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Analysis of Thermal Parameters of Hemp Fiber Insulation †

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Abstract: Nowadays, sustainable construction is a key factor for reaching net-zero emissions of carbon dioxide all over the world. This goal is impossible to achieve by merely reducing the energy consumption of end-users. A more holistic approach should be taken, adopting sustainable industrial practices that use environmentally friendly materials on a large scale. This paper presents the analysis of the hydrothermal properties of hemp thermal insulation plates. We carried out extensive measurements and the analysis of the thermal conductivity coefficient, drying-out dynamics, and water absorption. The study was performed with experimental insulation samples based on the fiber obtained from hemp stems, prepared using different adhesive powders. The dimensions of the analyzed samples were 300 × 300 mm. The proposed samples are not yet available in mass production. Hemp does not flower in the Baltic region and was traditionally used for soil regeneration. Thus, using this raw material increases the added value of agricultural residues. Three series of hemp fiber samples with different substances and pressing modes were evaluated in the study. Each set of samples consisted of four plates with varying thicknesses and two different densities: 200 kg/m^3 and 300 kg/m^3. All samples exhibited a significant increase in moisture absorption and a strong correlation with the increase in thermal conductivity. The average thermal conductivity of the test samples ranged from 0.0544 to 0.0594 W/mK. The impact of the adhesive powder on the thermal conductivity was found to be extremely small. However, the values obtained were much higher than those for traditional thermal insulation materials, allowing to utilize the local agriculture residues and providing material for the construction of eco-friendly buildings.

Keywords: energy efficiency; thermal insulation; hemp insulation; thermal conductivity; moisture content

1. Introduction

Nowadays, hemp is one of the most promising and widely used thermal insulation materials, known for its durability and environmental friendliness. Hemp is obtained from local natural fibers and can be used in the innovative production of materials [1,2].

For many centuries, hemp has been cultivated as one of the oldest crops. Until the 19th century, it was one of the main ingredients for household products such as ropes, clothing, medical preparations, etc. [3]. Hemp has been regaining popularity in Europe for the last twenty years as a type of natural fiber with numerous applications in diverse areas due to its overall environmental qualities, in particular, its low environmental impact [4].

The only difference with other European countries is that hemp plants cannot flower in Latvia because of the climatic conditions; however, in Latvia, it is still possible to use the stem, which fulfills the same function [5,6].

The rapid development of sustainable and carbon-neutral buildings makes hemp fibers a potentially effective building material which is widely studied [2,7]. One of the trends is hemp concrete, an example of vegetal concrete, which provides reduced carbon emissions and has a low environmental impact. The behavior of this material in different climatic conditions and its properties have been considered in numerous studies [8]. Different characteristics of hemp as a building material, including its thermal characteristics as well as the properties of hempcrete with several binders have been investigated [9,10].

Another option using hemp for the building envelope is the thermal insulation of the building. The first studies considering hemp fibers as a potential material for thermal insulation and describing the thermal resistance properties of hemp fibers and the possibilities for the production of hemp insulation were carried out in Latvia during the period 2010–2012 [11,12].

It is very important to take into consideration not only the physical properties of insulation materials but also the environmental and health impacts. Comparing the environmental impact from the life-cycle of glass wool, sheep wool and hemp fiber, ref. [12] found that the latter demonstrated the best indicators.

A detailed analysis of the hemp-growing process and the chemical structure of raw hemp is presented in [4].

One of the main characteristic features of hemp is its porous structure, which reduces thermal conductivity and helps obtain natural conditioning effects. At the same time, the highly developed porous cellular structure makes the material vulnerable to moisture conditions. Nowadays, thermal insulation composites with hemp are widely studied [7,13,14].

The role of hemp fiber materials in the world market of insulation materials is quite insignificant at present. However, considering the importance of the global environmental impact and sustainability of the construction business, it is a very promising sustainable material for insulation [6]. The changes in hemp cultivation in European countries play a key role in the development of this material [4].

One of the most popular global tendencies is searching for solutions aimed at not only reducing the total energy consumption but also at saving embodied energy. The growth of energy prices and shortages of local fossil energy sources in all regions stimulates measures intended for increasing the energy production from renewable energy sources. In addition to increasing the share of renewable energy production, the thermal insulation of buildings also plays a major role in the overall energy balance [15].

Throughout the ages, people living in continental and moderate continental climate, where winter's lowest temperatures may drop to −20 °C, were always trying to find the best solutions to make their homes warmer. For example, all walls were covered with fur skins during the Middle Ages. As centuries passed, better solutions were introduced: air cavities were provided in buildings with masonry walls, and roofing sheets were used as the insulation material for wooden walls. Nowadays, there are diverse ongoing experiments with novel, more sustainable materials [16,17]. However, there are not enough studies confirming the benefits of hemp cultivation or its prospects for the future economy and interaction of the sustainable agriculture and environment.

Based on comparative studies carried out in [18], it can be concluded that the production of hemp thermal insulation has a much lower contamination balance. Estimates of the lifecycle of different insulation materials have revealed that thermal insulation materials made of hemp are biodegradable and do not cause the slightest pollution after the buildings are reconstructed or dismantled, in contrast to chemical thermal insulating foam, which causes serious chemical contamination when dispersed into the environment. It should be mentioned that the environmental impact of glue is much larger compared to raw hemp. Hydrothermal performance was mostly tested within the framework of this study. In the case of real mass production, the adhesive can be replaced by environmentally friendly products. For example, potential alternatives are described in [19]. Hemp thermal insulation material has several advantages. Firstly, it repels rodents because of its distinct smell, so it will not be damaged by mice. Secondly, hemp thermal insulation naturally regulates the humidity in a room in a given range [11,20], so there is no need to install additional conditioners or air humidifiers. Hemp ultimately acts as a heat-source battery: as the sun heats up the building, solar energy is accumulated in the hemp layer, and the building does not become overheated. Conversely, the hemp layer transfers the heat energy to the building in cold weather [21], and as a result, residential heating can be started later.

Recently, attention has been paid not only to the overall appearance and comfort of buildings but also to such aspects as environmental protection and health care. The operation of buildings can have a negative impact on the environment and human health, which is what drives the recent trends towards ecologically clean materials in construction and renovation. Choosing safe materials helps not only to reduce the negative impact on the environment but also to improve the microclimate of the building [22].

Eco-friendly materials are materials that have little impact on the environment, i.e., the emission of toxic substances in the production, operation, processing and disposal of materials is minimal. In addition, these materials do not have a negative impact on human health and contribute to a favorable indoor microclimate. Usually, the following main criteria are taken into account when determining the eco-friendliness of a material:

- Energy:

The production of different thermal insulation materials requires considerable energy consumption. Thermal insulation produced from more natural raw materials requires less energy that is produced from artificial raw materials. Thermal conductivity is one of the most important physical characteristics of insulation materials, describing the ability of a material to transfer heat and has the most significant impact on energy efficiency. Average data for the energy used to produce different heat insulation and building materials are given in Figure 1. While vast amounts of information have been accumulated for most insulation materials, hemp insulation is still not in mass production and the available data are limited to a small amount of experimental studies [23,24]. According to [25], the energy consumption required for producing extruded polystyrene (EPS) is twice the energy consumption of glass wool and is four times greater than that of stone wool. The average data of the energy used to produce different heat insulation and building materials are shown in Figure 1.

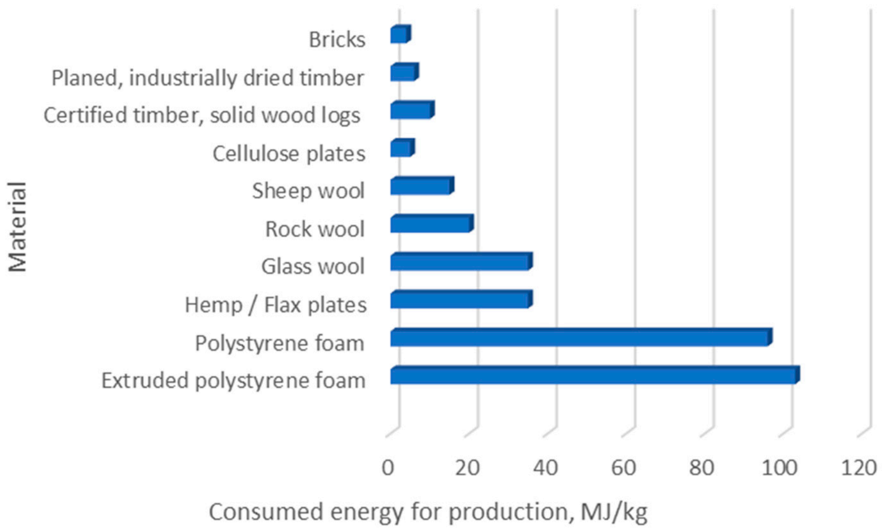

Figure 1. Consumed energy for thermal insulation and construction materials.

The thermal conductivity of hemp insulation is comparable with that of other eco-friendly insulation materials, as shown on Figure 1. However, the main target group of materials are innovative materials for further development rather than mass-produced insulation. The eco-friendly thermal insulation materials are much more expensive in comparison to the traditional thermal insulation materials almost in all cases [26] and the price is less crucial than the environmental effect. This study focuses on the fibers from the hemp used for soil regeneration before it ripens. The easier the extraction, processing and purification of the raw materials used in the production, the lower the energy consumption and consequently the lower the greenhouse gas emissions. The choice of thermal insulation materials is greatly reduced if the energy from renewable sources (water, wind, sun) is used in the production process [27].

- Pollution and waste:

The production or preparation of materials usually leads to greenhouse gas emissions as well as other gases that contribute to precipitation in the form of acid rain. For example, the cement industry is one of the largest sources of carbon dioxide and carbon oxide emissions. Materials that generate dust and other air pollutants, as well as organic solvents, emit volatile organic compounds, can have a negative impact on the health of the personnel participating in the construction, assembly and operation. For example, the release of formaldehyde from wooden boards (MDF or OSB) can cause allergic reactions or even cancer. Vinyl wallpapers can release phthalates that can damage the endocrine system [28]. Thus, natural materials that do not contain chemicals or at least have no toxic effects should be first choice.

- Local Production:

Using local materials has several advantages over deliveries from other regions. Firstly, less energy is used to transport the materials, thus reducing the greenhouse gas emissions and the environmental damage [29,30]. It is worth mentioning that acquiring local materials strengthens the economy and stimulates job creation.

- Recycling and Reuse:

Each material has its own environmental impact, the so-called 'ecological footprint', taking into account energy consumption, resource use and environmental pollution, especially at the production stage. It is very important to assess the entire lifecycle of the heat insulation material, including possibilities to minimize the environmental impact at every stage, in particular, comparing different solutions for the material's recycling and decomposition. The environmental impact can be reduced by making greater use of the production recycled in the manufacturing process. Some materials can be easily used even repeatedly, for example, cellulose plates or ceramic roof plates. Recycling some materials, for example, old windows and slate roof sheets is problematic. Other materials cannot be recycled at all, for example, polyurethane insulation foam.

- Longevity:

Choosing long-lasting materials not only saves money, but also reduces the amount of waste to be transported to landfills, as well as the amount of raw materials and energy needed to produce the required end materials. In some cases, despite the high amount of energy needed to produce the material, it is more appropriate to choose a material with a longer service life.

2. Methods

The overall methodology is based on the thermal conductivity, water absorption and drying measurements for the hemp thermal insulation samples which were fabricated especially for the purposes of the study [31].

We considered different samples of hemp fiber produced from stems. Samples with the geometry of 300 × 300 mm were evaluated (see Figure 2).

Figure 2. Slabs of hemp fibers with dimensions of 300 × 300 mm.

The water absorption, the thermal conductivity and the drying process were investigated.

The slab samples were produced by blending the wet-preserved stem fiber mixture with chopped stems of dry hemp. The first mixture was blended and mixed using two extruders, then the final grinding was performed with the disk mill. The finished hemp stem fiber mixture was dried at +150 °C. The binders used in the fiberboard manufacturing process should bind to the fibers so that the panels are stable, with a resistant shape and satisfactory properties. Synthetic binders are most often used in the production of fiber panels.

In order to prepare hemp thermal insulation samples, raw material was mixed with a phenol formaldehyde (PF) resin glue. Other samples were produced using a carbamide–formaldehyde resin glue.

Three hemp fiber sample series were made with different binders for the experimental part of the study. The samples were put into the press under 100 bar for 4.5 min. The value of pressure under the press varied from 1.5 to 6.1 mPa. The detailed process of the sample preparation procedure is described in [31]. All initial parameters are shown in Tables 1–3.

Table 1. Components of the samples from the first series.

No. of Sample	Components before Pressing					Samples after Pressing			
	Dry kg	Preserved kg	Adhesive kg	V, m^3	$\frac{kg}{m^3}$	kg/after Pressing 0.3 × 0.3 m	A, m	B, m	H, m
1-1	0.9	2.25	0.54	0.009	200	1.8	0.3	0.3	0.1
1-2	0.45	1.125	0.27	0.0045		0.9			0.05
1-3	0.28	0.7	0.168	0.00288		0.576			0.032
1-4	0.2	0.5	0.12	0.00216		0.432			0.024

Here, dry (1) corresponds to the chopped green mass of dry hemp straw, with the fraction size of ~10–20 mm, and humidity of 15%; Preserved (2) corresponds to the green pulp of preserved crushed hemp straw, with the fraction size of ~10 mm, and moisture of 60%; Adhesive (3) corresponds to a Kleiberit 871.0 carbamide–formaldehyde resin glue.

Table 2. Components of samples from the second series.

No. of Sample	Components before Pressing					Samples after Pressing			
	Dry kg	Preserved kg	Adhesive kg	V, m^3	$\frac{kg}{m^3}$	kg/after Pressing 0.3 × 0.3 m	A, m	B, m	H, m
2-1	0.6	3.429	0.36	0.009	200	1.8	0.3	0.3	0.1
2-2	0.3	1.714	0.18	0.0045		0.9			0.05
2-3	0.192	1.097	0.1152	0.00288		0.576			0.032
2-4	0.144	0.823	0.0864	0.00216		0.432			0.024

Table 3. Components of samples from the third series.

No. of Sample	Components before Pressing					Samples after Pressing			
	Dry kg	Preserved kg	Adhesive kg	V, m^3	$\frac{kg}{m^3}$	kg/after Pressing 0.3 × 0.3 m	A, m	B, m	H, m
3-1	1.8	4.5	0.81	0.009	300	3.6	0.3	0.3	0.1
3-2	0.9	2.25	0.31	0.0045		1.8			0.05
3-3	0.576	1.44	0.2	0.00288		1.152			0.032
3-4	0.432	1.08	0.15	0.00216		0.864			0.024

The analyzed hemp fiber plate samples were extruded by pressing in a heated press. The pressing process consisted of several stages. The pressing time and the distance between the heating surfaces were determined at each stage. At the end of each series, the lower platform of the press was moved to zero and the slab sample was automatically removed from the press.

The following standards were used:

LVS EN ISO 12570:2002 "Hygrothermal performance of building materials and products. Determination of moisture content by drying at elevated temperature (ISO 12570:2000/Amd 1:2013)".

GOST EN 12087-2011 "Thermal insulating products for building applications—Determination of long-term water absorption by immersion". Water absorption method for long-term immersion.

LVS EN ISO 10456+AC:2013 L "Building materials and products—Hygrothermal properties—Tabulated design values and procedures for determining declared and design thermal values".

LBN 002-19 "Building envelope heating technology".

2.1. Drying Process after Water Absorption

Water absorption negatively affects the thermodynamic properties of thermal insulation materials. Excess water content increases the thermal conductivity of all materials. The water absorption was measured in this study for three different samples taken from each series. The samples were weighed and measured.

The entire water absorption process took several days for each sample, because the procedure had to be repeated for each sample until its absorption was complete. As the first step, the samples were submerged and fixed in a bath full of water at a temperature of 20 ± 5 °C; the water was 12 mm higher than the upper part of the sample. The samples stayed in the bath for one hour, then they were taken out and the remaining water was drained from the panels. The whole process was repeated in the same way after 24 h.

The density of the hemp fiber sample can be calculated using the formula:

$$\rho_W = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{v_w} \quad (1)$$

where ρ_W is the density of the slab, $\frac{kg}{m^3}$;

m_w is the mass of the sample, kg;

v_w is the volume of the sample, m^3;

$a_w * b_w * l_w$ are the dimensions of the sample (width * thickness * length), m.

2.2. Further Drying Process

It is remarkably difficult to eliminate the moisture from the building materials in real conditions, and it is even impossible in other materials, but moisture from insulation carries the greatest complications for the building. For this reason, it is vitally important to analyze the drying process taking into consideration the real conditions.

The drying process was considered for three different panels of hemp stem fiber samples taken from each series. The samples were weighed and measured.

Hemp fiber samples impregnated with the water were placed in the oven heated to 30 °C. All results were written down at different times, the samples were weighted after two hours, and the weighing process was repeated after 1, 2 and 3 days. Then, the oven was heated up to 60 °C and the samples were weighted again after 1 and 4 h.

2.3. Thermal Conductivity Measurements

A Fox 600 Heat Flow Meter was used to measure the thermal conductivity of the slab samples: it is an instrument for measuring the thermal conductivity of large samples by the ISO 8301 and ISO 8302 standards.

The thermal conductivity coefficient was measured for each sample of the hemp fiber panel. The thickness of the samples was recorded before measuring the thermal conductivity. The samples were placed between two plates in the test stack and a temperature gradient was established over the thickness of the material. The plates were positioned to a user-defined thickness which was measured previously.

The aim of the performed measurements was to estimate thermal conductivity values under the given conditions, still not for the material certification for mass production. The thermal conductivity was determined, both for dry samples (after drying) and after conditioning at 23 °C and 50% relative humidity, as well as for the samples in laboratory conditions.

The following parameters were set on heat flow meter equipment:

The temperature of the hot plate of 20 °C;

The temperature of the cold plate of 0 °C.

The declared thermal conductivity coefficient of hemp fiber board samples in accordance with the EN 10456: 2010 standard can be found by calculations.

The final thermal conductivity coefficient was obtained as the arithmetic mean:

$$\overline{\lambda} = \frac{\sum_n \lambda}{n}, \frac{\mathrm{W}}{\mathrm{m} * \mathrm{K}} \tag{2}$$

Samples of each series were impregnated under laboratory conditions and tested with the Lasercomp Fox 600 Heat Flow Meter to determine the thermal conductivity coefficient at different levels of humidity (see Figure 3). The results are shown in Table 4.

Figure 3. Thermal conductivity measurements of the samples.

Table 4. Thermal conductivity coefficient depending on the humidity.

No.	Sample	Moisture Content, %	Thermal Conductivity Coefficient λ, W/m·K			Interval for Average Thermal Conductivity λ, W/m·K	Increasing of Thermal Conductivity in Comparison to Dry Sample, %
			0 °C	20 °C	Average		
1st series							
1	1-2	0	0.05637	0.05567	0.0560	0.0568	-
		4.2	0.05659	0.05778	0.0572	0.0580	2.12
		15.0	0.07289	0.07635	0.0746	0.0716	33.25
		19.3	0.08781	0.09057	0.0892	0.0906	59.27
2nd series							
2	2-2	0	0.05509	0.05487	0.0550	0.0568	-
		4.3	0.05559	0.05691	0.0563	0.0580	2.27
		10.2	0.06223	0.06760	0.0649	0.0716	18.03
		22.4	0.07637	0.08555	0.0810	0.0906	47.20
3rd series							
3	3-2	0	0.05733	0.06150	0.0594	0.0568	-
		3.8	0.05838	0.06269	0.0605	0.0580	1.91
		8.7	0.07281	0.07757	0.0752	0.0716	26.58
		21.4	0.09392	0.10931	0.1016	0.0906	71.07

The differences of the thermal conductivity coefficient depending on the moisture content allow to trace how thermal conductivity increases as a percentage of the dry thermal conductivity with increasing moisture content in comparison to dry conditions.

In addition, the effects of different glues were considered. Tables 5 and 6 show the thermal conductivities for samples with different glues: phenol formaldehyde resin (PF) and urea–formaldehyde resin (UF).

Table 5. Thermal conductivity coefficient of the samples with the phenol formaldehyde (PF) resin glue.

No.	Sample	Sample Height, cm	Thermal Conductivity λ, W/m·K			
			Measurement No.	0 °C	20 °C	Average
			Phenol Formaldehyde Resin (PF)			
			1st series			
1	1-1	9.985	1st measurement	0.06274	0.05206	0.0574
		9.972	2nd measurement	0.05559	0.06713	0.0614
		9.971	3rd measurement	0.05700	0.06056	0.0588
Average		9.976				0.0592
			2nd series			
2	1-2	4.927	1st measurement	0.05529	0.05375	0.0545
		4.940	2nd measurement	0.05584	0.05629	0.0561
		4.936	3rd measurement	0.05308	0.05638	0.0547
Average		4.934				0.0551
			3rd series			
3	1-3	2.918	1st measurement	0.05119	0.05058	0.0509
		2.900	2nd measurement	0.05243	0.05235	0.0524
		2.907	3rd measurement	0.05137	0.05267	0.0520
Average		2.908				0.0518
			4th series			
4	1-4	2.293	1st measurement	0.05159	0.05099	0.0513
		2.913	2nd measurement	0.05209	0.05107	0.0516
		2.765	3rd measurement	0.05157	0.05246	0.0520
Average		2.657				0.0516
			Average			0.0544

Table 6. Thermal conductivity coefficient of the samples with the urea–formaldehyde (UF) resin glue.

No.	Sample	Sample Height, cm	Thermal Conductivity λ, W/m·K			
			Measurement No.	0 °C	20 °C	Average
			Urea–Formaldehyde Resin (UF)			
			1st series			
1	1-1	9.985	1st measurement	0.06737	0.08155	0.0745
		9.972	2nd measurement	0.05307	0.06744	0.0603
		9.971	3rd measurement	0.06466	0.06870	0.0667
Average		9.976				0.0671
			2nd series			
2	1-2	4.927	1st measurement	0.05712	0.05813	0.0576
		4.940	2nd measurement	0.05738	0.05841	0.0579
		4.936	3rd measurement	0.05545	0.05891	0.0572
Average		4.934				0.0576
			3rd series			
3	1-3	2.918	1st measurement	0.0577	0.05718	0.0574
		2.900	2nd measurement	0.0568	0.05609	0.0564
		2.907	3rd measurement	0.05466	0.05808	0.0564
Average		2.908				0.0568
			4th series			
4	1-4	2.293	1st measurement	0.05639	0.05606	0.0562
		2.913	2nd measurement	0.05608	0.05612	0.0561
		2.765	3rd measurement	0.05391	0.05728	0.0556
Average		2.657				0.0560
			Average			0.0594

Some minor differences in the dependence of the measured thermal conductivity on thickness can be explained by the peculiarities of the measuring equipment. The smaller samples require less time to reach thermal equilibrium. Such difference can be neglected since the goal of the study was to obtain the overall data on the properties of hemp thermal insulation boards rather than the exact data for material certification.

3. Results and Discussion

3.1. Results for Water Absorption

The results obtained for the water absorption of samples of hemp fiber slabs are summarized in Table 7.

Table 7. Difference of the thickness for dry and water-absorbed hemp samples.

No.	Sample	Thickness of Sample before Submergence, mm	Thickness of Sample after Water Absorption, mm	Difference of Thickness, %
		1st series		
1	1-1	9.97	10.42	4.51
2	1-3	2.91	3.05	4.81
3	1-4	2.65	2.79	5.28
		2nd series		
4	2-1	9.40	9.86	4.89
5	2-3	3.11	3.25	4.50
6	2-4	2.72	2.86	5.15
		3rd series		
7	3-1	10.23	10.68	4.40
8	3-3	4.14	4.32	4.35
9	3-4	3.02	3.17	4.97

High water absorption has been identified for hemp fiber slabs. The average water absorption was 201.9% by mass and 36.2% by volume for the samples from the first series, 202.8% by mass and 40.2% by volume for the samples from the second series, however, 189.2% by mass and by 48.0% by volume for the samples from the third series.

It has to be taken into account that the wall construction consists of a layer of wind protection, a vapor barrier and a render, so it is not theoretically possible for the layer of insulation to absorb that much water. Actually, the enclosed layer of insulation is protected from the outdoor conditions in a correct wall construction. The moisture can get into the wall construction in the case of poor or damaged waterproofing; if the temperature between the inside and the outside differs, the condensate forms in the wall (dew point).

It is difficult to compare hemp fiber insulation with the materials offered on the market. The water absorption for insulation like foamed polystyrene, or extruded polystyrene foam, is below 5%. Practically speaking, insulation made of hemp fiber slabs cannot come into contact with water, as is the case for glass wool insulation and stone wool insulation. This means that in case of installation in a wooded frame wall, a water vapor barrier must be placed on the indoor side to protect against moisture absorption.

Moreover, it should be considered that hemp is a flammable material and it has to be installed according to fire regulation and fire protection should be provided.

The difference in the thickness of the samples varied within 5%, which is acceptable for organic unfilled porous materials.

As a result of these measurements, it was determined that the water absorption of slabs of hemp stem fiber insulation was significant. The high absorption of water negatively affects the properties of the thermal insulation material, increasing thermal conductivity and density. All structures built in moist conditions should be dried before a hemp board can be installed.

3.2. Results for the Drying Process

Drying in laboratory conditions can be equated to the perfect drying process in real weather conditions; however, the conditions are far from perfect in reality, involving rain, differences between temperature, low average temperature, etc.

The samples absorbed water for 24 h. As a result, the samples from the first series increased in mass by 252% with respect to the initial dry condition, the samples from the second series by 270%, and the samples from the third series increased their volume by 261%. The samples were dried in the laboratory for three days at a temperature of 20 ± 2 °C. After 3 days, the samples from the first series dried out by 97% with respect to their saturated condition, the samples from the second series by 128%, and the samples from the third series by 124%. The drying process continued at a temperature of 30 °C for one more day. As a result, the samples from the first series dried out by 143% with respect to their saturated condition, the samples from the second series by 187% and the samples from the third series by 196%. Finally, the samples were left for drying at a temperature of 60 °C for one more day, and then the samples from the first series dried out by 210%, with respect to the saturated condition, the samples from the second series by 297%, and the samples from the third series by 286%.

The data were plotted into a graph reflecting the dependence of the drying process on the amount of moisture (Figure 4).

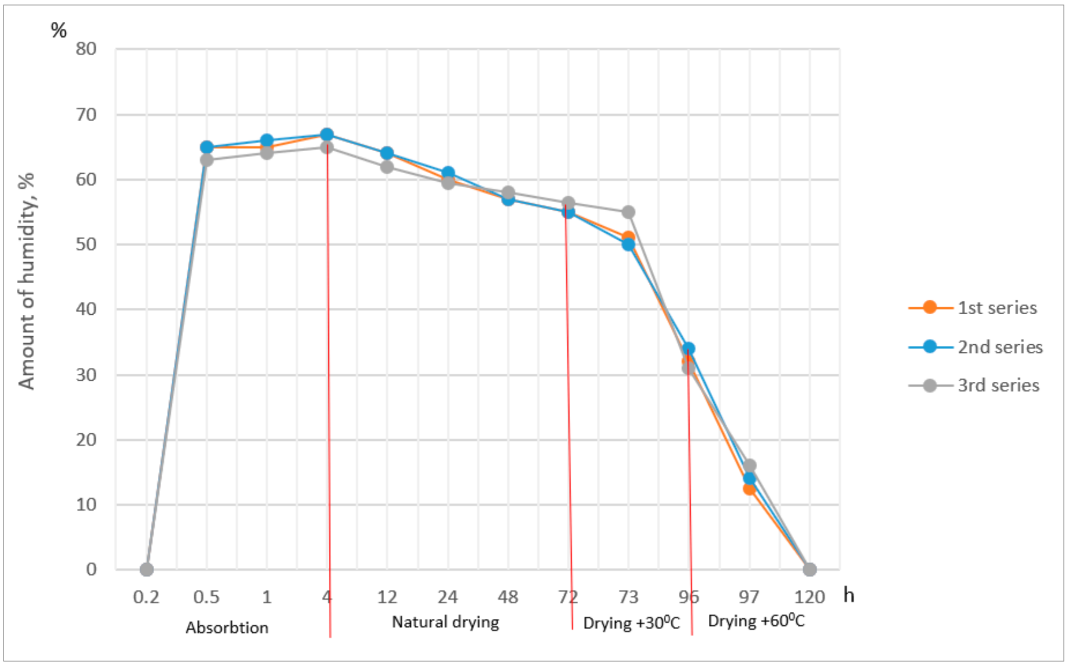

Figure 4. Drying process depending on the moisture content.

It has to be taken into account that the thermal insulation materials in constructions may not dry out completely in different conditions. For this reason, it is necessary to find a method for letting water flow out of the structure if the moisture content is too high. Additionally, as the insulation materials are covered from at least three sides, they interact with other materials. This mostly affects horizontal roofs and similar structures; a typical problem for façades is rainwater filtered through the decorative wall layer.

The results of the drying process are clear evidence that the insulation made of hemp fiber produced from the stems should not come into the contact with water.

3.3. Results for Thermal Conductivity of the Samples

The thermal conductivity coefficient depending on the moisture content is shown in Figure 5.

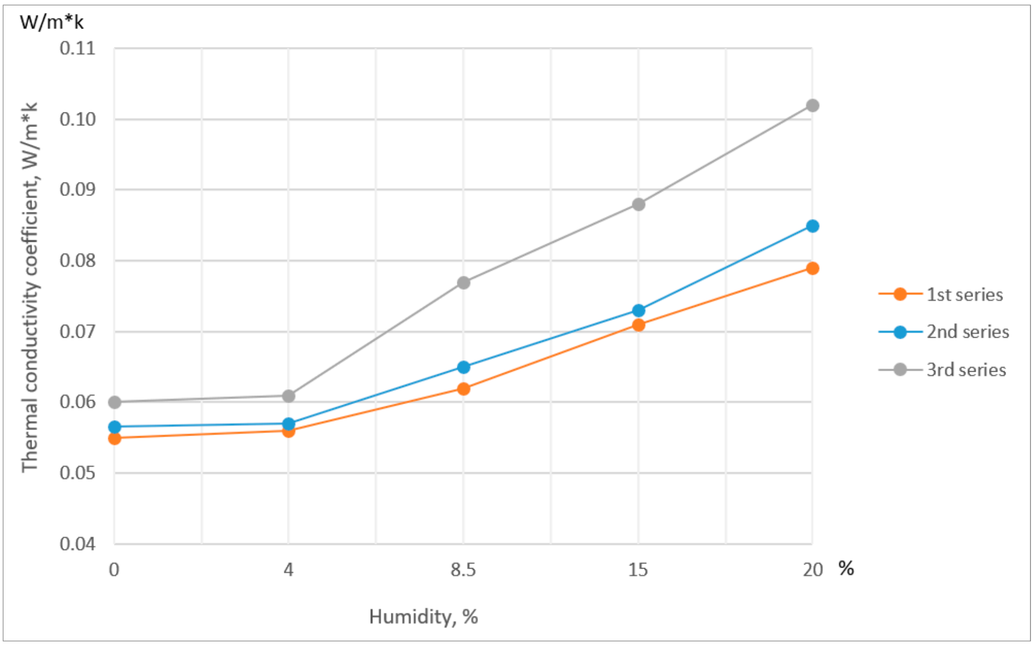

Figure 5. Thermal conductivity depending on the moisture content.

After the experiment, the data from the samples were compiled into tables. The average thermal conductivity was 0.0544 $\frac{W}{m*K}$ for the samples from the first series, 0.0594 $\frac{W}{m*K}$ for the samples from the second series, and 0.0655 $\frac{W}{m*K}$ for the samples from the third series.

The data collected could be transformed to the declared value based on the EN 10456: 2010 standard. The declared value was 0.059 $\frac{W}{m*K}$ for the first series, 0.068 $\frac{W}{m*K}$ for the second series and 0.08 $\frac{W}{m*K}$ for the third series.

According to the requirements of the EN 10,456 standard, the number of samples used in the experiment and tests has to be more than 10 but only three series of samples were used in this study. Our goal was to find the initial properties of hemp thermal insulation boards. Thus, these data could not be used for material certification and declared value calculations.

Discrepancies in the results of measurements indicate that it is impossible to provide smooth moisture distribution in the samples in artificial laboratory conditions. Of course, this process is also not particularly smooth in real conditions. However, the results show that the samples under contact with water increase the thermal conductivity coefficient (Figure 5). Furthermore, if the amount of moisture is larger than 20%, the sample stops performing its main insulating function altogether.

Our most important finding is that the insulation material made of hemp fiber produced from stems restores its good qualities of the thermal conductivity coefficient when it dries out. However, there is a risk that if such an insulation material comes into contact with water, it may not dry out completely without additional measures in real conditions.

4. Conclusions

Based on the literature survey, we can conclude that a hemp thermal insulation plate has an embedded energy as low as 30–35 MJ/kg, and may be considered as a sustainable building material with low environmental impact. The existing technologies also allow to use it as an environmentally friendly adhesive.

We identified the main thermal properties of the insulation material, namely, the thermal conductivity coefficient, volume, moisture content, thermal conductivity and moisture absorption. The difference in the sample thickness varied within 5%, which is acceptable for organic unfilled porous materials. Three series of samples made of hemp fiber from stems were made with different binders for the experimental part of the study. The samples were put into the press under a pressure of 100 bar for 4.5 min.

The study revealed that the average thermal conductivity factor was 0.0544 W/mK for the first series of samples, 0.0594 W/mK for the second series, and 0.0655 W/mK for the third series. Our findings confirmed how water injection into the material increases the thermal conductivity coefficient. The thermal conductivity increases by up to two times at a moisture content above 20%. The effect of adhesion on thermal conductivity is minor and could be neglected.

The major disadvantage of hemp thermal insulation plates is the extremely high water absorption. The average increase in all samples was 198% by mass and 40% by volume. This means that such an insulation material should be used in a controlled environment, excluding any kind of contact with precipitation or any other source of water during storage and transportation, because full drying is impossible in natural conditions at a building site in case of water absorption.

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