Determination of material parameters of thermal insulation boards for the application on interior side of historical walls

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Abstract. At the reconstruction works on historical buildings, considerable financial means are spent. Therefore, it is desirable to assess the durability of applied materials in the particular conditions of a specific building. This cannot be done effectively without the knowledge of their hygric and thermal properties which can be used as input parameters of computational models. In this paper, hygric and thermal properties of several types of materials which can be used as interior thermal insulation layers in reconstructions of historical buildings on Czech territory, among them calcium silicate, hydrophilic mineral wool, and sheep wool, are investigated. Experimental results show that all analyzed materials can be considered as suitable for interior thermal insulation systems of historical building envelopes, in general. Their hygrothermal performance in specific applications should though be verified using computational simulations, taking into account the complex character of some historical construction systems.

1. Introduction
The interior thermal insulation of exterior walls is not an easy task but it can be considered as an effective solution how to save energy and increase thermal comfort for historical constructions. The application of interior thermal insulation systems on historical buildings should be analyzed from the point of view of their composition and hygrothermal performance because there are many risks, such as interstitial condensation or frost damage. There are two main possibilities how to build an interior insulation system, either it can be tight or it can be based on a capillary active material. The main risk of a tight system is that the external walls are not able to evaporate accumulated moisture; it can lead to decreasing of freeze/thaw resistance \([1–3]\) and increasing the moisture content in the interior. If a capillary active system is used, capillary active thermal insulation is able to redistribute the condensed water. It can lead to higher moisture content in the thermal insulation material and to an increase of its thermal conductivity \([4]\). As there are substantial risks for both systems, the interior thermal insulation must be designed very carefully.

Computational models present a very effective tool for the hygrothermal assessment of renovated structures, which can then be used for the service life assessment and possible planning of subsequent reconstructions, but computer simulations should be performed with care because the hygrothermal analysis of any historical building can involve quite a few uncertainties which may affect negatively the accuracy of obtained results. The quality of computer simulations depends on the quality of input...
parameters. One of them are external climatic data, such as temperature and relative humidity, solar radiation, and driving rain over one year, and prescribed indoor conditions like temperature and relative humidity. Very important input parameters are initial conditions as the initial moisture content in a building construction. Other important input parameters are material characteristics of all components of the studied system. The basic physical properties like bulk density, open porosity and matrix density are fundamental parameters in that respect. Water vapor transport and storage is expressed by water vapor diffusion coefficient and sorption isotherm. Among liquid water transport parameters, water absorption coefficient and moisture diffusivity in dependence on moisture content are utilized in the models. Thermal properties are represented by thermal conductivity and specific heat capacity in dependence on moisture content. In this paper complete sets of heat and moisture transport and storage parameters of selected thermal insulation materials in dependence on moisture content are determined.

2. Investigated materials
Two modern synthetic materials and one natural were investigated. Calcium silicate (CS) is a material which often serves also as an insulation for high temperatures. The second material is mineral wool (MW) which is primarily used for plant growing and green roofs. Both materials have a high ability to transport liquid water, therefore they can be utilized in interior thermal insulation system. The third material is sheep wool (SW).

3. Experimental methods
3.1. Basic physical properties
As fundamental physical material characteristics, the bulk density $\rho$ [kg·m$^{-3}$], the open porosity $\psi$ [Vol.-%] and the matrix density $\rho_{\text{mat}}$ [kg·m$^{-3}$] were determined. For synthetic material calcium silicate and mineral wool the water vacuum saturation method [5] was used. Because the sheep wool is a deformable material, its bulk density was determined using the mass and linear dimensions. The matrix density of sheep wool was measured by water vacuum saturation method.

3.2. Water vapor transport properties
The water vapor permeability characterizes the material ability to transport water vapor under a vapor pressure gradient. In this study the dry cup method was employed [5]. The sealed cups containing silica gel were placed into a controlled climatic chamber with 50% relative humidity and weighted periodically. Measurements were carried out for two weeks at temperature 25 °C. The water vapor diffusion permeability $\delta$ [s] was then calculated according to the equation

$$\delta = \frac{\Delta m \cdot d}{S \cdot r \cdot \Delta p_p}$$

(1)

where $\Delta m$ [kg] is the amount of water vapor diffused through the sample, $d$ [m] is the sample thickness, $S$ [m$^2$] is the specimen surface, $r$ [s] is the period of time corresponding to the transport of mass of water vapor $\Delta m$, and $\Delta p_p$ [Pa] is the difference between partial water vapor pressure in the air under and above specific specimen surface.

The water vapor diffusion coefficient $D$ [m$^2$·s$^{-1}$] and the water vapor diffusion resistance factor $\mu$ [-] were determined on samples with dimensions of 100 x 100 x 20 mm and calculated according to Eq. 2 and Eq. 3, respectively.

$$D = \delta \cdot \frac{R \cdot T}{M},$$

(2)
where $R$ [J mol$^{-1}$ K$^{-1}$] is the universal gas constant, $M$ [kg mol$^{-1}$] is the molar mass of water and $T$ [K] is the absolute temperature.

$$\mu = \frac{D_o}{D},$$

(3)

where $D_o$ [m$^2$ s$^{-1}$] is the diffusion coefficient of water vapor in the air.

### 3.3. Liquid water transport properties

The water absorption coefficient $A$ [kg m$^{-2}$ s$^{-1/2}$] and the apparent moisture diffusivity $\kappa$ [m$^2$ s$^{-1}$] were measured using water sorptivity experiment [6, 7]. The specimens were water- and vapor-proof insulated on four lateral sides and the face side was immersed 1-2 mm into water. Increase of the mass was then recorded by automatic balance. Measurements were conducted on samples with square cross sectional area of dimension 100 mm and the water absorption coefficient $A$ [kg m$^{-2}$ s$^{-1/2}$] was then calculated by formula

$$i = A \cdot \sqrt{t},$$

(4)

where $i$ [kg m$^{-2}$] is the cumulative water absorption, $t$ [s] is the time of the suction experiment. The water absorption coefficient was then employed for the calculation of the apparent moisture diffusivity in the form [6]

$$\kappa \approx \left( \frac{A}{w_e-w_0} \right)^2,$$

(5)

where $w_e$ [kg m$^{-3}$] is the saturated moisture content and $w_0$ [kg m$^{-3}$] the initial moisture content. Inverse analysis of moisture profiles using Boltzmann transformation was used for determination of the moisture diffusivity dependence on the moisture content. For such calculations, basically just one moisture profile is needed. However, the more measured profiles, the higher accuracy of the method. Such method consists in application of Boltzmann transformation which converts all measured moisture profiles in various times into a single profile. The method is supposed to be used only when the boundary condition on the dry end of the specimen is not yet effective [8].

$$\kappa(\mu_x) = \frac{1}{2t_0} \left( \frac{du}{dx} \right)_{x_0}^\infty \int x \frac{du}{dx} dx,$$

(6)

where $u$ [kg kg$^{-1}$] is the moisture content by mass, $\mu_x$ [kg kg$^{-1}$] is the value of moisture content at the position $x = x_0$. The moisture profiles were measured by the gravimetric method. The moisture diffusivity was calculated from 3 moisture profiles within this paper.

### 3.4. Sorption isotherms

The water vapor adsorption isotherms were measured using the desiccator method [5]. The samples were placed into the desiccators with different salt solutions to simulate different values of relative humidity. The initial state was dry sample. The mass of samples was measured in specified periods of time until steady state value of mass was achieved. Then, the moisture content by mass was calculated.

### 3.5. Thermal properties

The thermal conductivity $\lambda$ [W m$^{-1}$ K$^{-1}$] and the specific heat capacity $c$ [J kg$^{-1}$ K$^{-1}$] were measured using the commercial device Isomet 2104 (Applied Precision, Ltd.). The measurement is based on
analysis of temperature response of the analysed material to heat flow impulses. The heat flow is induced by electrical heating using a resistor heater having a direct thermal contact with the surface of the sample. The measurement of sheep wool was conducted by needle probe on samples with dimensions of 70 x 70 x 300 mm. Calcium silicate and mineral wool were measured by using surface probe.

4. Experimental results

4.1. Basic physical properties
The basic physical properties are given in Table 1. The lowest bulk density achieved sheep wool, the highest calcium silicate. The porosity of all materials was very high.

| Material | $\rho$ [kg m$^{-3}$] | $\rho_{mat}$ [kg m$^{-3}$] | $\psi$ [%] |
|----------|----------------------|-----------------------------|-----------|
| MW       | 126.5                | 2608                        | 95.1      |
| CS       | 264.5                | 2508                        | 89.5      |
| SW       | 15.0                 | 1155                        | 98.7      |

4.2. Water vapor transport properties
The water vapor transport properties are shown in Table 2. All materials were able to transport water vapor very easily.

| Material | $\delta$ [s] | $D$ [m$^2$s$^{-1}$] | $\mu$ [-] |
|----------|--------------|---------------------|-----------|
| MW       | 4.90E-11     | 6.74E-6             | 3.43      |
| CS       | 6.15E-11     | 8.44E-6             | 2.83      |
| SW       | 1.44E-11     | 1.32E-5             | 1.93      |

4.3. Liquid water transport properties
The water absorption coefficient and apparent moisture diffusivity are given in Table 3 and Figure 1. The lowest ability to transport liquid water exhibited sheep wool. The highest water absorption coefficient and apparent moisture diffusivity achieved hydrophilic mineral wool. The high ability to transport liquid water had also calcium silicate. The liquid water transport parameters are very important for interior thermal insulation materials. Therefore, the application of sheep wool should be considered with care.
Figure 1. Water absorption as function of time

Table 3. Water absorption coefficient and apparent moisture diffusivity

| Material           | A         | κ          |
|--------------------|-----------|------------|
| Calcium silicate   | 1.256     | 2.31 E-6   |
| Mineral wool       | 2.004     | 4.43 E-6   |
| Sheep wool         | 0.07      | 4.42 E-9   |

Moisture diffusivity in dependence on moisture content is shown in Figure 2. The highest moisture diffusivity had mineral wool, for calcium silicate it was only slightly lower. The lowest ability to transport liquid moisture exhibited sheep wool. The results were in the agreement with the measurements of water absorption coefficient and apparent moisture diffusivity.

Figure 2. Moisture diffusivity in dependence on moisture content
4.4. Sorption isotherms
The sorption isotherms of all studied materials are shown in Figure 3. The highest capability of adsorbing gaseous moisture showed sheep wool. On the other hand, mineral wool adsorbed almost negligible amount of water vapor.

4.5. Thermal properties
The values of thermal conductivity and specific heat capacity in dry state are shown in Table 4, thermal conductivity and specific heat capacity in dependence on moisture content are presented in Figures 4 and 5.

The highest thermal conductivity in dry state achieved calcium silicate; mineral wool and sheep wool exhibited almost 50% lower values. The effect of moisture content on thermal conductivity of all materials was very significant; they lost their insulation capabilities already for moisture contents as low as 5-10%. This underlined the high importance of their liquid water transport parameters.

The highest specific heat capacity in dry state achieved sheep wool, mineral wool and calcium silicate exhibited significantly lower values. The specific heat capacity as a function of moisture content was calculated according to the theoretical procedure described in [9], under the assumption that this heat storage parameter is an additive quantity in the sense of the linear theory of mixtures:

\[
c_{\text{wat}}(w) = \frac{\rho_{\text{dry}} c_{\text{dry}} + \rho_w c_w w}{\rho_{\text{dry}} + \rho_w w},
\]

where \(\rho_{\text{dry}}\) [kg·m⁻³] is the bulk density of dry material, \(\rho_w\) [kg·m⁻³] is the density of water, \(w\) [m³·m⁻³] is the moisture content by volume, \(c_{\text{dry}}\) [J·kg⁻¹·K⁻¹] is the specific heat capacity of dry material, and \(c_w\) [J·kg⁻¹·K⁻¹] the specific heat capacity of water. The specific heat capacity of all three materials increased rapidly with increasing moisture content, which was due to high specific heat capacity of water.
Table 4. Thermal conductivity and specific heat capacity in dry state

| Material      | Thermal conductivity [W·m⁻¹·K⁻¹] | Specific heat capacity [J·kg⁻¹·K⁻¹] |
|---------------|----------------------------------|-------------------------------------|
| Calcium silicate | 0.0654                          | 972                                 |
| Mineral wool  | 0.0421                           | 718                                 |
| Sheep wool    | 0.0420                           | 1940                                |

Figure 4. Thermal conductivity in dependence on moisture content

Figure 5. Specific heat capacity in dependence on moisture content
5. Conclusions

Three types of thermal insulation materials, namely calcium silicate, hydrophilic mineral wool and sheep wool were investigated in the paper. The main results can be summarized as follows. The lowest bulk density showed sheep wool, the open porosity of all materials was very high. All three thermal insulations were very open to water vapor transport. The highest ability to transport liquid water exhibited hydrophilic mineral wool, calcium silicate was only slightly worse. The lowest liquid water transport parameters had sheep wool. On the other hand, sheep wool presented a very high capability of water vapor adsorption, even higher than calcium silicate. Thermal conductivity of all three materials was sufficiently low for low moisture contents only. Their ability of transporting fast the liquid water was thus imperative for their proper function in building envelopes.

Acknowledgments

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