Abstract

Besides having positive impact on sustainable development, natural building materials also have technical properties comparable with standard materials and important additional qualities. This article focuses on thermal, moisture and biological properties of thermal insulating materials based on vegetal and animal fibres.

There is a lack of data regarding natural building materials and furthermore the properties of these types of materials can be site-dependent. Therefore the natural insulating materials have been tested for thermal, moisture and biological properties. In the research array, there were following materials: treated sheep wool, raw sheep wool, wood fibre, hemp, flax, straw bale and compressed straw panel. The main examined parameters are the thermal capacity, thermal conductivity, volume density and sorption isotherm, which are stated and compared. In addition to that, the microbiological identification tests were made together with the mould growth observation.

The results of all tests and measurements are stated and discussed in the article with the emphasis on the situation in the real building stock where the test bordering conditions possibly occur

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1. Preface

1.1. Context

Being the largest contributor to the world’s waste production, building industry should focus on sustainability [13]. Natural and recycled materials have remarkably lower environmental impact than the ones standardly produced. These materials are well-performing in the life cycle assessment, even their thermal and moisture properties seem to be favourable. On the other hand, there is a lack of comparable data, regarding available natural building materials. Moreover, the properties of these types of materials can be site-dependent (different densities, raw materials and processing). Therefore it is important to analyse and collect new data. A set of measurements has been done during last year to add data to the present state of knowledge.

The main argument against the use of natural building materials is their durability and constancy of material qualities. The description of the thermal, moisture and biological characteristics of natural insulations, earth plasters and clay building elements is the main aim of the project held at Czech Technical University in Prague, Department of Building Structures. This paper discusses the test results obtained for the first material array, the insulating materials.

1.2. Material samples selection

The selection of the materials was done based on multiple research results, ie. [10], [11], [12] and on the previous research carried out by the authors [1]. The environmental impact (global warming potential, primary energy input and acidification potential) of the concrete frame building can be significantly lowered by using better performing concrete to lower down the mass of concrete needed. Together with that, the building impact can be lowered more by utilizing the sustainable building envelope made of natural or recycled materials. Therefore, the test array was set to describe natural insulating materials, which are the important compound of such composition. The test specimens were following:

- Compressed straw bale,
- Flax fibre,
- Treated sheep wool,
- Untreated sheep wool,
- Wood fibre,
- Hemp fibre,
- Ordinary mineral wool as reference for selected measurement.

All these materials are supposed to be used in the building envelope walls, roof or ceiling composition etc. and they are suitable as the main insulating layer of those compositions. The materials for all the test specimens were taken from similar batch (one plate or bale). The samples came from the standard products obtained at the local market without any additional treatment.

2. Material tests

After the environmental-oriented material selection, the description and comparison of the other properties was the next step. The tests were carried out to ensure the sufficient knowledge for the natural material application: thermal conductivity, heat capacity, volume density, sorption parameters and basic mold tests.

The material tests were made at the Faculty of Civil Engineering at Czech Technical University in Prague and at the University Centre for the Energy Efficient Buildings in Buštěhrad, Czech Republic.

2.1. Thermal conductivity, thermal diffusivity

For the thermal qualities description, the dynamic measuring method was applied in the beginning. Measuring was performed using portable measuring device ISOMET 2114 with the needle probe IPN 1100. This particular method
was selected because of the speed of measuring process and multiple results obtained from one measurement (thermal conductivity, volume heat capacity and thermal diffusivity). The instrument applies a dynamic measurement method analyzing the time dependence of thermal response on pulse transmitted from the heat flow into the material. The heat flow is generated by electrical energy by the probe which is in the direct contact with the measured material. All measurements were done multiple-times to get the relevant data. The measurement accuracy in the range 0,015–0,7 W.m⁻¹.K⁻¹ is 5 % for the particular instrument [2]. For the thermal conductivity particularly, the data was compared with the heat flow meter measurement done according to the [3] where the compliance of the measurement was in the accuracy tolerance.

2.2. Volume density, heat capacity

The volume heat capacity values are obtained from the previously described measurement at the same time. Determination of the density was carried out according to the European Standard EN 1602:2013. [4]

Table 1. Measured material parameters

<table>
<thead>
<tr>
<th>Number</th>
<th>Sample</th>
<th>Thermal conductivity λ [W.m⁻¹.K⁻¹]</th>
<th>Thermal diffusivity α [m².s⁻¹]</th>
<th>Dry density ρ [kg.m⁻³]</th>
<th>Volume heat capacity cp [J.m⁻³.K⁻¹]</th>
<th>Specific heat capacity cm [J.kg⁻¹.K⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Straw bale</td>
<td>0.065</td>
<td>0.43</td>
<td>98.0</td>
<td>0.16</td>
<td>1.58</td>
</tr>
<tr>
<td>2</td>
<td>Flax fibre</td>
<td>0.052</td>
<td>0.54</td>
<td>27.0</td>
<td>0.10</td>
<td>3.60</td>
</tr>
<tr>
<td>3</td>
<td>Hemp fibre</td>
<td>0.052</td>
<td>0.52</td>
<td>36.2</td>
<td>0.10</td>
<td>2.75</td>
</tr>
<tr>
<td>4</td>
<td>Wood fibre</td>
<td>0.048</td>
<td>0.39</td>
<td>51.5</td>
<td>0.12</td>
<td>2.40</td>
</tr>
<tr>
<td>5</td>
<td>Treated sheep wool</td>
<td>0.063</td>
<td>1.23</td>
<td>11.3</td>
<td>0.05</td>
<td>4.55</td>
</tr>
<tr>
<td>6</td>
<td>Untreated sheep wool</td>
<td>0.062</td>
<td>1.03</td>
<td>29.7</td>
<td>0.06</td>
<td>2.02</td>
</tr>
<tr>
<td>7</td>
<td>Mineral wool - reference</td>
<td>0.039</td>
<td>0.43</td>
<td>14.9</td>
<td>0.09</td>
<td>6.04</td>
</tr>
</tbody>
</table>

Fig. 1. Comparing volume heat capacity (a) and thermal conductivity (b).
The materials were dried out in a drying room at 50 °C to the constant weight. The next step was to measure of the linear dimensions of the samples according to the EN 12085 [5]. Length, width and height were measured by the electronic digital caliper with a resolution of 0,01 mm. A Samples’ volumes were calculated from these dimensions. Results for the material array are stated in the Table 1.

2.3. Sorption

Recording of hygroscopic sorption properties was carried out according to the European Standard EN ISO 12571:2013. [6]

All natural materials and the reference material were measured in sets of three samples. Each of them had a weight about 50 g. Larger samples take longer time to stabilize at the equilibrium weight, and taking too small samples (less than 10 g) in account may lead to inaccuracy in weighting.

![Fig. 2. Sorption isotherms (moisture content mass by volume)](image)

The materials were dried out in a drying room at 50 °C (higher temperatures may change the structure of some natural materials) at the equilibrium weight.

The experimental measurement of sorption properties was carried out in the glass desiccator at constant temperature and atmospheric pressure. A data logger for measuring relative humidity and temperature was placed inside each desiccator.

Aimed level of relative humidity in the desiccator was created by saturated solutions. These present the particular points in the sorption curve. The first step has been measured using a saturated solution of LiCl (RH 11,3 %). All samples were exposed to that environment until reaching the equilibrium weight. This state was achieved when the weight change during 24 hours was less than 0,1 %. The weight was measured using a digital lab scale with precision of 0,001 g. Next points in the sorption curve were made using saturated solution of KC₂H₃O₂ (RH 24,0 %); K₂CO₃ (RH 43,2 %); NH₄NO₃ (RH 62,0 %); NaCl (RH 75,5 %); KCl (RH 85,5 %); KNO₃ (RH 95,0 %); K₂SO₄ (RH 97,6 %%). The relative humidity values mentioned in the parenthesis are only proximate. Exact RH values were measured with a datalogger. The Fig.2 shows the measured results of the sorption isotherms.
3. Biological health risk

Talking about the natural materials, it is very important to complete the knowledge of the material with the information about biological qualities. There was no mould growth observed in the samples, while they were in the usual interior environment condition. The simple mould identification was made in the laboratory: all the material samples were put into the environment suitable for the mold growth (nutrient agar at temperature of 25°C, RH above 80%). These conditions may occur in the wrong designed building details or in the case of faults in the structure composition. This test showed the predominant mould types naturally present in each material. The results are summed up in the Table 4, the potential risks description is done according to [7] and [8].

Table 4. Possible mould growth risks according to [7] and [8]

<table>
<thead>
<tr>
<th>Material</th>
<th>Mould Identification</th>
<th>Possible risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheep wool</td>
<td>Alternaria alternata</td>
<td>pathogenic, frequent, highly toxic, causing allergy and asthma, cutaneous infections, paranasal sinusitis, osteomyelitis and peritonitis in patients on continuous ambulatory peritoneal dialysis (CAPD)</td>
</tr>
<tr>
<td></td>
<td>Stachybotrys sp.</td>
<td>possibly toxic, causing stachybotryotoxicosis</td>
</tr>
<tr>
<td>Flax fibre</td>
<td>Acremonium sp.</td>
<td>seldomly pathogenic: hyalohyphomycosis, arthritis, osteomyelitis, peritonitis, endocarditis, pneumonia, cerebritis and subcutaneous infection.</td>
</tr>
<tr>
<td>Wood fibre</td>
<td>Penicillium (expanzum, biverticillata)</td>
<td>pathogenic, toxic (patulin), carcinogenic</td>
</tr>
<tr>
<td>Hemp fibre</td>
<td>Penicillium (biverticillata)</td>
<td>pathogenic, toxic</td>
</tr>
<tr>
<td>Straw bale</td>
<td>Alternaria alternata</td>
<td>pathogenic, frequent, highly toxic, causing allergy and asthma, cutaneous infections, paranasal sinusitis, osteomyelitis and peritonitis in patients on continuous ambulatory peritoneal dialysis (CAPD)</td>
</tr>
<tr>
<td></td>
<td>Fusarium sp</td>
<td>pathogenic, seldom, causing mycotoxicosis</td>
</tr>
</tbody>
</table>

4. Discussion

From the test results it is obvious that thermal conductivity of thermal insulation materials based on natural fibers is 25% higher than mineral wool. This usually is the only parameter on which is the focus within building design approach. To follow the environmental goals mentioned in the beginning of this paper and by [13], we should consider also other properties. For instance, the volume heat capacity is 11% (natural fibres) or 78% (mineral wool) higher with straw bale. Considering that during the design process can favourably affect the thermal comfort of the building.

Porous materials can absorb moisture from the air inside their structure. It depends primarily on the size and the inner surface of the pores. The results show that the natural insulation materials sorb more air humidity than the reference material from mineral wool. This ability is due to more complex organic structure of natural materials and it can contribute to creation of healthier indoor environment in the buildings [14].

It is possible to substitute easily insulating materials as mineral wool for natural insulating material (i.e. two-by-four design for wooden building). Insulating layers made of flax, hemp and especially wood fibres have competitive thermal conductivity values (Fig.1b) and are produced in mats of standard size. This brings the need to design constructions slightly thicker to achieve equal thermal resistance (U-value).

Straw has the highest thermal capacity (Fig.1a) and best sorption properties among all tested materials. On the other hand it has higher thermal conductivity which would lead to greater wall thickness for equal thermal resistance as e.g. with mineral wool. But when the way of processing straw into straw bales is considered, the construction would anyway have greater thickness.

The important difference brought by using natural insulating material is significantly better sustainability. Compared to mineral wool, primary energy input, global warming potential or acidification potential levels of natural insulations are about 95% lower [9].
The health risk is low in properly designed buildings. The toxic nature of fungi spores could be present in natural insulations shows that proper and safe construction design is extremely important for natural materials. In buildings built with the amateur approach or buildings where the risk of failure in structures is high (i.e. RH value grows up above 80 % together with the temperature above 15 °C), natural insulating materials can cause illnesses as proven by our biological health risk analysis.

5. Conclusion

Natural insulations can be favourably used in standard buildings in combination with common building materials to achieve more sustainable solution and healthy indoor environment. It was found that natural insulations have comparable thermal properties to common building insulation materials and can bring advantages in thermal and moisture buffering.

The biological pollution has been tested under laboratory conditions (use of agar, increased stable temperature and moisture). It is a question whether the conditions that would promote biological degradation will occur in real constructions. Therefore a long term testing in real Czech weather conditions is held to study the real risk of fungus growth.

Acknowledgements

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References