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The possibilities of modification of crop-based insulation materials applicable in civil engineering in low-energy and passive houses

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Abstract

Currently in Europe there is a growing trend towards low energy and passive houses where natural materials are often used. These materials are very promising in terms of environmental protection. The use of green thermal insulation materials brings a significant reduction of energy requirements of buildings which is their major benefit. Previous research shows that crop-based thermal insulating materials exhibit very good thermal insulation and acoustic properties. However, their structure is different from conventional insulation materials (EPS, XPS, PUR, and MW) and their hygrothermal behaviour is much different. This article focuses on studying the behaviour of fibrous green insulations under humidity and moisture load. The test samples of the materials were treated with different types of hydrophobic agents before testing. The goal of the experiments was to reduce the sensitivity of the insulation to humidity and moisture (i.e. reduce their hygroscopicity). The chemical treatment of the fibres should improve the practical properties of the thermal insulation materials and extend their service life after they have been incorporated in a structure and attacked by moisture.

Keywords: green insulations, low-energy and passive houses, impregnation, technical hemp, thermal conductivity, equilibrium moisture content.

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1. Introduction

Global warming and climate changes associated with it are often discussed in many countries worldwide. Many organisations are working on new and often stricter regulations and directives with the purpose of improving the energy performance of buildings and reducing the impact that building materials have on the environment. The best known among them is probably the “Kyoto Protocol” [1]. It is a protocol to the United Nations Framework Convention on Climate Change (UNFCCC or FCCC), which focuses on countering global warming with the goal of reducing and controlling the concentration of greenhouse gases (GHG) in the atmosphere. The Kyoto Protocol was adopted in 1997 and entered into force in January 2005 and September 2011. A total of 191 countries have signed and ratified the treaty.

“Agenda 21” [2], an action plan of the United Nations (UN), moves in the same direction. It is connected with sustainable development in the 21st century and it was the outcome of the UN Conference on Environment and Development (UNCED), which took place in Rio de Janeiro in 1992. It is a similar plan with a global scope and it focuses on all areas where people can directly influence the environment. This agenda was adopted by national as well as sub-national UN organisations, governments and majority groups for whom this issue is relevant.

In Europe, there is the currently valid Directive 2002/91/EC [3] of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. It focuses on establishing a common methodology, creating minimum standards for energy performance, energy certification and regular inspections. Another initiative is European Project 20-20-20, whose goal is for the whole planet to reduce energy consumption by 20 %, reduce carbon emissions by 20 % (compared with the 1990 level) and increase the use of renewable energy resources by 20 % by the year 2020 [4].

Civil engineering is a branch of industry which has a strong impact on the environment. Much research has been conducted in the past years, providing evidence for the fact that civil engineering is one of the greatest energy consumers. This fact is caused not only by the buildings themselves (their construction and use) but also by the process obtaining raw materials and manufacturing building materials from them. The production of a great many building materials is rather harmful to the environment (both in terms of energy consumption as well as CO2 emissions). This is the reason for the worldwide interest in the development of low-energy building materials. In the case of building structures, the effort is to optimise the design of buildings with low energy requirements and make extensive use of eco-friendly materials for their construction. Good energy performance of buildings is closely connected with the integrity of the building envelope since it affects the building’s total energy requirements. Reducing the energy consumed by heating and cooling then reduces the emissions of greenhouse gases. Currently, this issue is being addressed mainly by constructing low-energy, passive and nearly zero-energy buildings.

This paper focuses on certain parts of the development of crop-based insulation materials and the modification of some of their key properties. Many experts have dealt with this topic and their results indicate that these materials are promising for the future, especially in terms of sustainable development [5–20]. These materials are eco-friendly and easy to recycle; they come from renewable resources and provide very good thermal insulation properties. However, they have open pore structure and they behave in a specific way when moisture travels through their matrix. For this reason it is also necessary to focus on the issue of the hygroscopic behaviour of green insulations and the danger of degradation of their thermal insulation properties at high moisture. Many authors focus on this issue, e.g. Azra Korjenic together with Thomas Bednar from the Vienna University of Technology. They have developed an advanced model of absorption and desorption of moisture in fibrous materials. This model takes into account air pockets inside fibrous insulations, which can separate the layers of the material into smaller parts [21].

This research involved spraying samples of hemp-based insulation with hydrophobic agents for subsequent analysis of the influence of relative humidity on their thermal insulation properties and also for the determination of equilibrium sorption moisture.

Nomenclature

ρ	bulk density
λ_{dry}	thermal conductivity in dry state
λ_{moist}	thermal conductivity (80% relative humidity)
$u_{23,80}$	equilibrium moisture content (temperature 23 °C, relative humidity 80 %)

2. Choosing suitable insulation and hydrophobic agents

Drawing on literary surveys and research previously conducted at Brno University of Technology, a hemp-based insulation was chosen for the analysis of the effect of moisture on the final thermal insulation properties. The insulation was supplied in the form of mats of 80 mm in thickness and its composition was as follows:

- 82–85 % of hemp,
- 10–15 % of bi-component polypropylene fibre,
- 3–5 % of sodium carbonate (fireproofing component).

Fig. 1: A sample of the hemp-based insulation and his structure

Four types of hydrophobic impregnation available on the construction market in the Czech Republic (commonly used as textile or footwear impregnation) were chosen for the examination of the insulation's hygrothermal behaviour after it had been hydrophobised. They were also selected based on previous research. These were:

- H1 – impregnation mainly for leather products. It contains alkanes (25–50 %), butane (20–40 %), petrol petroleum fraction (10–25 %), propane (2.5–5 %), n-butyl-acetate (2.5–5 %) and dimethoxymethane (2.5–10 %);
- H2 – a silicone-based impregnation, used for the waterproofing of technical fabrics such as tents or backpacks. The main components are a silicone polymer, butane and naphtha;
- H3 – an isopropyl alcohol produced for textile and footwear impregnation;
- H4 – a preparation used primarily for waterproofing of shoes. It is an aerosol containing alkanes, cycloalkanes, isoalkanes, benzen (all components in 50–100 %), propane and butane (25–50 %) and n-butyl-acetate (< 2.5 %).

3. The application of agents and testing of selected properties

Since all the hydrophobic agents were aerosols, they were sprayed onto the thermal insulation mats. Two coats were applied – the first one in the amount of 1 % and the second in 2 % of the total mass of the sample. After the two coats, the samples were left in a laboratory environment (temperature 20±2 °C, relative humidity 50±3 %) and then additionally dried in a dryer at 75 °C until they reached constant mass. Table 1 shows an overview of the samples (1 set of reference samples, without impregnation and 4 sets of samples with impregnation). The values showed within are always an average made from 3 samples from each set.

Table 1. An overview of the samples after impregnation.

Type of impregnation	Sample	Mass before impregnation [g]	Amount of impregnation [%]	Mass after impregnation [g]
REF	1	230.54	0	230.54
	2	231.02	0	4231.02
H1	1a	231.92	1	234.24
	1b	236.74	1	239.11
	2a	225.65	2	230.16
	2b	222.48	2	226.93
H2	1a	228.93	1	231.22
	1b	224.15	1	226.39
	2a	235.46	2	240.17
	2b	225.33	2	229.84
H3	1a	222.98	1	225.21
	1b	225.01	1	227.26
	2a	222.81	2	227.27
	2b	222.01	2	226.45
H4	1a	222.32	1	224.54
	1b	226.28	1	228.54
	2a	227.09	2	231.63
	2b	232.95	2	237.61

Next, the following properties were determined for the samples. The tests were performed according to the standards in written brackets:

- Determination of linear dimensions and bulk density (EN 822, EN 823, EN 1602);
- Determination of equilibrium moisture content (EN ISO 12571);
- Determination of thermal conductivity (EN 12667, ISO 8301).

3.1. Determination of linear dimensions and bulk density

The width and the length of each sample were always measured in three places using a metal ruler with 0.5 mm resolution. The measurements were then averaged and rounded to the nearest 1 mm. Table 2 shows the resulting values. The sample thickness was measured during the determination of thermal conductivity at a nominal holding pressure of 50 Pa.

The bulk density was calculated as the ratio of the mass of a dry sample to the product of the sample's linear dimensions and thickness. Table 2 shows an evaluation of the average values.

Table 2. Average bulk density values determined for dry samples.

Sample	m [g]	l [mm]	b [mm]	d [mm]	ρ_v [kg·m^{-3}]
REF	218.02	293	292	69.97	36
H1-1	218.52	301	296	70.92	35
H1-2	212.27	303	291	70.12	34
H2-1	215.26	305	286	70.27	35
H2-2	221.49	294	303	69.92	36
H3-1	209.69	295	287	70.06	35
H3-2	212.97	294	295	69.96	35
H4-1	209.37	300	284	69.99	35
H4-2	211.83	294	294	69.92	35

The average values of bulk density in a dry state ranged from 34 kg·m^{-3} to 36 kg·m^{-3}.

3.2. Determination of equilibrium moisture content

The equilibrium moisture content was determined according to EN ISO 12571. The samples were placed in a climate chamber maintaining a given temperature 23 °C and relative humidity and regularly weighed until they reached stable mass. The measurements were performed at 50 % relative humidity (laboratory humidity) and 80 % relative humidity (moisture attack in real application). Table 3 below shows the resulting values of the samples' moisture content.

Table. 3 The calculated values of equilibrium moisture content [%] by relative humidity.

Sample	Dry	Relative humidity [%]	
		50	80
REF	0	9.5	14.9
H1-1	0	9.7	15.0
H1-2	0	9.4	10.3
H2-1	0	9.9	15.1
H2-2	0	9.7	10.1
H3-1	0	9.5	15.0
H3-2	0	9.4	10.5
H4-1	0	9.5	14.5
H4-2	0	9.4	10.7

The obtained values of moisture content show no significant difference between the reference and the other samples at 50 % relative humidity. However, at 80 %, the samples with 1 mass % of the hydrophobic agents show higher values of equilibrium moisture content compared with the final values at 2 mass %. The lowest values of moisture content of samples with only 1 mass % of impregnation were found in samples H4-1, H1-1 and H3-1 with 14.5 % and 15.0 %. At the same relative humidity but with 2 % of impregnation, the samples with the best results were H2-2 and H1-2 with 10.1 % and 10.3 %.

3.3. Determination of thermal conductivity

The thermal conductivity of the samples was determined in the steady state by means of the hot plate method in accordance with EN 12667. The following two devices were used for the measurements: the Lambda 2300 from

Holometrix Micromet and the Lasercomp Fox 630. The measurements were taken at a mean temperature of +10 °C and temperature gradient of 10 °C. Three measurements were made on each sample, after which an average value was calculated. The evaluation of the result is in Table 4. The data in Table 4 shows how the values of thermal conductivity change with the type and amount of impregnation.

Table 4. Average values of thermal conductivity determined on dry samples at 50 % and 80 % relative humidity.

Sample	Relative humidity [%]		
	0	50	80
REF	0.0414	0.0451	0.0498
H1-1	0.0422	0.0462	0.0485
H1-2	0.0416	0.0440	0.0476
H2-1	0.0424	0.0456	0.0519
H2-2	0.0422	0.0444	0.0513
H3-1	0.0410	0.0431	0.0506
H3-2	0.0415	0.0435	0.0487
H4-1	0.0415	0.0434	0.0503
H4-2	0.0414	0.0423	0.0500

The obtained values were used in constructing the dependences of thermal conductivity on relative humidity, taking into account the type and amount of impregnation.

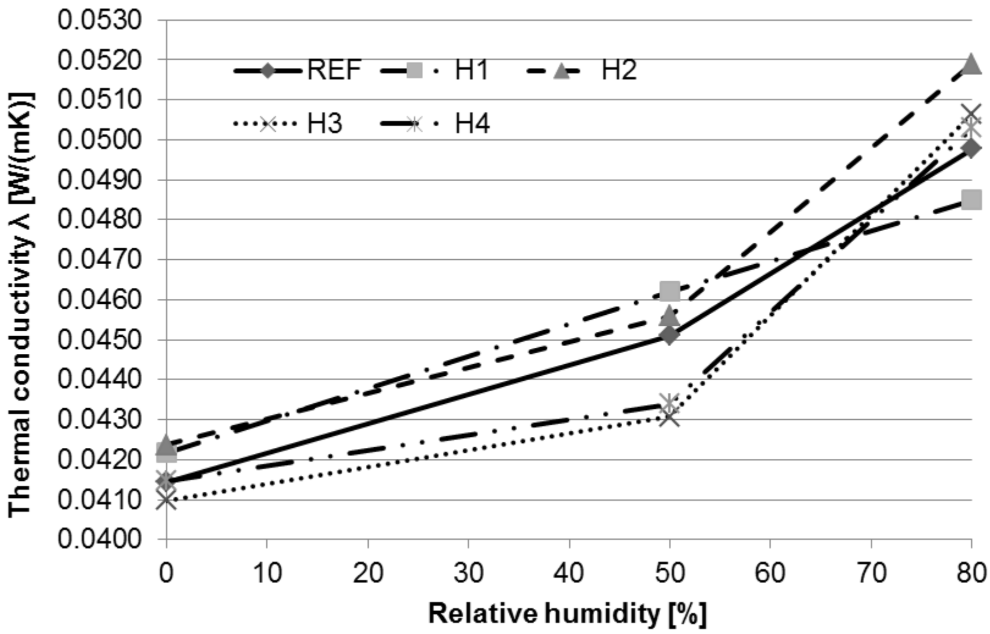

Fig. 2 The dependence of thermal conductivity on relative humidity for samples with 1 mass % of impregnation

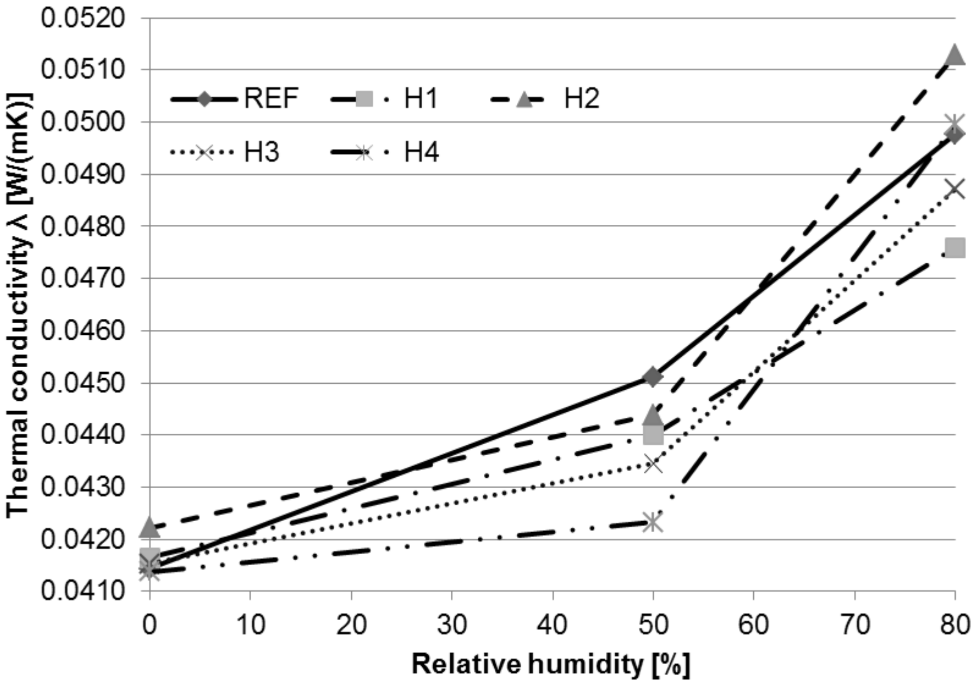

Fig. 3 The dependence of thermal conductivity on relative humidity for samples with 2 mass % of impregnation

The data shows that the values of thermal conductivity increases with rising relative humidity. Sample H1 performed the best both in the case where 1 as well as 2 mass % of impregnation was applied; its thermal conductivity values in the humid environment are the lowest of all the other samples (including the reference). The sample treated with agent H2 in fact shows higher values of thermal conductivity compared with the reference. Both diagrams above (Fig. 2, Fig. 3) show an increase in thermal conductivity with increasing relative humidity. Next, the relative difference in thermal conductivity between the moist (i.e. at equilibrium moisture content u23,80) and dry state was evaluated.

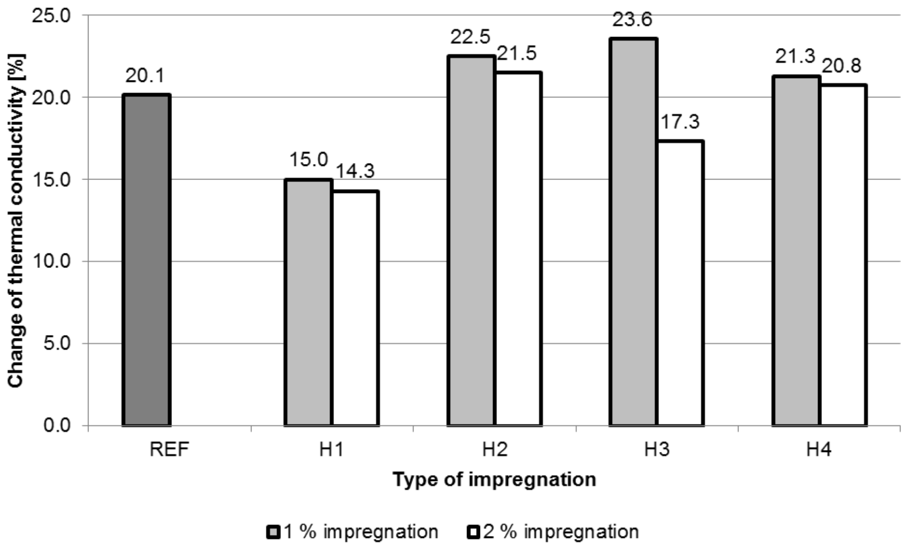

Fig. 4 Percentage difference between the values of thermal conductivity resulting from a change in moisture content

The influence of the different types of impregnation is visible in the comparison of thermal conductivity in the dry and moist state. The results displayed in Fig. 4 show that the smallest difference between thermal conductivity in the dry and moist state were found in samples treated with agent H1 in both mass concentrations. This result is to be expected given the agent's performance in the tests of thermal conductivity in dependence on relative humidity, where it reached the best results of all. Another sample exhibiting the smallest difference was H3 with 2 mass % of impregnation applied. The differences between the thermal conductivity in the dry and moist state found in the other samples were greater than in the reference sample.

4. Conclusion

This paper dealt mainly with the research in the hygrothermal behaviour of hemp-based thermal insulation modified by selected hydrophobic agents. The samples were treated with 1 % and 2 % of hydrophobic agent by sample mass while the reference sample was left untreated. The goal was to examine the effect of these agents on the hygrothermal behaviour of the samples of insulation and to study the dependence of their thermal insulation properties on relative humidity. Also, the values of equilibrium moisture content were calculated.

Table 5. An overview of the values of selected properties.

Sample	ρ [kg·m^{-3}]	λ_{dry} [W·m^{-1}·K^{-1}]	λ_{moist} [W·m^{-1}·K^{-1}]	$u_{23,80}$ [%]
REF	36	0.0414	0.0498	14.9
H1-1	35	0.0422	0.0485	15.0
H1-2	34	0.0416	0.0476	10.3
H2-1	35	0.0424	0.0519	15.1
H2-2	36	0.0422	0.0513	10.1
H3-1	35	0.0410	0.0506	15.0
H3-2	35	0.0415	0.0487	10.5
H4-1	35	0.0415	0.0503	14.5
H4-2	35	0.0414	0.0500	10.7

The data in Table 5 shows that some types of treatment had no positive effect both in terms of sorption properties and thermal conductivity.

The best humid-environment sorption properties, compared with the untreated sample (14.9 mass %), were found in samples treated with H1 (10.3 mass %) and H3 (10.1 mass %); both were applied in the amount of 2 % by sample mass. The values of equilibrium moisture content at 50 % relative humidity show no significant improvement in the treated samples compared with the reference. Thus, no positive influence of the impregnation on the values thermal conductivity in the moist state was proved. An improvement in thermal insulation properties can only be observed in samples treated with agent H1. Both concentrations (1 mass % and 2 mass %) resulted in a reduction of thermal conductivity in the moist state by 4.6 % on average compared with the untreated sample.

In summary of all the tests and result evaluations performed, the most effective hydrophobic agent appears to be the shoe and leather impregnation; i.e. H1. Given the values of sorption moisture content, this applies specifically to the application of 2 mass %, where there was a positive influence on all the properties being observed.

In conclusion, as long as the natural-fibrous material is not exposed to high relative humidity (above 60 %) for an extended period of time, there is no significant harm to its thermal insulation function and, with appropriate building design, can be used in modern low-energy and passive buildings.

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