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THERMAL PROPERTIES OF INSULATING MATERIALS MADE FROM HEMP FIBRES

BY

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Abstract. The ecological footprint of residential buildings has seen a significant increase due to the permanent desire to improve comfort and aesthetics. The construction and rehabilitation of the existing building stock in accordance with the European standards known as "passive house", implies the minimization of external energy consumption. Thus, the thermal insulation materials used to reduce heat transfer play an essential role in the effort to reduce the environmental footprint generated by residential buildings. Hemp is an important candidate for making heat-insulating materials. Hemp stems find their use as basic fibres inside non-woven materials used to produce heat-insulating materials with applications in the field of construction or composite materials. The energy balance between the amount of energy saved and that of obtaining heat-insulating materials, as well as the type of raw materials used for their manufacture, is a critical factor for achieving the goal of reducing ecological impact.

Keywords: hemp, agricultural waste, residential buildings, non-woven, thermal insulation material.

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1. Introduction

In 2020, the residential sector consumed 27.4% of the total energy used at EU level for heating and cooling residential space, water heating, lighting, and other uses. The largest share of consumption, over 62%, is used for heating. (Eurostat, 2022) Due to urbanization and demographic growth, the forecast is for an increase in energy consumption required by the residential sector and implicitly in CO_2 emissions generated by the construction sector.

The annual consumption value for a building to be considered passive is below 42 kWh/m^2 to provide the necessary heat, hot water, and electricity. More than half of the heat transfer within a building takes place at the level of the envelope (Ascione, 2019). Depending on the origin, availability and chemical nature of the raw materials used for the manufacture of thermal insulation materials, they can be classified into three main groups: conventional, state-of-the-art, and sustainable. Sustainable heat-insulating materials made from natural raw materials, agricultural residues, and recycled materials have the lowest impact in the production phase and from the point of view of incorporated carbon (Kuman, 2020).

Hemp is an easy-to-grow plant with various applications such as obtaining fibers, pods, and seeds. In Europe, there exists a longstanding cultural tradition spanning centuries within the textile industry, wherein fibers are transformed into ropes, non-woven materials, and various fabrics, including bags and technical inserts (Carus, 2013). With the advent of petroleum-based synthetic fibers, the industrial hemp crops for fibers experienced a sharp decline and only in recent years, due to the search for ecological alternatives, have they experienced a revival.

In recent years, there has been growing interest among farmers in cultivating hemp to produce seeds used for oil, protein meals, and medicinal purposes. Consequently, the stalks left after harvesting these crops are often regarded as agricultural waste. The utilization of hemp stems, particularly those resulting from the harvesting of inflorescences for CBD oil or seed extraction, aims to enhance the profitability of hemp cultivation. The cultivation techniques employed, such as stimulating plant branching through the application of cuttings to increase seed and inflorescence production, result in highly branched plants arranged in multiple directions. This branching significantly impacts the variation in fiber length obtained from these plants (SCDA, 2022).

Due to the specific methods used in cultivation and harvesting for these purposes, the resulting hemp fibers are less suited for traditional applications such as thread production for fabrics or ropes. However, they prove valuable as basic fibers in non-woven materials, which are used in the production of heat-insulating materials with applications in the construction industry, or as reinforcement in composite materials. These alternative uses not only contribute to the overall utility of hemp but also enhance its economic potential by tapping into the growing demand for sustainable, eco-friendly materials. (Kymäläinen, 2008).

Heat-insulating materials made from hemp fibers are part of the category of conventional insulation materials but considering the origin of the raw material (agricultural waste) they can be considered as part of the category of sustainable heat-insulating materials. The use of agricultural waste for the design of ecological and locally sourced alternatives is intensively researched. Thus, we can list initiatives such as thermal and sound insulating panels made from corncobs (Paiva et al, 2012), cotton stalks (Zhou et al, 2010), durian peel and coconut (Khedari et al, 2004), oil palm fibers (Agoudjil et al, 2011), leaves of pineapple (Kumfu & Jintakosol, 2012), rice and wheat husk (Muthuraj et al, 2019)], sunflower stalks (Binici et al, 2019), straw bales (Sabapathy & Gedupudi, 2019), wood waste (Barreca et al, 2019) and others.

To produce heat-insulating and sound-absorbing materials, the main methods used to obtain the fibrous layer are carding-folding or aerodynamic. The consolidation methods adopted influence the characteristics of the heat-insulating non-woven materials, thus obtaining products with a weight between 80-2000 g/m^2. The most common consolidation methods used to obtain voluminous thermal insulation materials are those that use bicomponent/thermoplastic fibers or liquid adhesives and hot air currents (AGIR, 2002). The need to use fibres or binding substances in manufacturing heat-insulating materials from hemp, but also the problems related to the reaction to fire, and increased hydrophilicity are just some of the issues that represent an impediment to their widespread employment.

Finding simple and economically efficient technological solutions for separating the fibers from hemp stems and using them in valuable products will contribute to the relaunch of hemp crops. The variants investigated in this study, including both the fibrous layer formation (carding-folding) and its consolidation processes, offer significant advantages. Among these are the relatively low costs associated with the proposed equipment, which is commonly used in the textile industry. Additionally, the versatility of the consolidation methods allows for their adaptation based on specific economic and environmental requirements (Zamfir, 2008).

2. Materials and Methods

The agricultural waste of the hemp crop for inflorescences used for this study was pre-processed to separate dust from fibres. The steps required to process hemp stems to obtain hemp fibres with an advanced degree of individualization and cleaning necessary to achieve the fibrous layer are shown in Fig. 1.

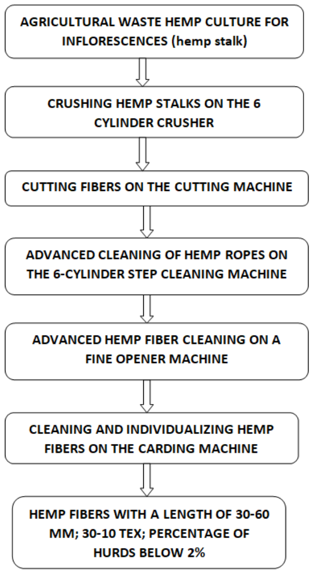


Fig. 1 – Stages of preliminary processing of hemp stems.

The considerations related to the surface layout, the variety of fibrous materials that can be processed, the resulting characteristics of the fibrous layers, and consequently the non-woven textiles, alongside economic factors, led to the selection of the carding-folding process as the method for creating the fibrous layer in this experiment. Another argument that recommends this process for making the fibrous layer refers to the simplicity of the technological line specific to the carding-folding process, which is composed of a card and a folding machine equipped with carts and conveyor belts (horizontal folder).

In Fig. 2 the overall scheme of a carding-folding aggregate and the fibrous layer obtained are displayed.

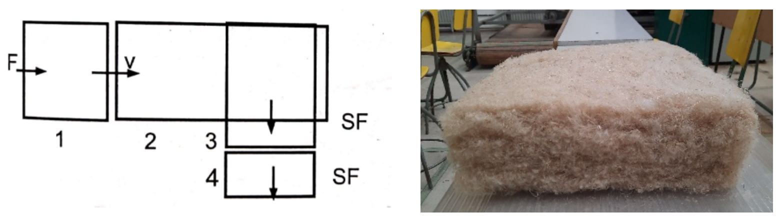


Fig. 2 – The overall scheme of an aggregate to obtain the fibrous layer by the carding-folding method and the fibrous layer obtained. F- fibers; SF- fibrous layer; 1- feeding-mixing-unraveling-carding aggregate; 2- folding machine; 3- strip for taking up the fibrous layer; 4- conveyor belt for the fibrous layer during consolidation.

The characteristics of non-woven textile materials depend, mainly, on the characteristics of the fibres and the technological processes of manufacturing the fibrous layer, but in close connection with the technologies of strengthening the fibrous layer.

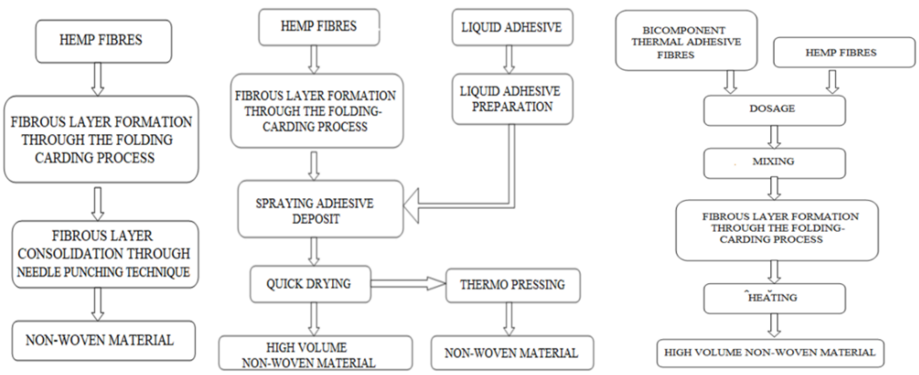
In the experiment, there were used three methods of strengthening the fibrous layer obtained by the carding-folding method:

✓ **By needle punching technique** on the AMIT interweaving machine the fibrous layer made of 100% hemp fibers with a length between 30-60 mm and a length density (tex) between 30-10 tex;

✓ **With spray liquid adhesives bonding** – polyvinyl acetate with a content of 48% dry substance. Spraying was carried out using the Einhell TC-SY electric paint spray gun over the fibrous layer made of 100% hemp fibers with a length between 30-60 mm and a length density (tex) between 30-10 tex. The glue was dried in an electric oven at a temperature of 105ºC for 10 minutes;

✓ **With bicomponent fibres** by heat treatment in an electric oven at a temperature of 1500 C for 5 minutes of the fibrous layer made by the preliminary mixture of 90% hemp fibers with a length between 30-60 mm with a length density (tex) between 30-10 tex and 10% bicomponent polyester fibers with a fiber length of 51 mm and a length density (den) of 4 den. The bicomponent polyester fiber used is manufactured by conjugate spinning of general polyester and low melt modified polyester at approximately 110ºC.

Block diagrams of the three consolidation methods are shown below in Fig. 3.



(a) (b) (c)

Fig. 3 - Technological flow block diagram for (a) needle punching technique consolidation; (b) consolidation with liquid adhesives; (c) consolidation with bicomponent fibres.

Fig. 4 shows the samples obtained by the three methods of strengthening the fibrous layer manufactured with the carding-folding method.

a b c

Fig. 4 – (a) sample consolidated by needle punching technique; (b) sample consolidated with liquid adhesives; (c) bicomponent fibre reinforced sample.

For the accuracy of the results and their comparison with the variants of heat-insulating materials based on hemp fibers existing on the construction materials market, it is necessary to use the same measurement standard, namely ASTM-5334-08, but also the ambient conditions used for the determinations made on the samples (temperature 15.50ºC and humidity 58.9%). Commercial variants of thermal insulation materials use standards such as EN 12667:2001 and EN-ISO-10456 to determine thermal conductivity and thermal capacity, and there are also manufacturers that do not specify the used standard.

According to the standards, the necessary measurements were made to characterize the properties of the thermal insulating nonwoven material variants studied. Density (ρ) kg/m^3, coefficient of thermal conductivity (λ) W/mK and heat capacity (Cp) J/m^{3}K were determined. Thermal conductivity and thermal capacity of a thermal insulation material are two thermophysical properties that strongly influence the energy performance of a building.

The coefficient of thermal conductivity (λ) and heat capacity (Cp) were measured with the ISOMET 2114 apparatus according to the ASTM-5334-08 standard (ASTM, 2008). The apparatus used is a portable instrument for direct heat transfer measurement for a wide range of isotropic materials (plastic, glass, insulating materials and minerals). The dynamic method used for measurement considerably reduces the time required compared to the traditional static method. The needle type probe was used to make the measurements. The needle probe can be used for soft solid materials where it is possible to simply insert the probe needle into the material being measured or it is possible to find a precise opening for the needle. The minimum required thickness of the material around the needle probe is from 20 mm to 40 mm, depending on the thermal conductivity of the material being measured. Fig. 5 shows the measurement method.

Fig. 5 – Measurement of the thermal conductivity and thermal capacity of the thermal insulation material.

The density (ρ) of the obtained samples was determined by measuring the dimensions and weighing the samples before and after the consolidation process. The density of the fibrous layer obtained by the carding and folding method and used for this study is 25 kg/m^3.

3. Results and discussion

The coding of the variants and the determined characteristics of the heat-insulating materials consolidated by the methods proposed in this study are presented in Table 1, as well as the average values of the main heat-insulating materials made from hemp fibres on the market (Lekavicius, 2015).

Table 1
Properties of thermal insulation materials from hemp fibers

Consolidation Variant	Variant Code	Density (kg/m^3)	Thermal conductivity coefficient (W/mK)	Thermal capacity (10^6J/m^{3}K)
Heat-insulating material reinforced by needle punching technique	IMT	172.00	0.0651	0.1827
Thermal insulation material reinforced with liquid adhesives	ADMT	42.00	0.0568	0.1006
Thermal insulating material reinforced with bicomponent fibers	BIMT	35.00	0.0554	0.089
The mean of commercial thermal insulation materials	CMT	35.00	0.04	0.0018

Figures 6, 7 and 8 show graphically the values obtained for the 3 samples made by different consolidation methods, as well as the average value of heat-insulating materials based on hemp fibers that are sold on the market.

As seen, the values obtained for the samples made by strengthening with bicomponent fibers and polyvinyl acetate fall within the values of similar products on the market, namely 25-42 kg/m^3.

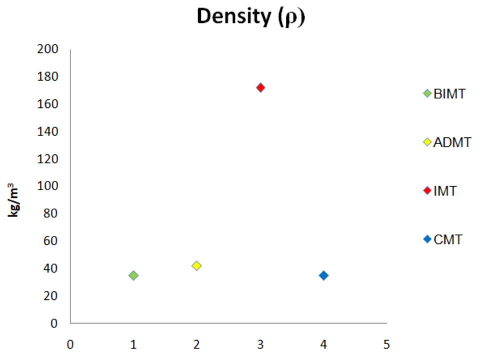


Fig. 6 – Density of heat-insulating materials.

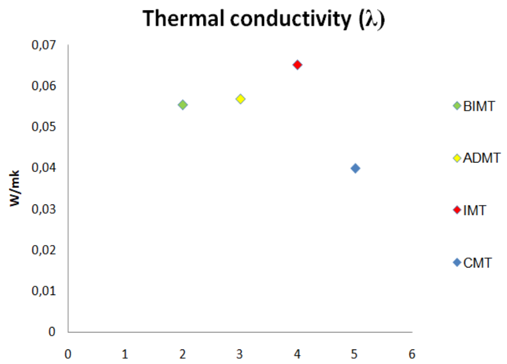


Fig. 7 – Thermal conductivity of heat-insulating materials.

The sample consolidated by needle punching technique (172 kg/m^3) has the density in the range of hemp products (Thermo-Hanf® Step, 2022) intended for use under parquet with values between 160-180 kg/m^3.

The coefficient of thermal conductivity (λ) expresses the ability of a material to transmit heat (through thermal conduction) when subjected to a temperature difference. The lower the thermal conductivity value, the better the thermal insulation capacity of the analyzed material.

The thermal conductivity values obtained for the non-woven materials made by different consolidation methods are lower than those sold on the profile market. Thus, this is 38% higher in the case of the thermal insulation material reinforced with bicomponent fiber and 42% in the case of the one reinforced with liquid adhesives compared to the average value of similar materials. The highest value is found in the case of consolidation by needle punching technique, because through this operation the fibrous layer is strongly compacted, registering a decrease in the volume of embedded air, also highlighted by the steep increase in density (172 kg/m^3).

Heat capacity (Cp) describes the amount of heat energy required to raise the temperature of a material. If a material has a low specific heat capacity, then a relatively low amount of heat is required to raise the temperature of the material and conversely, a material with a high specific heat capacity will require comparatively more energy to raise the temperature by the same amount.

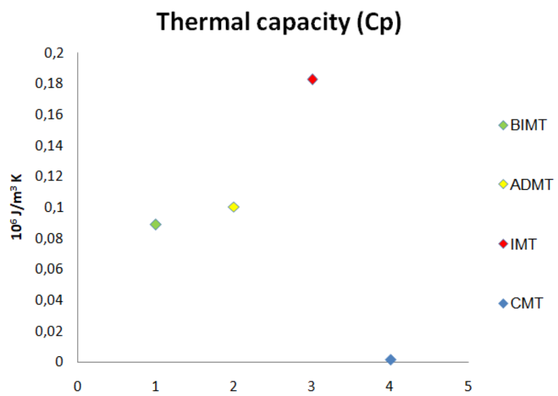


Fig. 8 – Thermal capacity of heat-insulating materials.

Fig. 8 shows that from a thermal capacity standpoint, IMT stands out as the most effective material, offering the highest thermal capacity and best thermal inertia ($0.1827 \cdot 10^6$ J/m^3K). This results in slower heating and cooling, which contributes to more efficient energy management over time. The higher thermal capacity value obtained in the case of the variant reinforced by needle punching technique expresses the ability of the thermal insulation material to heat up in a longer period but to also cool down more slowly, resulting in better thermal inertia. On the other hand, ADMT ($0.1006 \cdot 10^6$ J/m^3K) and BIMT ($0.089 \cdot 10^6$ J/m^3K) offer lower thermal capacities, with ADMT being more efficient in terms of conductivity and lighter in weight. CMT ($0.0018 \cdot 10^6$ J/m^3K), representing standard commercial materials, exhibits the poorest thermal properties in this comparison.

All in all, from the point of view of thermal capacity, the values obtained are better than the average of heat-insulating materials based on hemp that exist on the market, but the choice of material will depend on the specific application requirements – whether prioritizing thermal inertia (IMT) for energy efficiency over longer periods or lightweight and quick response (BIMT or ADMT) for more specialized needs.

4. Conclusions

Density has an important role in the design of a thermal insulation material because it significantly impacts both the amount of raw material required and the thermophysical performance of the resulting material. A lower density typically means a higher volume of entrapped air, which is advantageous for enhancing insulation capacity. This characteristic is notably influenced during the initial stages of fiber processing, particularly when crushing and separating the fibers from the wooden portion of the hemp stems. In this phase, the intensity with which the defibration and individualization of the hemp fibers are carried out is of great importance. The finer the fibers, the more effectively an optimal air-to-fiber ratio can be achieved, which, in turn, maximizes the material's thermal insulation properties.

Of particular note in this study is the variant reinforced with bicomponent fibers, which exhibited the best thermal performance. This superior outcome can be attributed to the consolidation process employed, which does not exert mechanical stress on the fibrous layer. Instead, the bicomponent fibers are integrated into the mixture during the carding and mixing phase, ensuring a more uniform and stable structure. This method preserves the integrity of the fibrous layer, allowing for optimal insulation characteristics without compromising its structural stability.

In contrast, other consolidation methods such as needle punching and liquid adhesive application involve mechanical or chemical actions that can lead to a significant reduction in volume. The needle punching process, which involves repeated penetration of barbed needles through the fibrous web, results in a compression of the material, which can lead to a decrease in its overall thickness and, consequently, its insulating capacity. Similarly, the use of liquid adhesives sprayed under pressure during consolidation results in a settlement of the fibrous layer, further diminishing its thermal performance. These methods, while effective in providing structural integrity to the fibrous layer, ultimately lead to a trade-off between mechanical strength and insulation efficiency.

It is therefore vital to carefully consider the consolidation technique when designing thermal insulation materials, as the choice of method can have significant implications for both the physical properties and the overall performance of the material. While techniques like needle punching and adhesive bonding may be suitable for applications where mechanical stability is prioritized, the use of bicomponent fibers represents a promising alternative for enhancing thermal insulation without compromising material integrity.

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STUDIU COMPARATIV ASUPRA MATERIALELOR TERMOIZOLANTE REALIZATE PRIN DIFERITE METODE DE CONSOLIDARE DIN FIBRE EXTRASE DIN DEȘEURILE AGRICOLE ALE CULTURII DE CÂNEPĂ PENTRU INFLORESCENȚE

Amprenta ecologică a clădirilor rezidențiale a cunoscut o creștere semnificativă din cauza dorinței permanente de îmbunătățire a confortului și esteticii. Dezideratul la nivel european este construcția și reabilitarea fondului existent de clădiri în conformitate cu standardele europene ce poartă denumirea de ”passive house”, fapt ce presupune minimizarea consumului de energie din alte surse. Astfel materialele termoizolante utilizate pentru reducerea transferului de căldură joacă un rol esențial în diminuarea amprentei de mediu generată de clădiri. Cânepa este un candidat important pentru realizarea unor materiale termoizolante. Fibrele de cânepă își găsesc utilizarea ca fibre de bază în interiorul materialelor nețesute utilizate pentru realizarea de materiale termoizolante cu aplicații în domeniul construcțiilor sau materiale compozite. Bilanțul energetic dintre cantitatea de energie economisită și cea de obținere a materialelor termoizolante precum și tipul de materii prime utilizate pentru fabricarea acestora, reprezintă un factor critic pentru atingerea scopului de diminuare a impactului ecologic.