. This is also reflected by the decreased need for non-renewable primary energy, calculated by means of the global “non-renewable energy performance index” (Figure 5, column 4), which went from 141.27 kWh/m² per year to 112.63. The “renewable energy performance index” (Figure 5, column 5) instead was stable, as no changes in the MEP systems were planned and the value of 0.24 was a consequence of the fact that the heating system was natural gas (methane) powered. CO₂ emissions (Figure 5, column 6) had a 20% reduction, going from 26 to 21 kg/m² per year. The 20% decrease in the EP_{gl,nren} index brings the examined building one level up in the EU energy label classifications (Figure 5, column 7), from E class to D class, which can be considered a good result bearing in mind that the simulated intervention affects only the wall plasters not covered by frescoes.

Focusing on the economic aspect, realizing 1 m² plaster with a thickness, for example, of 15 mm would cost 5.00 € and 15.50 € in row materials using a standard gypsum-lime plaster and a hemp-lime one, respectively. To this value, the labour cost should also be added, at different percentages depending on the technique required for the plaster laying: the product cost is around 70% for gypsum-lime (hand-coating process) and around 30% for hemp-lime (considering the spraying procedure). The total cost is 16.00 € for gypsum-lime and 22.00 € for hemp-lime plaster [65,66].

6. Conclusions

To increase the use of hemp in the AEC sector, the industrial production of this material needs to be profitable and competitive from an economic standpoint, creating coordinated actions, which affect different aspects of this particular industrial sector. Improving awareness for conscious consumption may contribute to the reduction of barriers hampering the establishment of hemp use.

In order to evaluate the energetic performance of hemp-lime plaster, a refurbishment intervention on a real case study building was simulated, substituting the standard gypsum-lime plaster with

a hemp-lime one. The energetic performance of the selected building was assessed in the present condition and hypothesized refurbishment scenario.

The results show that hemp-lime based plaster is capable of decreasing thermal dispersions by more than halving the thermal admittance and reducing to at least one third (but in other cases to one tenth or to zero) the dynamic thermal admittance and attenuation coefficient of the walls. However, the decrease in thermal admittance for all layouts was not sufficient to fulfil the regulatory requirements, which is why the winter performance of the entire building remains in the lowest qualitative class. Conversely, the application of hemp-lime plaster enabled meeting the limits established for dynamic thermal admittance and attenuation coefficient in all layouts but the hollow bricks one, resulting in an improvement to the summer performance class, from low to medium. With reference to steady state conditions, hemp-lime also eliminates the risk of moulds formation.

The overall energy performance of the building registers an improvement of approximately 20% compared to the condition with traditional gypsum-lime plaster, with a subsequent 20% decrease also in CO₂ emissions. This corresponds to a one-level improvement of the building energy class, from E to D. Although the building is still very far from A1 class, the obtained result can be considered satisfying, as the modelled improvement intervention concerns only substitution of most of the wall plasters.

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