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Fitness: sheep-wool and hemp sustainable insulation panels

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Abstract

FITNESs, *Fibre Tessili Naturali per l'Edilizia Sostenibile (Natural Textile Fibers for Sustainble Building),* is a research project concerning an experimental hemp and sheep wool insulation panel. The new panel has two main innovative features: unlike the already existing hemp and wool insulation mats, it is a semi-rigid product and it has a low environmental impact, as shown by the Life Cycle Assessment. FITNESs panels are particularly suitable for eco-building sector, they are 100% natural, recyclable and made with by-products from local production chains (Piemonte Region). The paper presents the results of thermal conductivity, acoustic absorption coefficient and thermal transmittance of an experimental wall measurements, in order to demonstrate the effectiveness of FITNESs panels as an insulation product for buildings.

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Keywords:

1. Introduction

The research team recently developed an innovative system with low environmental impact for the production of semi-rigid panels for thermal and acoustic insulation, obtained from recycled sheep's wool, from Piemonte region [1]. Starting from the previous work, a new semi-rigid panel was produced, where recycled sheep's wool is combined with hemp technical fiber.

Hemp (*Cannabis Sativa*) cultivation presents huge benefits for soils in crops rotation environmental field: this culture easily adapts to different types of climate and high yields can be produced with relatively low resources;

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moreover it exerts a restorative action on soils, leaving a considerable amount of organic waste, which benefits the cultures that follows in the rotation crops, as stated by Assocanapa [2, 3].

Moreover the high annual biomass production, and its strong ability to absorb CO_2 from atmosphere, hemp can be considered an interesting alternative source of energy valorization and biomass [4].

Interest in building for hemp materials especially relies in its recyclability, hygroscopic, water vapor permeability and durability properties, its resistance to mold and fungus attacks and the porous characteristics of fibers and shives; as well as its low environmental impact and low cost.

Hemp cultivation has deep roots in Italy, since medieval times, during Maritime Republics age when even in Piemonte region, particularly Carmagnola (To) gradually became a renowned center in the production and diffusion of hemp in the region and abroad. Up to 1960 Italy was among the first countries in the world for planted area and quality of products [5]. After a period following World War II in which hemp cultivation on our territory began gradually to disappear, it was re-introduced at the end of 1990s on a 350 ha area approximately; nowadays it is recovering importance thanks to the efforts of producers as Assocanapa and the recovered cooperation with industrial sectors on local short chain mechanism.

Products obtained from hemp stalks processing are shives (60-65%), fibers (20-25%) and dust (10-20%) [2]. Hemp fiber and shives find use in construction industry, particularly in bio-architecture, as raw materials for buildings thermal insulation, due to their physical characteristics [6]. Hemp shives begins to be widely used even in conventional buildings, often mixed with lime or cement to produce thermal insulating conglomerates.

Short Technical hemp fiber not meant for textile manufacture is currently quite hard to place on the market, also because of its reduced use in the paper manufacturing field [2]. In buildings it is mainly used to produce thermo-acoustic insulating panels or mats, but despite a good variety of hemp products for thermal and acoustic insulation of buildings, in most of the cases hemp is mixed with other synthetic materials and binders that make products not entirely biodegradable; furthermore there is also a lack of self-supporting rigid hemp panels on the market.

In Italy one of the main hurdles to hemp cultivation development is due to the lack of suitable machinery to separate fibers from shives, which generates significant production costs, while cost of fibers used in building insulating materials need to be relatively low [6]. Assocanapa and CNR IMAMOTER patented recently a prototype machine for hemp retting and defibering which could make the set up of a local short chain of hemp products of certain interest and more economically effective [7].

2. Fitness: sheep wool and hemp insulation panels

FITNESSs is a semi-rigid thermo-acoustic insulating panel made of a composite material, consisting of wool, which partially works as a binder - and hemp fibers. Even after the panel production process the two main components keep their own chemical and physical properties, as they remain separated by a zero thickness thin interface, which makes panels not homogeneous. Nevertheless the hemp fibers addition gives the product a relatively high density if compared with Cartonlana's, a 100% sheep wool semi-rigid panel realized during a previous research project, and an improved stiffness, due to hemp fibers tensile strength.

Hemp used for the production of the panels is cut and kept in the field for 4 months (October-February) to macerate. After maceration, it assumes a gray color and keeps a minimum shives residual, to be considered 1.25% of the weight approximately. Hemp shives is restrained by the fibers and can vary in size between 0.2 and 5 cm in length and 0.05 and 1 cm in thickness. Hemp fibers instead have 10 -70 cm length, but most of the fibers remain in a range between 10 and 20 cm length.

Wool comes from Piemonte region sheep breeding; it cannot be used in textile industry, due to its dark color and/or poor quality: fibers are too thick, and irregular length also. Sheep wool is usually washed and dried, but still contains plant debris trapped amongst fibers. As for hemp, treatments on the raw wool are reduced to a minimum, in order to minimize the energy consumption for the production of the panels. The production process consists in 3 main phases:

- The mixture of sheep wool and hemp fibers;
- The treatment with a soda solution in order to make wool fibers to release part of keratin protein, which works like a natural glue, pasting wool and hemp fibers together;

Fig. 1. a) Washed wool fleece, b) Hemp fibres retted in field, c) FITNESs panel

- The removal of soda solution and panel drying in oven.

Treatment with alkaline solutions increases plant fibers separation degree and consequently the composite homogeneity, since cellulose fibers swell, hydrophilicity increases and the fibers get separated by the partial hydrolysis of encrusting substances .

The parameters of the process (percentage of wool and hemp, duration of treatment, concentration of sodium hydroxide, drying time, etc.) have been varied, in order to produce several samples with different porosity, density and final physical and mechanical performance. The optimal recipe for the production of FITNESs panels has been defined on the basis of a selection between the different samples. The final result of the process is a semi-rigid panel, with an area of 0.468 cm^2 (90.00cm x 52.00 cm), a thickness of 4.50 cm and a weight of 3 kg, made of wool and hemp in equal weight. In order to optimize the panels production, the same water and soda solution, before being replaced, was used to produce two panels, respectively indicated as 1^{st} and 2^{nd} wash.

2.1. Environmental analysis and results

Technology assessment has been integrated with the LCA - defined by the UNI EN ISO 14040/44 [8,9]. FITNESs insulation panels have been compared with other experimental products – such as Cartonlana sheep wool panels [10] – and other insulation products already available on the building market, taking into account both thermal performance and environmental impacts. In order to compare the non renewable energy demand of different insulations products, each considered product mass needed to achieve a certain thermal resistance was taken into account (table1).

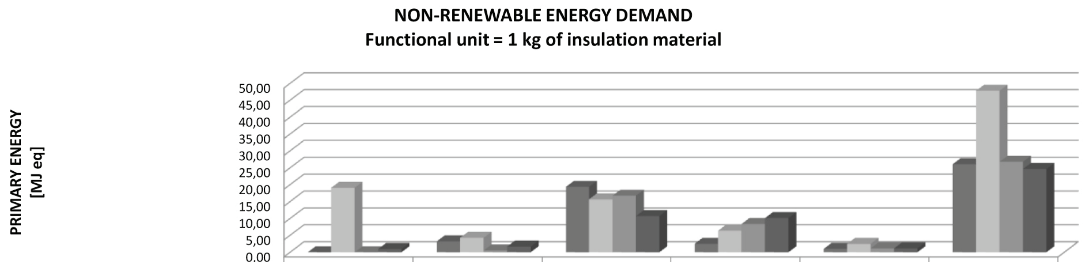
In the LCA study the inventory flows and the environmental burdens were associated to the cultivation of 1 ha of hemp in the regional territory (Piemonte, Italy) and to a final product which consists in hemp fibers (20%), hemp shives (75%) and dust (5%). Authors decided to use an economic allocation based on the current market prices of hemp products and the amount of their annual production.

The inventory flows and environmental burdens associated to the sheep wool collection, transport and processing activities (tumbling and scouring) was quantified, as described in Bosia et al. [10]. Finally, all the input and output flows (i.e. energy and additives) related to the washed wool and hemp mixture process were studied, in order to assess the potential environmental impacts.

All the inventory data for panels production were directly collected from the industrial partners of the research project, and then they were elaborated using the international database Ecoinvent 2.0. The Cumulative Energy Demand (CED) was the indicator used for the assessment of the environmental impacts.

Different insulating building products previously analyzed by the research group with the same LCA methodology and database were considered: Product A is a 100% sheep wool soft mat, product B is a sheep wool and PET semi-rigid panel, product C2 is the 100% sheep wool semi-rigid Cartonlana panel, product D2 is the hemp and sheep wool semi-rigid FITNESs experimental panel.

A specific eco-profile, reporting the environmental impacts of 1 kg of product was associated to each product; figure 2 shows the non renewable energy demand needed for each different process unit (raw material supply, raw material transport etc.), considering the process from cradle to gate. Observing the results, product B has the highest primary energy impact, mainly due to Polyester (PET) fleece supply, processing and transport from the north Europe. The other three products (A, C2, D2), 100% made of natural materials, require almost the same amount of non-renewable energy.



	raw material supply	raw material transport	raw material processing (i.e.wool scouring, hemp processing)	insulation material production	packaging	TOTAL
Product A (100% wool)	0,00	3,21	19,36	2,49	1,02	26,08
Product B (80% wool + 20% PET)	19,07	4,28	15,64	6,36	2,47	47,82
Product C2 (100% wool)	0,00	0,55	16,73	8,36	1,16	26,80
Product D2 (50% wool + 50% hemp)	0,96	1,69	10,74	10,12	1,15	24,66

Fig. 2. Eco-profiles of considered thermo-acoustic insulation materials. Environmental indicator: Cumulative energy demand (non renewable).

Afterwards, products A, B, C2 and D2 were compared with other thermal insulation materials using non-renewable energy demand literature data [11]. Each product thickness (cm) and mass (kg) were calculated in order to obtain the quantity of product needed to reach the imposed value of thermal resistance of 2.5 m^2K/W, for m^2 of surface, as shown in Table 1.

Table 1. Properties and quantities of insulation materials used in the comparison analysis: functional unit is defined as the mass (kg) of insulating board which involves a thermal resistance of 2.5 m^2K/W

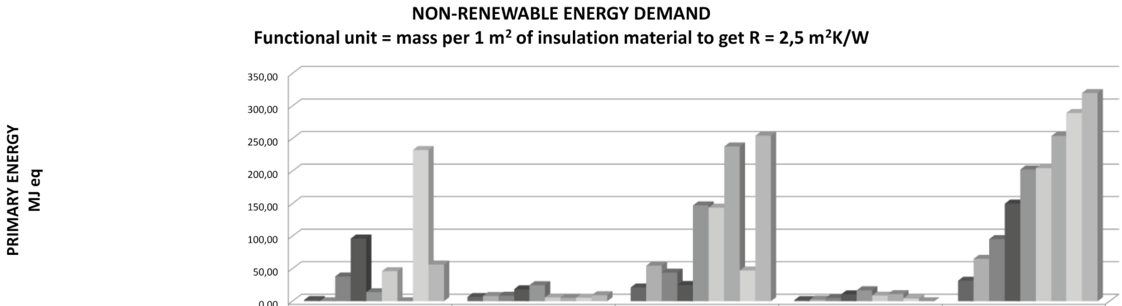
Insulation material	Thickness	Density	Thermal conductivity	Mass per unit area	Thermal resistance
-	[cm]	[Kg/m^3]	[W/m K]	[Kg/m^2]	[m^2 K/W]
Product A (100% wool)	10	25	0,040	**2,50**	2,5
Product B (80% wool + 20% PET)	9,5	21	0,038	**2,00**	2,5
Product C2 (100% wool)	10,25	92,5	0,041	**9,48**	2,5
Product D2 (50% wool + 50% hemp)	10,25	142	0,041	**14,56**	2,5
Sheep wool mat [9]	10	25	0,040	**2,50**	2,5
Kenaf fiber (with PET) [9]	10	100	0,040	**10,00**	2,5
Glass wool [9]	10	92,5	0,040	**9,25**	2,5
Rock wool [9]	10	92,5	0,040	**9,25**	2,5
XPS [9]	8,75	30	0,035	**2,63**	2,5

The non renewable energy demand of each product was then calculated considering the mass of insulation material as functional unit, as shown in figure 3. Looking at the results illustrated it can be stated that:

- semi-rigid panels have higher density which negatively influence their environmental impact results;
- conventional materials, such as XPS and glass wool, have the highest non renewable energy demand;

- soft sheep wool mat, both from literature and from direct LCA results (product A), has the lowest environmental impact, as it has considerably lower density then semi-rigid panels but even lower suitability in building insulation solutions, due to installation issues;
- compared with rigid XPS panels, the two experimental panels Cartonlana (C2) an FITNESs (D2) show a lower non renewable energy demand, despite of their higher density;

The great weight of insulation material production on the total non renewable energy demand of the two experimental panels Cartonlana and FITNESs is reasonably due to the experimental production process took into account, which should be optimized in an industrial scaling up.



	raw material supply	raw material transport	insulation material production	packaging	TOTAL
Sheep wool mat (Fassi, Maina 2009)	1,95	6,60	21,13	1,83	31,50
Product A (100% wool)	0,00	8,02	54,63	2,55	65,20
Product B (80% wool + 20% PET)	38,05	8,54	43,89	4,93	95,40
Kenaf fiber (with PET) (Fassi, Maina 2009)	96,30	18,30	24,80	10,60	150,00
Product D2 (50% wool + 50% hemp)	13,95	24,57	147,35	16,77	202,64
Rock wool (Fassi, Maina 2009)	46,16	5,83	143,93	8,70	204,61
Product C2 (100% wool)	0,00	5,22	237,88	11,00	254,10
XPS (Fassi, Maina 2009)	232,42	5,49	47,25	4,12	289,28
Glass wool (Fassi, Maina 2009)	56,43	9,25	254,38	0,00	320,05

Fig. 3. Life Cycle Impact Assessment of insulation materials used in the comparison analysis. Environmental indicator: Cumulative energy demand (non renewable).

Moreover a certain reduction of non renewable energy demand should reasonably achieved optimizing the insulation materials production process with a more efficient equipment, especially concerning the wool drying process. Furthermore, LCA results should be implemented with other environmental indicators to complete the impact assessment analysis, such as greenhouse gas emission [12, 13].

3. Thermal performances

3.1. Thermal conductivity measurement

The measurements were carried out by means of a Guarded Heat Flux Meter apparatus (GHFM) (fig. 4a) according to the methodology for the evaluation of the thermal conductivity of building products with high and medium thermal resistance (as shown in EN ISO 12667 [14]). The thermal conductivity of two different samples, rispectively A (1st wash) and B (2nd wash) with dimensions of 500 x 500 x 45mm (thickness) were measured.

In order to analyse the influence of the water content on the thermal conductivity, tests were performed with two different samples conditions:

- standard (the samples were stored for 1 month in the laboratory environment ~25°C and ~50% of relative humidity);
- dry (before tests the samples were dried in ventilated oven until the constant weight was reached);

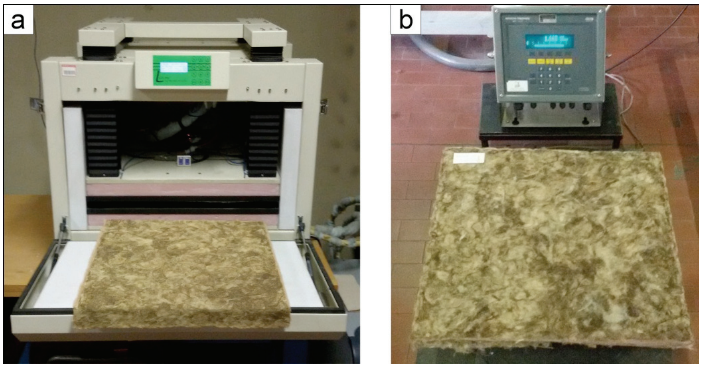


Fig. 4. a) Guarded Heat Flux Meter apparatus, b) weighing process.

The relative water content was estimated comparing the weight of the samples before and after the drying process (fig. 4b).

The apparatus is equipped with two plates which generates a stabilized temperature difference of 20°C, while a heat flux sensor is placed in the middle of the plates, covering an area of 254x254mm. Moreover, in order to assess the dependency of the thermal conductivity on the average temperature of the sample, the measurements were carried out at 25°C (λ_{25}) and 40°C (λ_{40}) of average temperature.

The thermal conductivity (λ) [W/(mK)] was calculated through equation (1).

$$\lambda_{eq} = (s \cdot \dot{q}) / \Delta T \quad (1)$$

Where: (s) is the sample thickness [m] (automatically measured by the instrument), ($\dot{q}$ is the specific heat flux [W/m^2] which cross the sample and (ΔT) is the temperature difference between the two faces of the plates [°C].

3.2. Thermal conductivity results

The results of the thermal conductivity measurement for the different specimens are reported in Table 2. As expected, results shows that the thermal conductivity (λ) is influenced by two main factors:

- sample average temperature: a temperature increment of 15°C (from 25°C to 40°C) determine an increment of λ respectively of ~7.6% (sample A) and ~10.8% (sample B), while in case of dry specimens the influence of temperature is less evident (between 4% and 5% respectively);
- relative water content: a water content of 7% (A) and 8% (B) determine an increment of the thermal conductivity compared to the dry samples, respectively of 3,5% and 4,2% at 25°C, while an increment between 7% A) and 10% (B) were observed at 40°C;

Furthermore, both samples (A and B which are characterized by the same value of dry bulk density ρ) reach similar results of thermal conductivity (the differences are in the range of the measurement uncertainty ~2%). Nevertheless the effect of the mean temperature on the thermal conductivity is less in the 1st wash sample compared to the 2nd wash sample. This fact depends on the different water content in the standard samples (respectively of 7% and 8%).

Table 2. Experimental results of thermal conductivity λ_{eq}.

Sample	Density ρ	Water content	$\lambda_{eq\ 25°C}$	$\lambda_{eq\ 40°C}$
-	[kg/m^3]	[%]	[W/mK]	[W/mK]
Sample A (dry)	133	-	0.039 ± 0.001	0.041 ± 0.001
Sample A (standard)	142	7%	0.041 ± 0.001	0.044 ± 0.001
Sample B (dry)	132	-	0.038 ± 0.001	0.040 ± 0.001
Sample B (standard)	142	8%	0.040 ± 0.001	0.044 ± 0.001

3.3. Thermal transmittance measurement

Besides laboratory measurements of thermal conductivity, in-situ measurements of thermal transmittance were carried out in a test box built by a drywall technology (dimension 4x2.5x3 m). As shown in Table 3, the tested wall was insulated by a double panel with properties comparable to standard sample (Table 2).

Table 3. Test box wall stratigraphy

Material (from internal to external side)	Thermal conductivity λ	Thickness
-	[W/(mK)]	[cm]
plasterboard	0.210	1.2
FITNESs panel (double panel)	0.040	9.0
concrete board	0.350	1.5

In situ measurements were carried out according to the heat flowmeter (HFM) method described in the standard ISO 9869 [15]. The north wall of the test box was chosen in order to avoid the influence of direct solar radiation, whilst internal conditions were kept constant by an electric heating system. Surface temperature sensors and two HFM probes were placed on the internal surface considering the wall homogeneity. Besides thermal flux measurements, indoor and outdoor air temperature were measured accordingly at both sides of the tested vertical element.

The data from the HFMs and the temperature sensors were acquired over a period of 10 days during winter time without interrupting the data acquisition process.

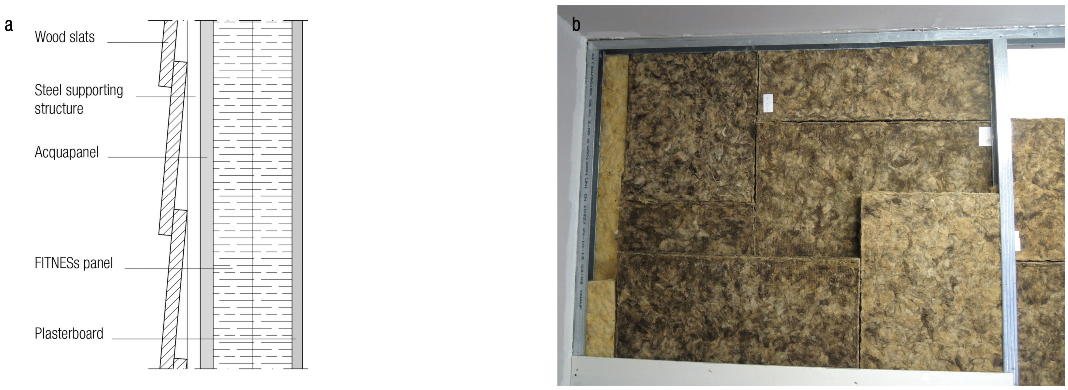


Fig. 5. a) Test wall stratigraphy, b) FITNESs panels installation on the test wall

3.4. Thermal transmittance results

Measured data through HFM probes and temperature sensors were processed using the progressive average method over the acquisition period, according to ISO 9869 [15].

The results of thermal transmittance measurements in two different points of the tested wall were U=0.42 W/(m^2K) and U=0.43 W/(m^2K) respectively and comparable to 0.41 W/(m^2K) of U value calculated considering the stratigraphy reported in Figure 5a. This test confirmed that FITNESs panels show a thermal performance comparable to other fibrous insulating materials such as fiberglass and mineral wool.

4. Acoustic performances

4.1. Sound absorption coefficient measurement

At the beginning of the FITNESs project, the acoustical characterization of sheep-wool and hemp panels was conducted on small samples analyzed by the Kundt's tube method. The sound absorption coefficient α was established in accordance with EN ISO 10534-2 [16] at the National Institute of Metrological Research (INRIM – Turin - Italy). The α values were ascertained by producing standing waves in two tubes with different diameter: 50 mm and 30 mm for measurements in low frequency (100-800 Hz) and high frequency (1000-5000 Hz) respectively. 36 - 46 mm thickness circular samples were placed at the end of the Kundt's tube during each test. Measurements were recorded at third-octave frequency band within the intervals of 100-5000 Hz and conducted at a air temperature of 22.3 °C, relative humidity of 41.5%, pressure of 99.4 kPa.

Further evaluation of the sound absorption coefficient was assessed on finished sheep-wool and hemp panels by means of a reverberation chamber at INRIM (Istituto Nazionale di Ricerca Metrologica). The test specimen was constituted by 12 m^2 of stiff panels with thickness 45 mm and density 142 kg/m^3, mounted on the floor of the reverberation chamber with the rough side selected as the absorption surface area (Fig. 6a).

Two acoustic tests were carried out: in the 1st test the absorption side of panels was covered with a transparent acoustic fabric, in the 2nd test the measurement was repeated without the fabric. The use of an acoustic fabric to wrap the panels (Fig. 6b) was considered in practical applications of reverberation control to protect absorbent material from damage and especially for aesthetic and hygienic reasons (i.e. to prevent fibers being lost).

According to standard EN ISO 354 [17], the sound absorption coefficient by reverberation chamber method was obtained through two reverberation time measurement sets of the test room with and without the specimen placed in it, within the intervals of 100-5000 Hz in third-octave frequency band. The reverberation room was equipped with diffusing panels to obtain a uniform distribution of acoustic energy and random direction of sound incidence on

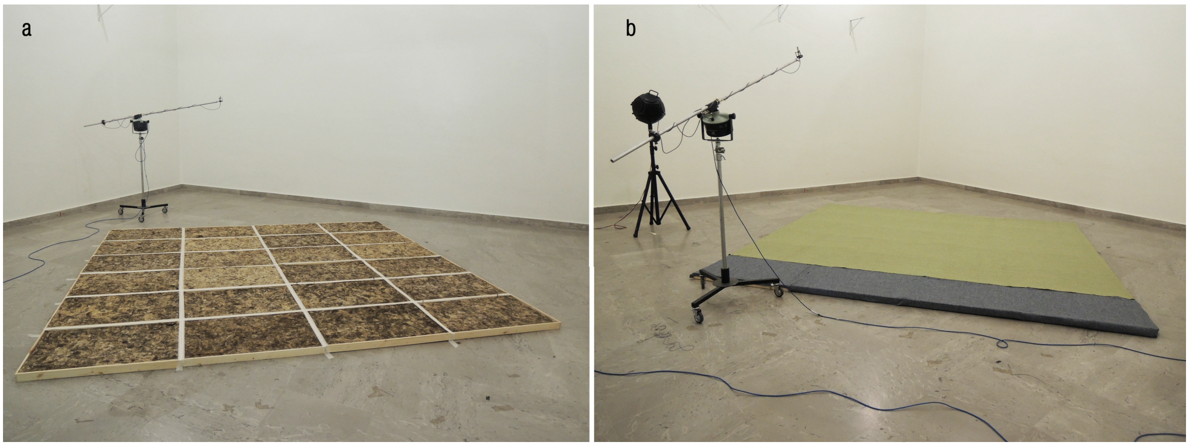


Fig. 6. (a) FITNESs panels placed in the reverberation chamber; (b) FITNESs panels covered by a transparent acoustic fabric during the acoustic test.

specimen. Test measurements were conducted at an air temperature of 22.8 °C, relative humidity of 51.7%, pressure of 98.5 kPa.

4.2. Sound absorption coefficient measurement: reverberation room

An overview of measured sound absorption coefficient within the frequency band of 100-5000 Hz is given in Figure 7, where the results of two tests in the reverberation chamber (panels wrapped with fabric, panels without fabric) and by the Kundt's tube method are compared.

It can be state that all tested specimens have a good performance at medium and high frequencies typical of acoustic fibrous materials. Regarding the reverberation chamber test, the panels covered with fabric show a better acoustic behavior also at lower frequencies (from 160 Hz to 500 Hz) since there is an air gap of 10 mm between the surface of each panel and the fabric. The different absorption behavior of samples tested by the Kundt's tube is mainly due to the normal incidence of acoustic energy on specimen rather than the random incidence occurring in the reverberation chamber.

In accordance with standard EN ISO 11654 [18], from the results in the reverberation chamber the weighted sound absorption coefficient was calculated obtaining a value of $\alpha_w = 0.65$ (MH) for the panels without fabric and $\alpha_w = 0.75$ (MH) for the panels covered with fabric. It is worth mentioning that in the previous research project called "Cartonlana", the panels based only on sheep wool showed a lower sound absorption coefficient ($\alpha_w = 0.55$ (MH)) by measurements in the reverberation chamber.

Since the FITNESs panels show a good performance at medium and high frequencies typical of acoustic fibrous materials (i.e. glass and rock mineral wool with same density), they can be considered suitable for acoustic treatments in indoor workplaces.

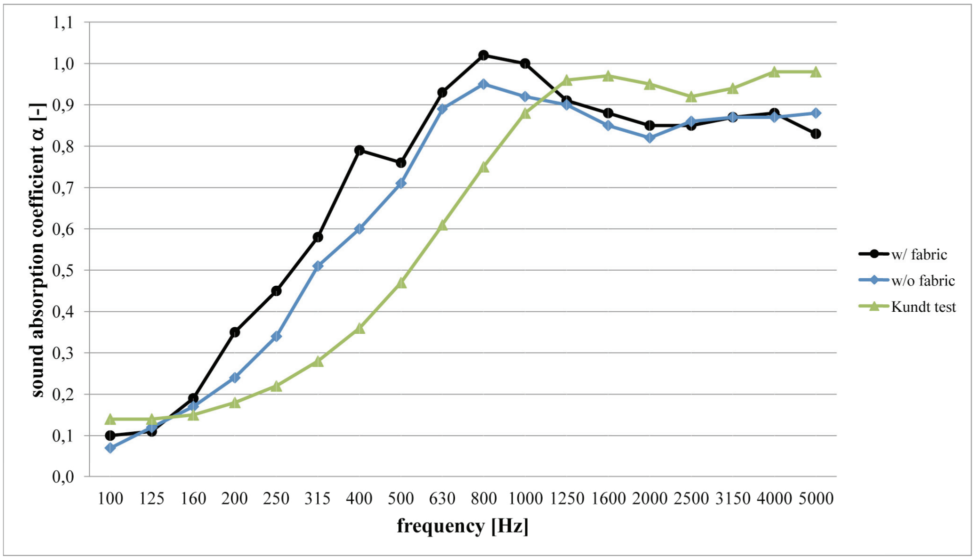


Fig. 7. Values of sound absorption coefficient α of tested FITNESs panels.

5. Results discussion

The research work carried out about wool and hemp production allowed to identify related byproducts with useful features to the product manufacture. Previous research experiences have enabled to build on an effective methodology for panel production and testing of its physical characteristics.

LCA approach shows FITNESs panels non renewable energy demand values are comparable with other high density fibers insulating materials, as shown in the simulation (figure 3). Due to the functional unit considered in the LCA analysis, high density materials show a relatively high non renewable energy demand value if compared with low density materials, at the same time, high density thermal insulation products, such as FITNESs, allow higher building envelope thermal performances in summer (higher thermal inertia). The comparison doesn't remark this benefit that however should be taken into account in the product global assessment.

Results of experimental measurements show as FITNESs is a competitive product in terms of thermal conductivity, comparable with other products on the market of thermal insulation materials and has significant acoustic absorption performance. It's application in an external wall built with dry technologies shows a good workability, despite cutting operations requires certain attention and confirm good thermal insulation performance results obtained with experimental measurement.

6. Conclusion

FITNESs panels can be considered as a further development of the previous research carried on the field of thermal and acoustic insulating materials, Cartonlana sheep wool panels; Comparing the two products characteristics in fact, thermal insulation performance and workability remains unaltered, while acoustic absorption performance is increased. Moreover, as a further remarkable result of LCA analysis it can be asserted that the addiction of hemp fiber in sheep wool panels contribute to decrease the product environmental impact, while it guarantee higher stiffness allowing an easy installation.

FITNESs, as well as Cartonlana, represents a sustainable and innovative alternative to waste of local low quality wool [19], further it's an opportunity to give impulse to local hemp cultivation and production, making use of less valuable hemp fibers, which hardly find place on the market.

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