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# Performance evaluation and research of alternative thermal insulations based on sheep wool

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ABSTRACT

Sustainability and energy efficiency in buildings are currently evaluated not only based upon thermal insulation thickness and heating demand, but also according to primary energy demand, $CO_2$ reductions, and ecological properties of the building materials. These properties are essential for a holistic assessment. To meet the requirements which are increasing in rigor, the demand for ecological building materials is growing dramatically, particularly insulating materials from renewable resources. Ecological insulation materials have been available on the market for a long time; however, conventional materials are still predominantly used.

Most builders are unsure whether the alternative materials meet the same performance requirements as conventional building materials and supporting scientific research and publications are difficult to find. In a joint project of the Brno University of Technology and Vienna University of Technology, the thermal insulation from sheep wool has been tested under various conditions. The building physics and acoustic properties were specifically tested which are important for durable and undamaged applications. The tests results show that the thermal insulation from sheep wool has comparable characteristics with mineral/rock wool, and in some applications even performs better. Additionally, in comparison to mineral wool, sheep wool is more ecological and has fewer damaging health aspects.

## 1. Introduction

The new approaches to energy-efficient and sustainable design do not only have goals to realize lower energy consumption, but also to apply of natural and local building materials while keeping construction costs to a minimum. The DIRECTIVE 2010/31/EU of the European Parliament and the European Council of 19 May 2010 on the energy performance of buildings requires that "the energy performance certificate should also provide information about the actual impact of heating and cooling on the energy needs of the building, on its primary energy consumption and on its carbon dioxide emissions" [1]. A new term is also introduced, "nearly zero energy building". A zero energy building (ZEB) is a conditional definition as each building needs and consumes energy. ZEB is a highly complex theoretical concept as it considers highly energy-efficient building designs, building materials, technical systems, and equipment to minimize the heating and electricity demand, mitigation of $CO_2$ emissions while maintaining sustainability [2]. These requirements are now being implemented across Europe. In order to obtain certificates with the best values, many building owners strive to obtain the lowest possible primary energy demand and $CO_2$ emissions.

Environmental certificates are widespread and increasingly popular such as BREEAM, LEED, DGNB, and Green Mark to name a few. The ecology of building materials is an extremely important requirement in all of the listed certifications.

The focus of some research is the importance of ecological and healthy design. Environmental awareness is now not only constrained to energy savings, but also is contained within ecologically sound construction, i.e. minimum energy input, resource consumption, and pollution production as a part of the production, installation, and use of insulation materials [3]. By using natural building materials in structures, human health can also be positively influenced [4]. Natural building materials regulate internal air humidity well and their characteristic aromas have a positive effect on the human psyche. In a straw bale test house in Germany, several important properties were systematically measured and showed excellent results for healthy living conditions [5]. Organic materials are generally water vapour permeable and can accumulate moisture by adsorption from the air. Other favourable properties of organic materials are the moisture absorption capacity into the internal porous system at increased air humidities, and

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**Fig. 1.** Photo of sheep wool and its applications in building construction.

conversely, gradual moisture release into the surroundings with decreasing air humidity [6]. This mechanism positively influences the indoor air humidity primarily in winter when prolonged periods of low indoor air humidity may be experienced.

The organic materials are more sensitive than common construction materials. Therefore, the possible applications of these materials should be precisely defined using proper measurements and simulations to verify functionality and durability [7].

The objective of a previous joint project between Brno University of Technology (VUT Brno) and the Vienna University of Technology (TU Vienna) was the development, optimization, and observation of the behaviour of thermally insulating materials composed of easily renewable raw material resources originating from agricultural sources (jute, flax and hemp) which could be used in new building structures and for renovation the existing buildings [8]. All input components were varied in the tests. The tests results have shown that the performance of the correct combination of natural materials is absolutely comparable with convectional building materials. Also in [9] was shown that natural materials can obtain very good properties.

Because of its natural properties and especially thermal efficiency, sheep wool is an excellent insulation material. Research and development of environmentally friendly thermal insulation materials made of natural sources have been underway for many years at the Institute of Technology of Construction Materials and Components to the Construction Faculty, VUT Brno. The effective cooperation with the TU Vienna was an incentive to study other possible alternative material sources that would be possible to apply as insulation materials. The main idea was to obtain a high-quality, environmentally friendly, and cost-effective insulation material with potential use in construction practice. The aim of the here presented study was to determine the basic physical characteristic values for thermal and acoustic insulation products from sheep wool, and the behaviour of these materials under diverse humidity conditions. Many different measurements were carried out in order to obtain the application limits of the sheep wool insulations and to explore the comparability with common insulations. The results of these measurements provided the basis for determining the general pre-requisites of suitability when using this natural and environmentally friendly insulation material.

## 2. Sheep wool and its qualities

Sheep wool is an easily renewable, easily recyclable and environmentally friendly source of raw material, which consists on average of 60% animal protein fibres, 15% moisture, 10% fat, 10% sheep sweat and 5% impurities.

The benefits of sheep wool include the following:

- Clean and easy to renew natural material source,
- Comfortable and easy to handle without potential risk to human health (irritation of the skin, mucous membranes etc.),
- Easy to recycle, eco-friendly,
- Self-extinguishing capability, the fibres do not support combustion, but char at high temperatures,
- Relaxation of the material, there is neither change in volume nor loss of elasticity,
- Highly hygroscopic, up to 35% [10] (Fig. 1).

The use of sheep wool as a source for the production of thermal insulation is interesting especially due to positive ecological and health properties. In addition to the “thermal and acoustic properties”, the “indoor climate healthiness” for each material should be evaluated. Further research needs are outlined in [11], drawing attention to the role of harmony and interdisciplinary teams in synergetic building health/sustainability studies.

A comparison between the environmental impacts of some traditional and natural insulation materials is shown in Fig. 2 [12]: cellulose, flax and sheep wool have the lowest impacts in the considered categories.

## 3. Preparation of test samples from sheep wool

Based on preliminary market research, raw sheep wool was prepared by washing with soap and water to remove the sheep fat to a maximum fat content of 1%. Test samples were prepared by laying carded sheep fleece perpendicularly (Struto technique) without the use of binders to a thickness of 80 mm. The mixture of sheep wool was mechanically fastened to a reinforcing cloth to strengthen the mat and enable insulation laminating to the desired thickness. To

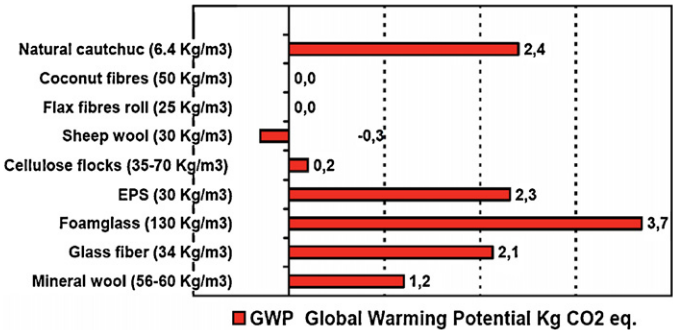

**Fig. 2.** Comparison of environmental impacts of conventional and natural materials.

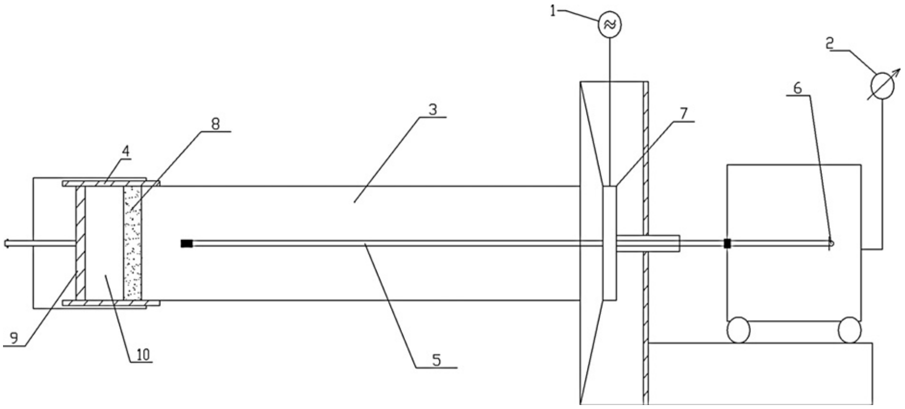

**Fig. 3.** Measuring equipment, called Kunte's Tube (1) Generator, (2) Analyser, (3) Tube, (4) Sample holder, (5) Probe, (6) Microphone, (7) Speaker, (8) Sample, (9) Piston holder, (10) Air cushion.

prevent moths, a moth-control fabric softener was used as well as the application of a flame retardant.

Using the prepared sheep wool samples of a given composition, the key characteristic values were sought for thermal and acoustic insulating materials that are important for the application of sheep wool products in building structures. For the use of natural materials as thermal and acoustic insulation materials, it is necessary to know the properties and behaviour of these depending on the environment to which they are to be exposed, given the very high and open pore structure of the samples.

The following laboratory investigations were conducted on the samples to determine the following:

- Physical properties (weight, linear dimensions, thickness, bulk density),
- Acoustic properties (sound absorption coefficient, dynamic stiffness),
- Thermal technical properties (thermal conductivity).

The subsequent relationships were determined using the measured values:

- Dependence of thermal conductivity on temperature,
- Dependence of thermal conductivity on moisture content,
- Dependence of thermal conductivity on bulk density,
- Dependence of thermal conductivity on thickness.

## 4. Methodology of the conducted laboratory measurements

### *4.1. Determination of linear dimensions, thickness and bulk density*

The determination of linear dimensions and thickness was carried out in accordance with EN 822 [13], EN 823 [14] and EN 12085 [15], with bulk density determined subsequently as the proportion of the weight and volume of the test sample to EN 1602 [16].

Tests were conducted using the following steps:

- Linear dimensions determined (according to [13–15]),
- Weight determined using laboratory scales with an accuracy of 0.5%,
- Bulk density, $\rho_a$ [kg m$^{-3}$], determined as a proportion of the test specimen mass, $m$ [kg] and its volume, $V$ [m$^{-3}$], under:

$$\rho_a = \frac{m}{V} \tag{1}$$

### *4.2. Determination of the sound absorption coefficient*

The sound absorption coefficient was established in accordance with EN ISO 10534-1 [17]. The sound absorption coefficient was ascertained by producing standing waves in a tube containing a circular sample of dimensions, 30 mm and 100 mm diameter, attached to the end of the tube. The measured maximum and minimum of standing wave sound pressure forms the basis for calculating the sound absorption coefficient [18].

For the waves within the interference tube, the following relationships apply:

$$\begin{aligned} p_{\max} &= p_1 + p_2 \\ p_{\min} &= p_1 - p_2 \end{aligned} \tag{2}$$

where $p_1$ is the direct wave sound pressure, and $p_2$ is the reflected wave sound pressure.

The value of the sound absorption coefficient $\alpha$ [–] is determined as follows:

$$\alpha = 1 - \frac{p_2^2}{p_1^2} \quad [-] \tag{3}$$

If we mark the sound pressure maximum and minimum relation as $n$ [–]:

$$n = \frac{p_{\max}}{p_{\max}} \quad [-] \tag{4}$$

The above relationship implies the following relationship for the sound absorption coefficient (Fig. 3):

$$\alpha = 1 - \left(\frac{n-1}{n+1}\right)^2 = \frac{4n}{(n+1)^2} \tag{5}$$

Laboratory measurements were conducted at a temperature of (20 ± 2) °C and pressure of (101.3 ± 2.7) kPa. The samples were placed in the holder. After switching on the equipment, the generator was set to the desired frequency. Afterwards, the acoustic probe was inserted into the sample to determine the sound pressure in the nearest antinode loop and the standing wave node. The acoustic pressure antinode loop was first found when the analyser, $U_{\max}$, output voltage was subsequently set to the full voltmeter variation on the corresponding gain. A sound pressure node was determined based on the movement of the probe towards the sample, where voltage $U_{\min}$ was read using a voltmeter. Measurements were recorded at third octave frequencies in the range of 100–3150 Hz. The results were evaluated to EN ISO 11654 [19] by determining the weighted sound absorption coefficient $\alpha_w$ [–]. Weighted sound absorption coefficient is one-number frequency

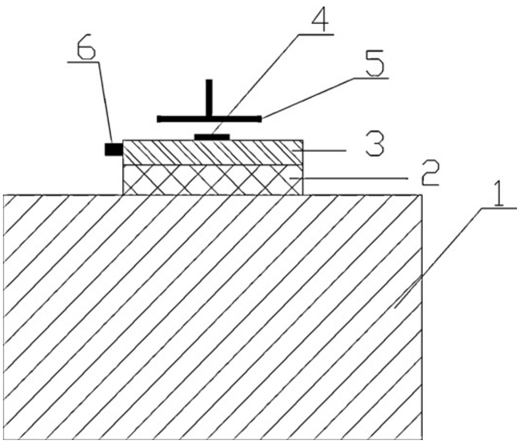

**Fig. 4.** Test system scheme: (1) Concrete plate, (2) Test sample, (3) Steel plate [areal weight $m' = 203.53$ kg m$^{-2}$ and dimensions, 200 ± 3 mm × 200 ± 3 mm], (4) Electromagnetic vibration exciter, (5) Hanger with a permanent magnet and adjusting screw, (6) Electromagnetic vibration sensor.

independent value, which is evaluated as value of reference curve after its movement on frequency of 500 Hz.

### 4.3. Determination of dynamic stiffness

Dynamic stiffness was determined in the laboratory using the resonance method as per EN 29052-1 [20]. The essence of the method is in establishing the basic resonant frequency of the mechanical system consisting of a planar test sample, size 200 mm × 200 mm, and a loading plate. Vibrations are excited during the test in the vertical direction, perpendicular to the plane of the sample (Fig. 4).

The total weight of the loading body (plate, sensor, and exciter) must meet the requirements of ČSN 73 0532 [21]: 8 ± 0.5 kg.

A 200 mm × 200 mm sample was placed on the base plate with an electromagnet on the sample. After connecting the measuring system, the resonant frequency was identified by gradually increasing the frequency of the excitation generator. Measurements were performed three times per sample. Dynamic stiffness of the sample with low resistance to flow was determined from the relationship [18,22]:

$$s' = s'_t + s'_a \quad [\text{MPa m}^{-1}] \tag{6}$$

where $s'_t$ is the apparent rigidity of the sample [MPa m$^{-1}$], and $s'_a$ is the dynamic stiffness of air [MPa m$^{-1}$].

$$s'_t = 4\pi^2 m' f_r^2 \quad [\text{MPa m}^{-1}] \tag{7}$$

where $m'$ is the loading plate surface mass [kg m$^{-2}$], and $f_r$ is the resonance frequency [Hz].

$$s'_a = \frac{111,000}{d} \quad [\text{MPa m}^{-1}] \tag{8}$$

where $d$ is the thickness [m].

### 4.4. Determination of thermal conductivity

The thermal conductivity, $\lambda$ [W m$^{-1}$ K$^{-1}$], was determined using a stationary method based on CSN 72 7012-3 (ISO 8301) [23,24]; which essentially induces a steady state temperature within the tested sample. Since reaching a steady state is not possible under normal conditions, a change in temperature over a given period of time, less than the contractually defined temperature change, based on the standard is considered to be the steady state. The Lambda 2300 device by Holometrix Micromet Inc., USA, was used for measurements. The sample size was 300 mm × 300 mm.

**Fig. 5.** Measuring device to determine thermal conductivity, Holometrix Lambda 2300.

The thermal conductivity coefficient was determined based on,

- temperature (10 °C, 20 °C, 30 °C, and 40 °C),
- moisture content (the thermal conductivity coefficient was determined for the natural moisture state; then for the dry state dried at 95 °C in an oven; and for the moistened state),
- and bulk density (Fig. 5).

## 5. Evaluation of the measurement results

### 5.1. Evaluation of linear dimensions, thickness and bulk density

The thickness of the test samples was determined based on the procedure cited in EN 823 [14]. Measurements were made on five 300 mm × 300 mm thermal insulation boards under a nominal pressure of 50 Pa. A total of 4 thickness values, $d$ [mm], were determined for each sample. Bulk density was determined in accordance with EN 1602 [16]. 300 mm × 300 mm test samples were used for ascertaining bulk density, with measurements conducted on a total of five test samples. Results are given in Table 1.

The resulting average thickness, $d$, of the test samples was detected to be 80 mm, and bulk density of the test samples, $\rho_v$, was established to be 20 kg m$^{-3}$.

### 5.2. Evaluation of the sound absorption coefficient

The sound absorption coefficient was determined in the laboratory using an acoustic interferometer on circular test samples (so-called Kunte's Tube). The dependence of the sound absorption coefficient on the thickness of the material was also studied. A total of 4 thickness values of the test samples were selected: 20, 30, 40 and 60 mm. The sound absorption coefficient tests were conducted in third-octave intervals within the frequency band of 100–3150 Hz as $\alpha_s$ [−]. The measured values are given in Table 2 and Fig. 6.

**Table 1**
Overview of measured and calculated thickness and bulk density values for the insulation product, thickness 80 mm.

| Sample | Thickness $d$ [mm] | Bulk density $\rho_v$ [kg m$^{-3}$] |
|---|---|---|
| 1 | 80.026 | 19.16 |
| 2 | 80.104 | 20.83 |
| 3 | 79.877 | 19.97 |
| 4 | 80.042 | 19.72 |
| 5 | 80.151 | 20.51 |
| Average | 80.040 | 20.04 |

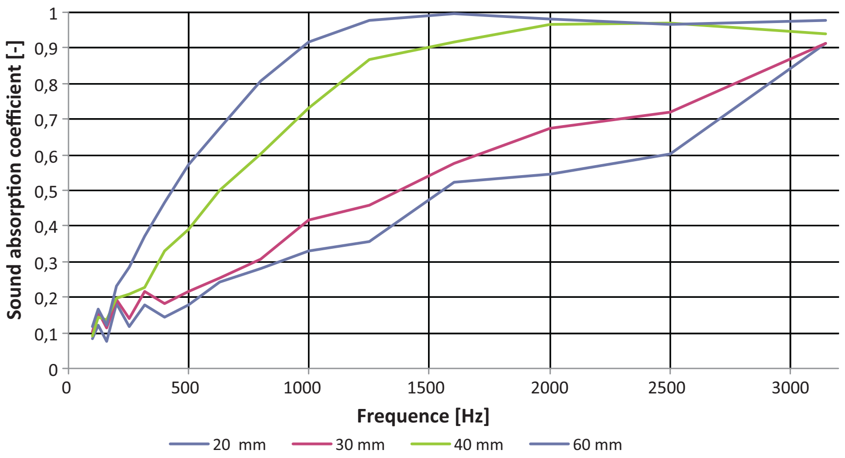

**Fig. 6.** Overview of the measured values for the test samples' sound absorption coefficient.

**Table 2**
Overview of measured values of sound absorption coefficient of testing samples.

| Frequency $f$ [Hz] | Sound absorption coefficient $\alpha_{ws}$ [−] | | | |
|---|---|---|---|---|
| | Thickness 20 mm | Thickness 30 mm | Thickness 40 mm | Thickness 60 mm |
| 100 | 0.082 | 0.102 | 0.090 | 0.119 |
| 125 | 0.122 | 0.158 | 0.144 | 0.166 |
| 160 | 0.077 | 0.113 | 0.137 | 0.120 |
| 200 | 0.181 | 0.194 | 0.196 | 0.230 |
| 250 | 0.117 | 0.141 | 0.210 | 0.285 |
| 315 | 0.179 | 0.215 | 0.228 | 0.370 |
| 400 | 0.144 | 0.181 | 0.331 | 0.465 |
| 500 | 0.177 | 0.217 | 0.392 | 0.572 |
| 630 | 0.242 | 0.255 | 0.499 | 0.673 |
| 800 | 0.281 | 0.306 | 0.602 | 0.808 |
| 1000 | 0.331 | 0.415 | 0.732 | 0.916 |
| 1250 | 0.355 | 0.46 | 0.866 | 0.978 |
| 1600 | 0.521 | 0.575 | 0.916 | 0.995 |
| 2000 | 0.544 | 0.675 | 0.966 | 0.980 |
| 2500 | 0.601 | 0.718 | 0.968 | 0.966 |
| 3150 | 0.911 | 0.914 | 0.938 | 0.977 |

The weighted sound absorption coefficient, $\alpha_w$, values were calculated based on EN ISO 11654 [19] using the sound absorption coefficient measured values, the former being used when classifying each sample of the respective thickness to the relevant sound absorption classes (see Table 3 and Fig. 7).

As is evident from these results, the frequency with the highest absorption decreases with increased insulation thickness, thereby increasing the weighted sound absorption coefficient value. Considering that major emphasis is placed on the frequency range of 500–2000 Hz for theoretical [18] calculating weighted sound absorption, an insulation thickness of 170 mm can be considered to be the most effective acoustic insulation. It is assumed, that maximum value of sound absorption coefficient reach porous material with thickness:

$$d = \frac{c}{4f};$$

where $c$ is the sound velocity [m s$^{-1}$] and $f$ is the frequency [Hz]. For any thickness above 170 mm, no increase in weighted sound absorption values results.

**Table 3**
Summary of weighted sound absorption coefficients including in sound absorption classes.

| Sample $n$ | $d$ [mm] | $\alpha_w$ | Level of sound absorption |
|---|---|---|---|
| 1 | 20 | 0.55 | D |
| 2 | 30 | 0.60 | C |
| 3 | 40 | 0.75 | C |
| 4 | 60 | 0.85 | B |

### 5.3. Evaluation of dynamic stiffness

Dynamic stiffness was determined using the resonance method in accordance with ISO 9052, with the relationship between the dynamic stiffness and the material thickness being subject to observation for sheep wool insulation materials. 200 mm × 200 mm test samples were prepared with thickness ranging from 40 to 175 mm, and larger thickness values being obtained by composing several samples of smaller thicknesses. Due to the fact that the test samples deformed after loading, two thickness values were recorded per trial:

- $d_0$ is the thickness of the sample prior to loading,
- $d$ is the thickness of the loaded sample.

The following table summarizes the measured values of dynamic stiffness in the loaded and unloaded states (Table 4 and Fig. 8).

The measured dynamic stiffness data shows that it is a dynamic and soft acoustic material (dynamic stiffness in all cases below 30 MPa m$^{-1}$). Dynamic stiffness decreases with increased material thickness.

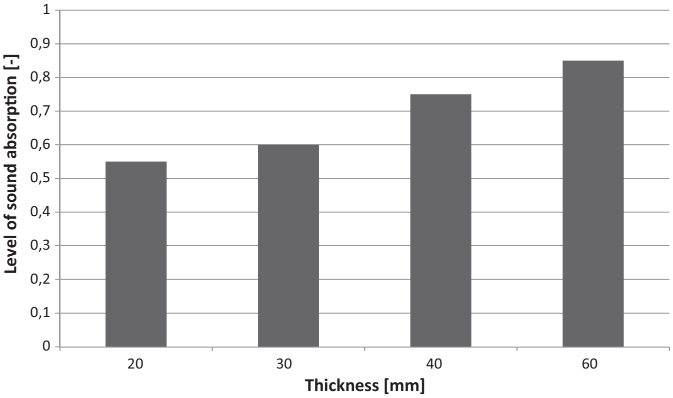

**Fig. 7.** Overview of the calculated weighted values of sound absorption coefficient for test samples of different thicknesses.

**Table 4**
Overview of dynamic stiffness, compressibility, and elasticity.

| Sample $n$ | Unloaded thickness $d_0$ [mm] | Loaded thickness $d$ [mm] | Dynamic stiffness $s'$ [MPa m$^{-1}$] |
|---|---|---|---|
| 1 | 39.5 | 9.8 | 15.81 |
| 2 | 77.7 | 26.61 | 6.67 |
| 3 | 106.78 | 34.43 | 5.09 |
| 4 | 146.73 | 44.86 | 3.89 |
| 5 | 175.2 | 53.9 | 3.29 |

### 5.4. Evaluation of thermal conductivity

The thermal conductivity coefficient was determined at steady state using the plate method measured by the Lambda 2300 device, Micromet Inc., Holometrix, USA. Manufactured sheep wool-based insulation mats were stored under normal laboratory conditions at a temperature of +23 ± 2 °C and relative humidity of 50 ± 3%. Samples were prepared from the mats with dimensions of 300 mm × 300 mm. The thermal conductivity coefficients were determined at varying mean temperatures: +10 °C, +20 °C, +30 °C and +40 °C. The temperature gradient, between the temperature and the cold plate, was 10 K in all cases. Furthermore, the test sample thickness was gradually modified by compression from 80 mm to 70, 60, 50 and 40 mm, resulting in a change in bulk density of the test samples. The measured values are shown in Table 5.

The relationships between the thermal conductivity coefficient and temperature or bulk density were compiled using the measured values in Figs. 9 and 10.

The upper plate was moved to change the material bulk density. The weight of the plate compressed and reduced the volume of air pores within the material test sample. A non-linear decrease in thermal conductivity coefficients with changes in bulk density can be observed in Fig. 10 above.

At a 50% increase in bulk density, from 20 kg m$^{-3}$ to 40 kg m$^{-3}$, the thermal conductivity coefficient decreased at 10 °C by 15%, at 20 °C by 18%, and at 30 °C and 40 °C by 21%.

With increasing temperature, the coefficient of thermal conductivity increased as well. Changing the temperature from 10 °C to 40 °C showed the greatest increase in the thermal conductivity coefficient for the bulk weight of 20 kg m$^{-3}$, at 25%, while the smallest change was measured for samples with bulk density of 40 kg m$^{-3}$, a change of 16%. The following functional dependencies can be determined within the thermal conductivity coefficient and bulk density relationship using the diagram in Fig. 10:

- $\lambda = 3 \cdot 10^{-5}\rho_v^2 - 0.0022\rho + 0.0811 \quad (\text{for} \quad \theta = 40\,^{\circ}\text{C})$
- $\lambda = 3 \cdot 10^{-5}\rho_v^2 - 0.0002\rho + 0.0774 \quad (\text{for} \quad \theta = 30\,^{\circ}\text{C})$
- $\lambda = 1 \cdot 10^{-5}\rho_v^2 - 0.0013\rho + 0.0629 \quad (\text{for} \quad \theta = 20\,^{\circ}\text{C})$
- $\lambda = 1 \cdot 10^{-5}\rho_v^2 - 0.0009\rho + 0.0537 \quad (\text{for} \quad \theta = 10\,^{\circ}\text{C})$

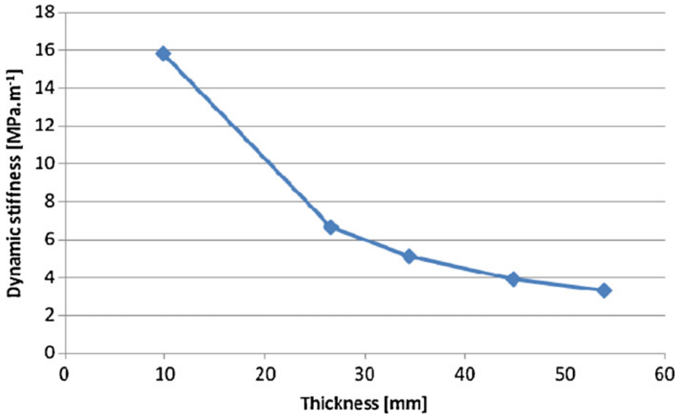

**Fig. 8.** Dynamic stiffness dependence on material thickness.

**Table 5**
Overview of thermal conductivity and bulk density.

| Sample $n$ | Thickness $d$ [mm] | Bulk density $\rho_v$ [kg m$^{-3}$] | Thermal conductivity $\lambda$ [W m$^{-1}$ K$^{-1}$] | Mean temperature $\theta_{mean}$ [°C] |
|---|---|---|---|---|
| 1 | 40 | 40 | 0.034 | 10 |
| 2 | 50 | 32 | 0.035 | |
| 3 | 60 | 27 | 0.037 | |
| 4 | 70 | 23 | 0.038 | |
| 5 | 80 | 20 | 0.040 | |
| 1 | 40 | 40 | 0.036 | 20 |
| 2 | 50 | 32 | 0.038 | |
| 3 | 60 | 27 | 0.040 | |
| 4 | 70 | 23 | 0.042 | |
| 5 | 80 | 20 | 0.044 | |
| 1 | 40 | 40 | 0.038 | 30 |
| 2 | 50 | 32 | 0.040 | |
| 3 | 60 | 27 | 0.042 | |
| 4 | 70 | 23 | 0.045 | |
| 5 | 80 | 20 | 0.048 | |
| 1 | 40 | 40 | 0.039 | 40 |
| 2 | 50 | 32 | 0.041 | |
| 3 | 60 | 27 | 0.043 | |
| 4 | 70 | 23 | 0.046 | |
| 5 | 80 | 20 | 0.050 | |

The largest increase was measured at the lowest bulk density due to the high porosity and increased intensity of air flow in the pore structure of the insulation. When increasing bulk density (within the observed range of bulk densities between 20 and 40 kg m$^{-3}$), thermal insulating properties of the material improve and its sensitivity to temperature decreases.

### 5.5. Evaluation of hygrothermal characteristics

The basic properties of sheep wool include high hygroscopicity, up to 30% under normal conditions. Wool is able to absorb large amounts of water and water vapour without changes in thermal and physical properties. When conducting the measurements, the wool was first dried at 105 °C in an oven. After drying, the test samples were conditioned at 23 °C in areas with relative humidity ranging between 15 and 95%. After the moisture within the test sample had stabilized, the thermal conductivity coefficient was determined at the selected humidity values. Measurements were carried out each time on the 80 mm thick test samples at varying mean temperatures (Table 6).

Fig. 11 clearly shows that up to 20% moisture content, the weight increase due to moisture content does not change the thermal conductivity coefficient significantly. The value of the thermal conductivity coefficient undergoes a significant increase for further increases in moisture content by weight (above 20%). The measured

**Table 6**
Overview of the measured coefficients of thermal conductivity and moisture content by weight.

| Sample-thickness 80 mm | |
|---|---|
| $w$ [%] | $\lambda$ [W m$^{-1}$ K$^{-1}$] |
| 0 | 0.036 |
| 20 | 0.041 |
| 30 | 0.047 |
| 52 | 0.070 |
| 70 | 0.081 |

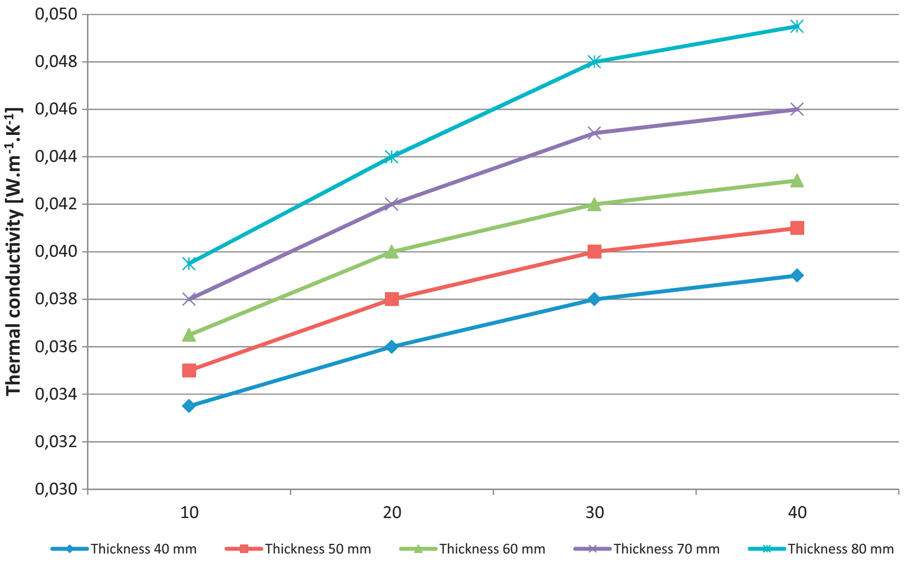

**Fig. 9.** Dependence of the thermal conductivity coefficient on temperatures for each test sample.

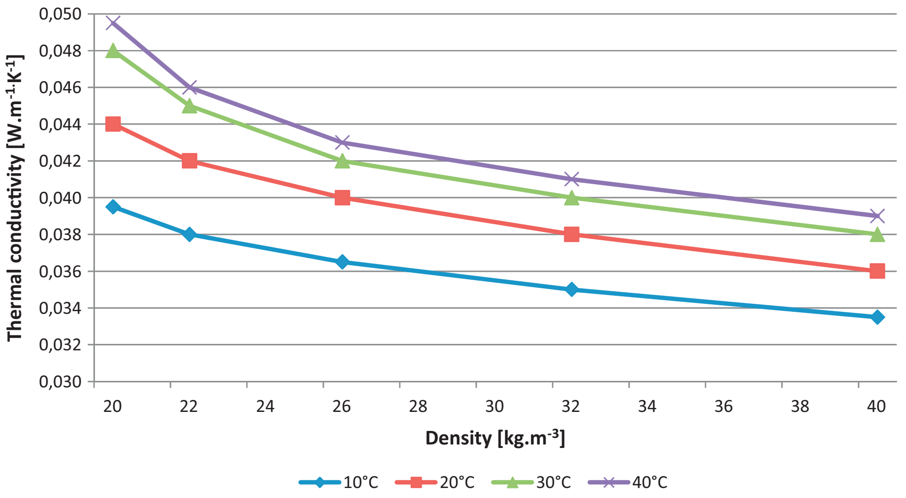

**Fig. 10.** Dependence of the thermal conductivity coefficient on bulk density when measured at 10 °C, 20 °C, 30 °C and 40 °C.

humidity values were applied to compile the sorption isotherm for +23 °C (Fig. 12).

The measured values clearly show that the sheep wool sample will exhibit sorption humidity around 20% under normal humidity conditions of 30–60% RH and at +23 °C, while its coefficient of thermal conductivity will be affected by humidity only to a minor extent.

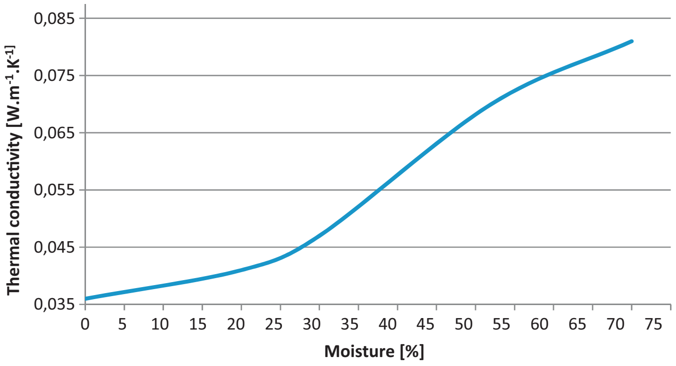

**Fig. 11.** Thermal conductivity coefficient curve based on the moisture content by weight for the 80 mm material.

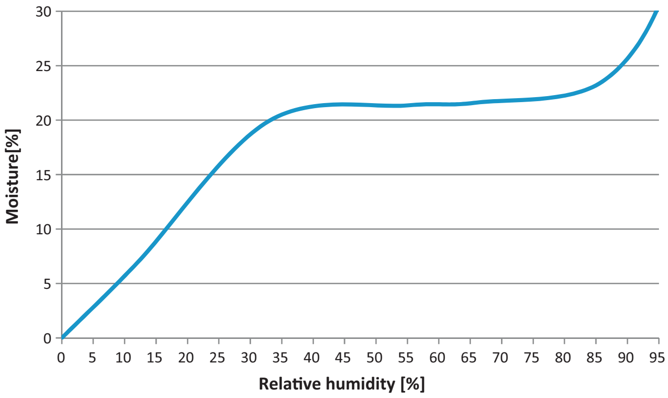

**Fig. 12.** The sorption isotherm of the sheep wool sample for +23 °C.

## 6. Conclusion

Guided by the current political objectives and strategies, technical developments of both the building envelope and building technology are increasing rapidly. Independent whether a single building or a whole community are considered, the achievable degree of sustainability and energy efficiency are presently evaluated according to the primary energy demand, $CO_2$ reduction and the ecological properties of the used materials.

To meet these requirements, the demand for ecological building materials is growing swiftly, especially for insulating materials composed from renewable raw materials. Since organic insulating materials are much more sensitive, further research is required in this area to investigate its behaviour and to show scientifically the optimization of the physical properties and to decrease the limitations of the material applications.

This paper detailed the investigations of sheep wool insulation that were performed. In order to investigate the hygrothermal and acoustic behaviour, the tests were carried out under both frequently occurring and strict climatic conditions. The results of our measurements clearly show where the application limits lie.

Based on the experimentally obtained measurement results, it can be stated that sheep wool is an excellent acoustic insulating material. Sheep wool has many advantages compared to commonly used acoustic insulations among which include environmental performance, ease of use, very low negative health impact by handling the material, and highly energy efficient production.

Sheep wool is mainly characterized by high hygroscopicity, which reaches up to 35%. The high ability to absorb moisture prevents condensation, regulates humidity and creates a pleasant indoor atmosphere. Moisture absorption and desorption from a porous material is very important for its functionality, see [25–29]. Another advantage is higher fire resistance.

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