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Studying the properties of particulate insulating materials on natural basis

Martina Reif*, Jiří Zach, Jitka Hroudová

Brno University of Technology, Faculty of Civil Engineering, Admas Centre, Veveří 331/95, 602 00 Brno, Czech Republic

Abstract

Recently, materials based on secondary raw materials have been the focus of attention of building companies and end users as well. The reason for this are mainly the low material costs, easy manufacture and application in building structures. Despite the lower cost compared to existing insulation materials, strict requirements are put on these thermal insulation materials.

In response to the constantly increasing need for insulation materials and given the general requirement of sustainability in the use of natural resources, the Faculty of Civil Engineering in Brno has for many years been engaged in the development of insulation materials made from natural fibres of agricultural origin. These materials show great promise in civil engineering. They have a low carbon footprint and low primary energy input. Experimental testing conducted in the past has revealed that the properties of these materials are comparable to those of the synthetic insulations available on the market. However, in terms of thermal insulation properties, the natural-fibre materials have different hygrothermal behaviour, which is due to the different structure of the insulations as well as the low value of thermal conductivity of the natural fibres (compared with e.g. glass or mineral fibres). The paper deals with the development of particulate insulation based on natural fibers, their behavior under different conditions and mainly with the examination of the thermal properties depending on moisture and bulk density. The paper also presents the results of research in the dependency of thermal insulation, acoustic and mechanical properties of the experimentally manufactured insulations on their bulk density.

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Keywords: Natural fibers; thermal conductivity; dynamic stiffness; moisture content

* Corresponding author. Tel.: +420-541-147-525.
E-mail address: reif.m@fce.vutbr.cz

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1. Introduction

Currently, strict requirements are put on energy cost savings in civil engineering, the lowest possible manufacturing costs of building materials and constructions. At the same time, the comfort of the building users is also subject to a high standard. Concerning the thermal insulation of buildings, materials based on natural and secondary raw materials, obtainable by the recycling of agricultural products, are being used still more frequently. Their undisputed advantage is the immediate availability of local resources. Not only does this reduce the list price, but it also accelerates the delivery. However, these materials suitable for the production of advanced insulation materials fall under a number of requirements. Primarily, these are the thermal properties of the fibers, which should be comparable with conventional fibers commonly used in the manufacture of insulating materials. For example the thermal insulation materials made of EPS, XPS have thermal conductivity values between 0.030 – 0.040 $W{\cdot}m^{-1}{\cdot}K^{-1}$, the cotton board with a density of 150–450 $kg{\cdot}m^{-3}$ have the thermal conductivity values ranging from 0.0585 to 0.0815 $W{\cdot}m^{-1}{\cdot}K^{-1}$, Recycled textile fibers reached values between 0.041 and 0.053 $W{\cdot}m^{-1}{\cdot}K^{-1}$ [1,2,3]. A thermal characterization of the straw bales material was performed by Goodhew et al.; they measured a thermal conductivity of 0.067 $W{\cdot}m^{-1}{\cdot}K^{-1}$ for a 60 $kg{\cdot}m^{-3}$ dense sample [4]. Yarbrough et al. evaluated the thermal insulation performance of particleboards made of rice hulls, an important by-product of rice cultivation. The thermal conductivity at 24 °C was between 0.0464 and 0.0566 $W{\cdot}m^{-1}{\cdot}K^{-1}$ the lowest value was measured for a 154 $kg{\cdot}m^{-3}$ dense sample [5]. Another important property of thermal insulating materials is their bulk density, which also closely influences their insulating properties water vapor resistance factor. The ability of a material to be not permeable to water vapor is measured by water vapor resistance (μ-value). The lower the value the higher the material vapor permeability. The μ-value value of 1 is assigned to air. EPS building insulators are characterized by a μ-value between 20 and 70, while coir-based materials are between 5 and 30. Mineral wools are characterized by very low values (under 5) whereas vapor barriers can reach values over 100,000 [6].

The paper examines the thermal properties of experimental materials at a different relative humidity. Furthermore, it aims to find the density of water vapor resistance factor, the dynamic stiffness and acoustic properties in dependence on bulk density.

2. Materials and methods

The test samples of thermal insulating materials were made from three kinds of natural fibers, namely straw, hemp and cellulosic fibers.

Cellulosic fibers – obtained by recycling commonly available waste paper. The paper is processed in production lines, where it is thoroughly pulped into cellulosic fibers.

Straw fibers – obtained by defibring the stalks and stems of dried cereals, mainly wheat.

Hemp fibers - this is industrial hemp, which was determined to be most suitable due to its good durability, stability and good thermal insulation properties.

The above-described fibers were used in four types of text mixtures:

1. Hemp fibers + cellulose fibers in the ratio of 60:40
2. Cellulose fibers 100%
3. Cellulose fibers + straw in the ratio of 30:70
4. Straw 100%

Samples of three bulk densities were made from each mixture. The samples from mixtures 1 through 3 had the bulk densities of 30, 45 and 60 $kg{\cdot}m^{-3}$, mixture number 4 was made into samples with the densities of 95, 110 and 120 $kg{\cdot}m^{-3}$ according EN 1602 [7].

Thermal conductivity

There were prepared specimens for testing according EN 12667 [8] and ISO 8301[9]. Their dimensions were 300 × 300 × 85 mm and they had the above-described bulk densities. These samples were subsequently tested for their thermal conductivity λ ($W \cdot m^{-1} \cdot K^{-1}$) at varied humidity. The samples were allowed to dry for several days until all moisture had left them. Then their thermal conductivity was determined. Afterwards, the samples were placed in a climate chamber at pre-set conditions: a temperature of 23 °C and 50% relative humidity and then at 23 °C and 80% relative humidity. After this, the thermal conductivity was measured again.

Vapor resistance factor

Vapor resistance factor was determined according EN 12086 [10]. Test specimens of the three bulk densities were prepared from each mixture.

Dynamic stiffness

The dynamic stiffness was determined using the resonance method according to ISO 9052-1 [11]. The principle of the test is to determine the resonant frequency of the system *fr* (the measured sample - loading body, vibrating in the vertical direction). The resonant frequency is determined by using a sinusoidal signal of constant amplitude, which is generated by a frequency generator-electromagnet system. The specimen was placed between two horizontal surfaces, a base and a loading element, which was a steel plate with the dimensions of (200 ± 3 mm) × (200 ± 3 mm). Excitation was provided by an electromagnet in the loading plate and a permanent magnet placed above the electromagnet. The resonant frequency at which the analyzer showed maximum displacement was searched for during the process of gradually increasing the excitation generator frequency. When evaluating the experiment it is necessary to first calculate the value of the apparent dynamic stiffness per a unit of area s'_t.

Acoustic properties

Acoustic properties were determined – the sound absorption coefficient α (-) according ISO 10534-1 [12] depending on the frequency in third-band intervals from100 Hz to 5000 Hz. An acoustic interferometer was used for the measurement. The sound absorption evaluation index DLα of the specimens was determined for an overall evaluation of the obtained results allowing for easier comparison.

3. Measurements and results:

In the first stage of the research, specimens were prepared from the materials for testing. These samples were subsequently tested for their thermal conductivity λ ($W \cdot m^{-1} \cdot K^{-1}$) at varied humidity. The results are in Table. 1.

Table 1. Determination of thermal conductivity under various conditions.

Mixture n.	Bulk density ($kg \cdot m^{-3}$)	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)		
		23 °C 50% moisture	23 °C 80% moisture	DRY
1	30	0.047	0.059	0.046
	45	0.046	0.058	0.046
	60	0.046	0.058	0.046
2	30	0.040	0.046	0.042
	45	0.039	0.050	0.039
	60	0.041	0.044	0.040
3	30	0.044	0.053	0.042
	45	0.043	0.052	0.040
	60	0.044	0.049	0.041
4	95	0.050	0.059	0.046
	110	0.047	0.057	0.045
	120	0.049	0.057	0.045

The results confirm that the moisture content influences the final values of thermal conductivity. When the test samples had high moisture content, they reached higher values of thermal conductivity. Mixture number 2, which was designed purely from cellulose fibers, shows the lowest sensitivity to rising humidity. At 50% relative humidity, the results for test specimens with bulk density of 30 kg·m^{-3} were even better than the values in dry state. However, the results for other bulk densities were not very different either. The results also show that the best values were reached by the test mixture no. 1–3 at a mean bulk density of 45 kg·m^{-3} and, in the case mixture no. 4, at a maximum bulk density of 120 kg·m^{-3}.

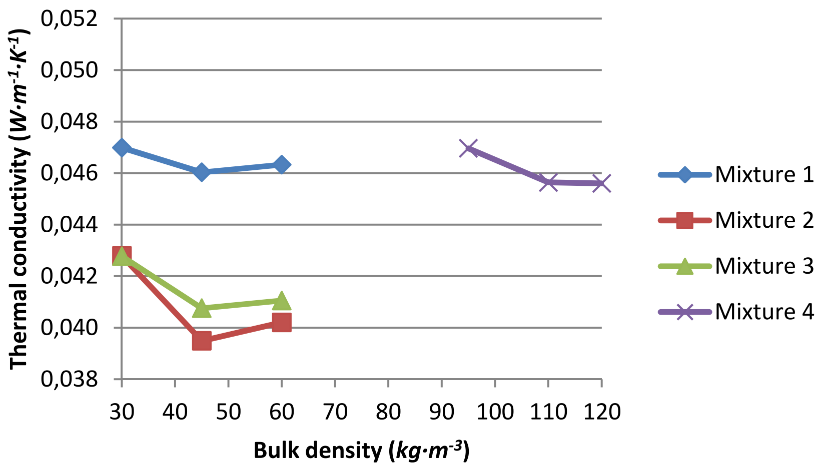

Fig. 1. Dependence of thermal conductivity on bulk density in dry state.

Next, the water vapor resistance factor was determined. Once again, test specimens of the three bulk densities were prepared from each mixture. The results are in Table 2.

Table 2. The results of water vapor resistance factor.

Mixture n.	Bulk density ($kg{\cdot}m^{-3}$)	μ (-)
1	30	4.201
	45	3.992
	60	4.402
2	30	4.512
	45	3.954
	60	5.119
3	30	3.615
	45	4.286
	60	4.043
4	95	4.541
	110	4.557
	120	4.741

The results for all the samples are comparable, although they behave differently depending on the bulk density. The test mixture based on cellulose fibers (mixture n. 1 and 2), reached the highest values at the highest bulk density and the lowest values at the bulk density of 45 kg·m^{-3}. The water vapor resistance factor of the test mixtures based on straw fibers rises together with their bulk densities. In the case of the combination of cellulosic and straw fibers with a higher ratio of straw fibers, the water vapor resistance factor rises only up to the value of bulk density of 45 kg·m^{-3} after that it decreases again. The measured values show that the tested materials can be considered diffusion-open.

Next, samples for the determination of dynamic stiffness at the highest tested bulk density were prepared. The results are shown in Fig. 3 below.

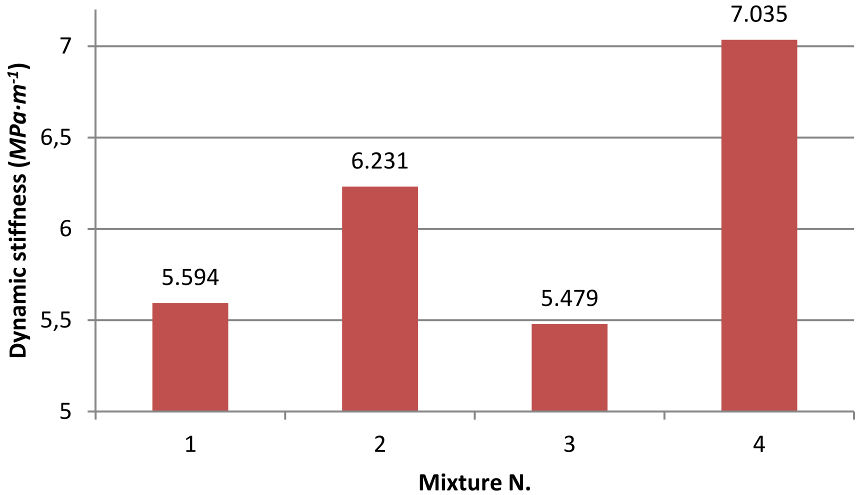

Fig. 2. Overview of the dynamic stiffness of the tested materials.

It can be said, based on the obtained values, that all the samples are dynamically soft materials.

Next, acoustic properties were determined (the sound absorption coefficient α (-)). The sound absorption evaluation index DLα of the specimens was determined for an overall evaluation of the obtained results allowing for easier comparison. The values of sound absorption evaluation index are listed in Table 3:

Table 3. Overview of sound absorption evaluation index DLα.

Mixture n.	Bulk density (*kg·m^{-3}*)	DLα (*dB*)
1	30	4.92
	45	8.07
	60	9.73
2	30	6.56
	45	8.58
	60	8.60
3	30	4.45
	45	7.48
	60	8.85
4	95	9.16
	110	9.62
	120	8.43

Most test samples reached the best values of sound absorption evaluation index with bulk density at 60 kg·m^{-3}. An exception is mixture based on straw fibers where a lower bulk density is sufficient for achieving very good acoustic properties. Mixture 1 based on hemp fibers and mixture 3 with higher content straw fibers, showed the most pronounced improvement of acoustic properties in dependence on bulk density.

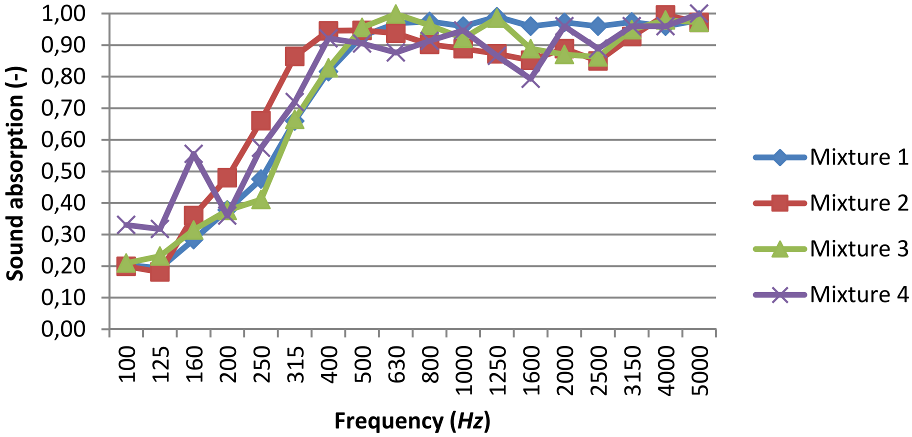

Fig. 3. Dependence of sound absorption on frequency.

4. Conclusion

The tested samples of the newly developed thermal insulation materials were subjected to a series of laboratory measurements and tests. In the first stage, their thermal properties in different conditions were tested: a temperature of 23 °C and a relative humidity of 0%, 50%, 80%. The mixtures were compressed into test boxes with the dimensions of 600 mm × 600 mm × 100 mm at different bulk densities: 30, 45 and 60 kg·m^{-3} for mixtures 1 to 3 and 95, 110 and 120 kg·m^{-3} for mixture 4. The best thermal insulation properties were achieved by the mixture based on 100% cellulosic fibers. The measurement results also offer the conclusion that this mixture is the least sensitive to relative humidity in terms of its thermal insulating properties. On the other hand, the greatest deterioration in thermal insulating properties occurred in the samples with higher content of straw fibers. Next was the evaluation of the dependency of thermal conductivity on bulk density of the individual samples, which found that the best properties were reached by the samples with the bulk density of 45 kg·m^{-3}. In the next step, the water vapor resistance factor was determined, which proved that the tested materials are diffusion-open. Afterwards the dynamic stiffness characteristics were determined. This property is important for use of these materials in horizontal structures, particularly floors. The results show that all the tested materials are a dynamically soft. Finally, the acoustic properties were determined – the sound absorption coefficient (-) depending on the frequency in third-band intervals from 100 Hz to 5000 Hz. It can be stated that the acoustic properties of the samples are very good. The best acoustic properties were found in samples with a higher bulk density of 60 kg·m^{-3}, with the exception of the mixture based on straw fibers, where the best values were achieved at a mean bulk density of 110 kg·m^{-3}.

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