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Measurements of Moisture Diffusion Coefficient of Wood Wool

KEYWORDS
Wood wool, natural building materials, thermal insulation, moisture diffusion, sorption kinetics

ABSTRACT
The moisture diffusion coefficient of wood wool was determined using two analytical methods – Crank's initial sorption method and Liu's method. Measurements were carried out for two ranges of relative humidity in the air around the samples (RH ranges from 0% to 45% and from 45% to 90%). Samples of two types of wood wool were analyzed: the first – with a declared thermal conductivity coefficient of 0.038 W/mK and the second – with a declared thermal conductivity coefficient of 0.036 W/mK. For the materials examined, the value of the moisture diffusion coefficient decreases as the relative humidity increases.

INTRODUCTION

Wood wool forms a thermal insulation material of natural origin. Its thermal performance is comparable to that of traditional thermal insulation materials, such as polystyrene foam or glass and mineral wool, the production of which is significantly more harmful to the environment [1]. Wood wool thermal insulation can be in the form of loose fibers for blowing or flexible boards. Pine wood is the only raw material utilized in the production of loose fibers for blowing. On the other hand, in the production of flexible panels of wood wool, a binder in the form of polyolefin fiber is added to the wood pulp after the pulping and drying processes of the woodchips.

Two types of boards of wood wool were used in the study. The first type is wood wool with a declared thermal conductivity coefficient of 0.038 W/m·K, further referred to as hard wool. The average measured density of the hard wool samples tested is 113 kg/m^3 (± 1kg/m^3). The second type is wood wool with a declared thermal conductivity coefficient of 0.036 W/m·K, further referred to as soft wool. The average measured density of the soft wool samples tested is 59 kg/m^3 (± 1kg/m^3).

Wood wool is usually used on the external side of buildings. In the work [2] a building made of doweled cross laminated timber and insulated with wood wool panels was studied. The wood wool, which is on the outside of the walls, is in this case covered only by untreated facade boards. It is highly likely that the wood wool insulation is exposed to conditions outside the building. Therefore, in this study an effort was made to investigate the kinetics of moisture sorption by wood wool over the entire real range of relative humidity. The study was divided into two stages. In the first stage, measurements were carried out at ambient relative humidity in the range of 0% to 45%, and in the second stage at ambient relative humidity from 45% to 90%.

METHODOLOGY

The samples used in the study were cut from wood wool boards. The main raw material used in the production of the wood wool boards used is pine wood. The approximate dimensions of the samples were 100 x 100 x 50 mm for hard wool and 100 x 100 x 60 mm for soft wool samples. The samples were dried to a constant weight before testing. Then the samples were taped on four sides with aluminum vapor-proof tape, so that the moisture sorption process occurs in one direction. After the samples were taped, they were put back into the dryer to remove the moisture absorbed from the environment.

Measurements were performed by application of a non-stationary method, based on measurements of moisture sorption kinetics. In non-stationary methods, the sorption process is driven by a change in the sample's ambient air humidity [3]. In this case, the change in ambient air humidity was achieved by placing the samples in a climate chamber with a set humidity inside the chamber. The set temperature during the measurements was 23°C (±1°). Changes in the weight of the samples over time were recorded using a balance (with an accuracy of ±0.001 g) placed inside the chamber. The measurement set-up is shown in figure 1. The research was performed for two different ranges of ambient humidity, that is, with a step change in relative humidity from 0 to 45% and from 45 to 90%. The step change in relative humidity means that the samples gradually sorbed moisture after they were displaced from the dryer to the climate chamber. In the first humidity range, the sorption process was carried out for 28 days, while in the second humidity range the process was carried out for 36 days.

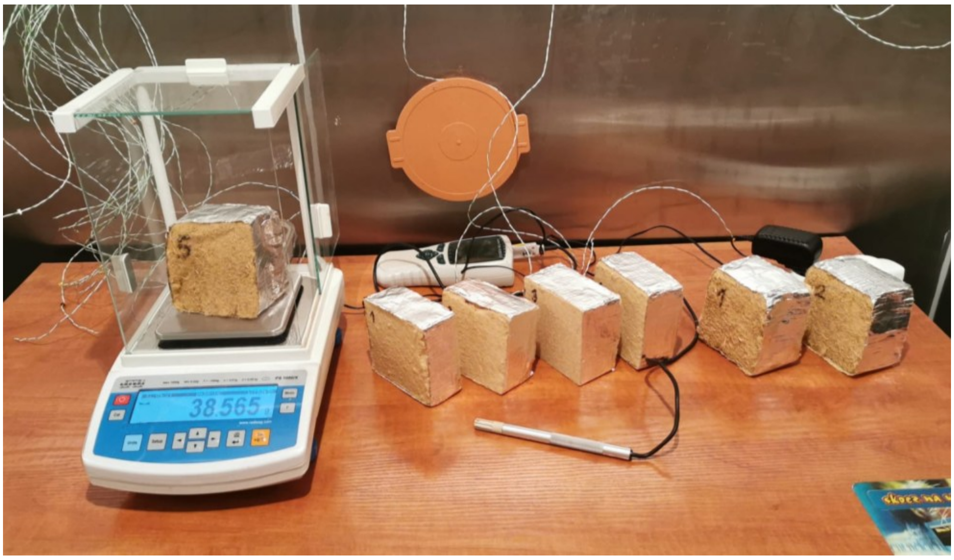

Figure 1. Measurement set inside the climate chamber

The moisture diffusion coefficient was determined by two analytical methods: the Crank's method (initial sorption procedure) and the Liu's method. These are non-stationary methods, and are therefore based on solving the diffusion equation in the form of Fick's second law given by equation (1).

$$(1) \quad \partial_t C^w = \partial_x (D^w \partial_x C^w),$$

where: t – czas [s], x – space coordinate [m], D^w – moisture diffusion coefficient [m^2 /s], C^w – moisture concentration in the sample (water mass in the sample relative to the mass of the dry sample) [kg/kg].

The initial sorption Crank method is based on the solution of the diffusion equation (1) with the assumption of an initial condition specified by formula (2) and boundary conditions of the first kind (3).

The initial condition states that the distribution of moisture concentration in the sample at the beginning of the process is homogeneous (2).

$$(2) \quad C^w(x, t = 0) = C_0^w$$

The boundary condition of the first type assumes that the value of moisture concentration in the surrounding air is equal to the value of moisture concentration in the pores on the outer surface of the sample, hereafter denoted as C_e^w (3).

$$(3) \quad C^w(x, t) = C_e^w$$

The solution of the diffusion equation assuming the initial condition (2) and boundary conditions (3) is the function

$$(4) \quad C^w(x,t) = C_0^w + (C_\infty^w - C_0^w)\left[1 - \frac{4}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1} exp\left\{\frac{-D^w(2n+1)^2\pi^2 t}{4h^2}\right\} cos\,\frac{(2n+1)\pi x}{2h}\right]$$

where: C_∞^w – equilibrium moisture content of the material [kg water/kg dry material], h – half of the sample thickness ($-h \ll x \ll h$).

Crank's method is also called the root-of-time method because it is based on graphs of sample mass increases as a function of the square root of time. Only measurement points from the initial range of the sorption kinetics curve that are aligned with a straight line are included in the calculation.

Liu's method is based on solving the diffusion equation (1) with the initial condition given by formula (2) and boundary conditions of the third kind (5).

$$(5) \quad -D^w \frac{\partial C^w}{\partial x} = \pm\kappa(C_\infty^w - C^w),\; x = \pm h$$

The boundary condition of the third kind assumes that the exchange of moisture between the edge of the sample
and the surrounding air occurs by convection. The solution of the diffusion equation (1) according to Liu's method is shown in equation (6).

$$(6) \quad C^w(x,t) = C_0^w + (C_\infty^w - C_0^w)\left[1 - \sum_{n=0}^{\infty}\frac{2Lcos(\beta_n x/h)\exp(-\beta_n^2 D^w t/h^2)}{(\beta_n^2 + L^2 + L)cos\beta_n}\right],$$

where: $\beta_n tg\beta_n = L$ and $L = \frac{\kappa h}{D^w}$.

In Liu's method, it is necessary to determine the time at which the sample reached half of the maximum (under the specified conditions) weight gain, i.e. the half time. The coefficient of moisture diffusion is determined from the values obtained at the moment as close as possible to the half time. In addition to the value of the moisture diffusion coefficient, this method also provides an opportunity to calculate the moisture uptake coefficient at the edges of the sample.

RESULTS & DISCUSSION

Figures 2–5 present the sorption kinetics curves of individual wood wool samples obtained from the experiment, in both analyzed relative humidity ranges. The individual hard wool samples are labeled T1, T2 and T6, while the soft wool samples are labeled M1, M2 and M3.

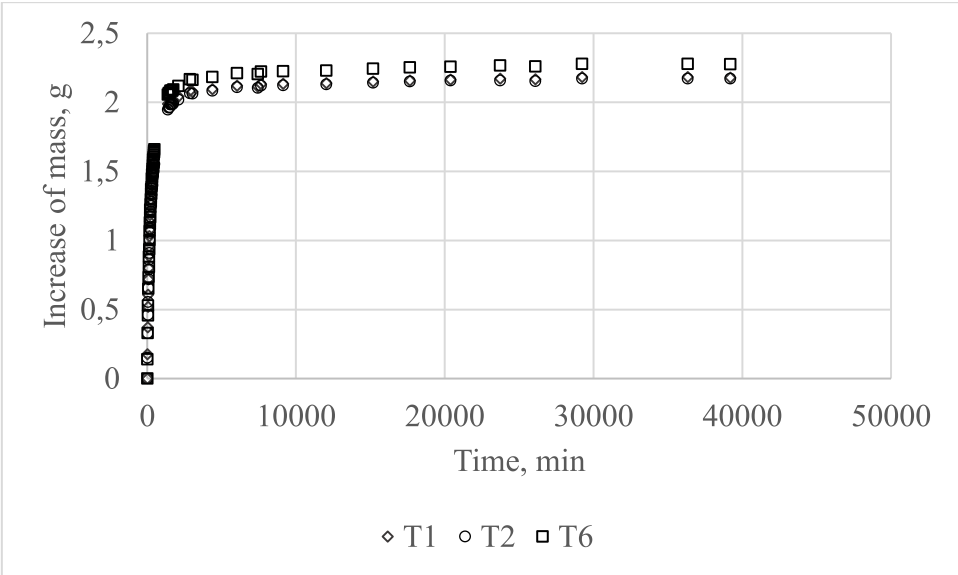

Figure 2. Sorption kinetics curves of hard wool samples. Range of relative humidity: 0%→45%

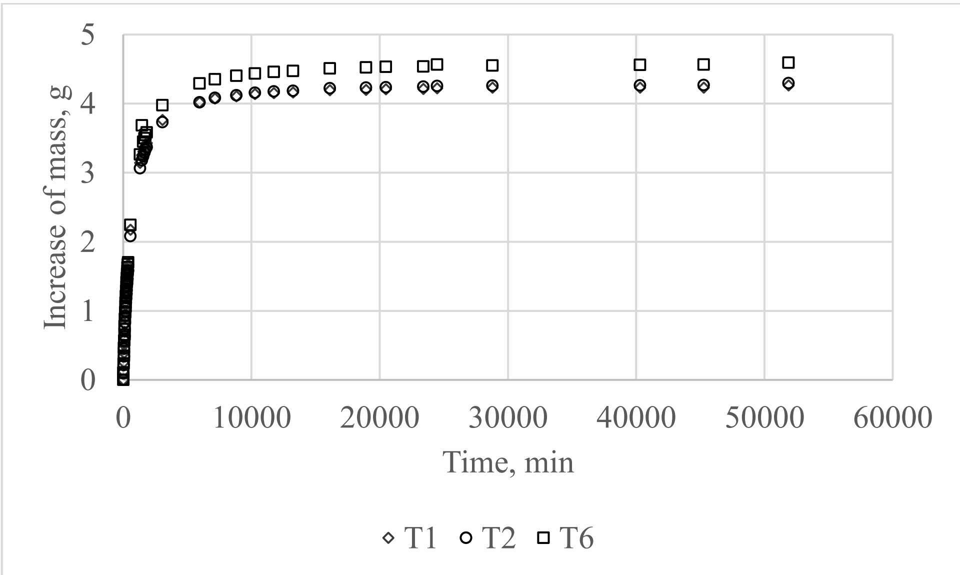

Figure 3. Sorption kinetics curves of hard wool samples. Range of relative humidity: 45%→90%

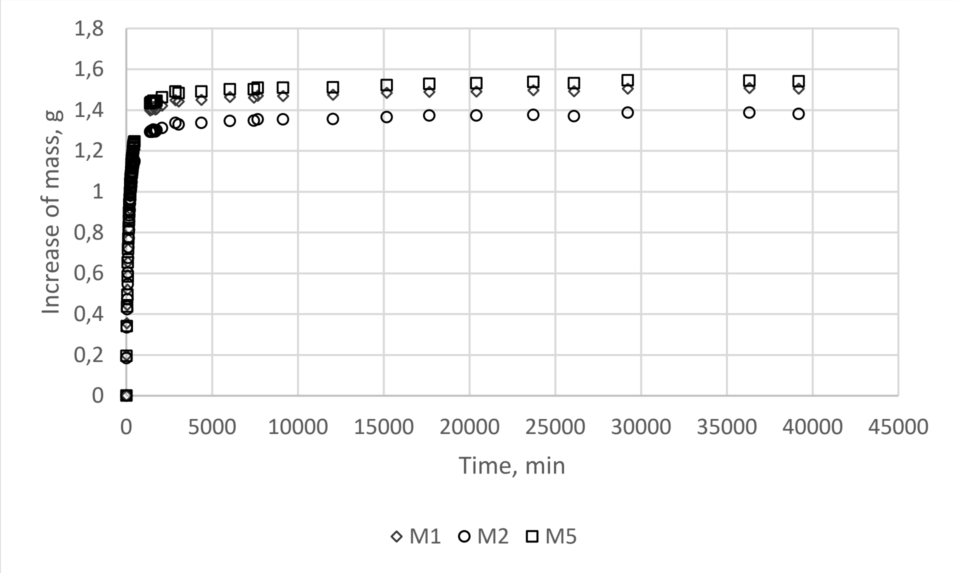

Figure 4. Sorption kinetics curves of soft wool samples. Range of relative humidity: 0%→45%

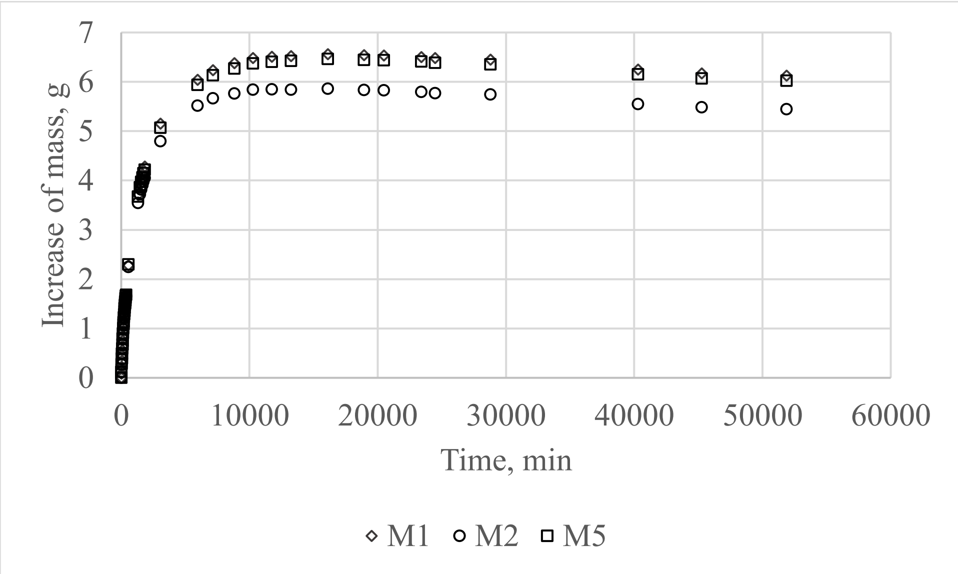

Figure 5. Sorption kinetics curves of soft wool samples. Range of relative humidity: 45%→90%

The moisture diffusion coefficient values obtained for individual samples and the average values of this coefficient for a given type of material are summarized in table 1. For both calculation methods, the value of the moisture diffusion coefficient is lower for the range of higher values of ambient relative humidity. This relationship has also been observed by the authors of the papers [4–6], among others.

Table 1. Values of moisture diffusion coefficient in m²/s – summary of the results

	Sample	Relative humidity range	
		0%→45%	45%→90%
Crank's method	T1	$1.14 \cdot 10^{-8}$	$0.285 \cdot 10^{-8}$
	T2	$1.06 \cdot 10^{-8}$	$0.285 \cdot 10^{-8}$
	T6	$1.07 \cdot 10^{-8}$	$0.289 \cdot 10^{-8}$
	Mean value	$1.09 \cdot 10^{-8}$	$0.286 \cdot 10^{-8}$
	M1	$2.12 \cdot 10^{-8}$	$0.235 \cdot 10^{-8}$
	M2	$2.30 \cdot 10^{-8}$	$0.286 \cdot 10^{-8}$

	M5	$2.48 \cdot 10^{-8}$	$0.296 \cdot 10^{-8}$
	Mean value	$2.30 \cdot 10^{-8}$	$0.272 \cdot 10^{-8}$
Liu's method	T1	$1.23 \cdot 10^{-8}$	$0.286 \cdot 10^{-8}$
	T2	$1.07 \cdot 10^{-8}$	$0.325 \cdot 10^{-8}$
	T6	$1.25 \cdot 10^{-8}$	$0.306 \cdot 10^{-8}$
	Mean value	$1.18 \cdot 10^{-8}$	$0.306 \cdot 10^{-8}$
	M1	$3.03 \cdot 10^{-8}$	$2.35 \cdot 10^{-8}$
	M2	$8.39 \cdot 10^{-8}$	$0.414 \cdot 10^{-8}$
	M5	$3.72 \cdot 10^{-8}$	$1.21 \cdot 10^{-8}$
	Mean value	$5.05 \cdot 10^{-8}$	$1.32 \cdot 10^{-8}$

The values of the moisture diffusion coefficient calculated by the Liu's method are greater than those calculated by the Crank's method. For hard wool, the values from Liu's method are 8.26% and 6.99% higher than those from Crank's method, respectively for the 0% to 45% and 45% to 90% relative humidity ranges. The values obtained for soft wool from the Liu's method are 119.57% and 385.29% greater than those from the Crank's method, respectively for the 0% to 45% and 45% to 90% relative humidity ranges. These differences may have to do with the specifics of each measurement method. In Crank's method, a different boundary condition is assumed than in Liu's method, which additionally takes into account the phenomenon of moisture uptake at the edges of the sample.

In table 2 the values of the moisture uptake coefficient at the edges of the sample are presented, as they were obtained using the Liu's method. This method is very sensitive to the accuracy of the determined half time. If the measurements fail to identify the instant when the sample reaches half of the final weight gain, errors occur, among other things, the κ coefficient may come out negative. In such cases, "<0" is entered in the table below.

Table 2. Values of the moisture uptake coefficient at the edges of the sample κ in m/s

Sample	RH range: 0%→45%	RH range: 45%→90%
T1	< 0	< 0
T2	< 0	< 0
T6	$19.9 \cdot 10^{-6}$	< 0
Mean value	-	-
M1	$10.2 \cdot 10^{-6}$	$0.279 \cdot 10^{-6}$
M2	$4.52 \cdot 10^{-6}$	< 0
M5	$10.5 \cdot 10^{-6}$	$0.763 \cdot 10^{-6}$
Mean value	$8.43 \cdot 10^{-6}$	-

On the basis of the method's assumptions, the calculations used measurements taken at the time nearest to half time (the time at which the sample reached half of its maximum weight gain under the given conditions). However, the measured values of the relative weight gain for soft wool at relative humidities in the range of 45 to 90% were much further away from half time. This can be clearly seen in figure 6, in which, at a relative weight gain of 0.5, the measurement points are missing. It turned out that the half time in this case fell at night, with an interval of 12 hours and 20 minutes between measurements. In order to improve the results obtained, the half time could be determined by approximating the mass increment curve, for example, using an exponential curve.

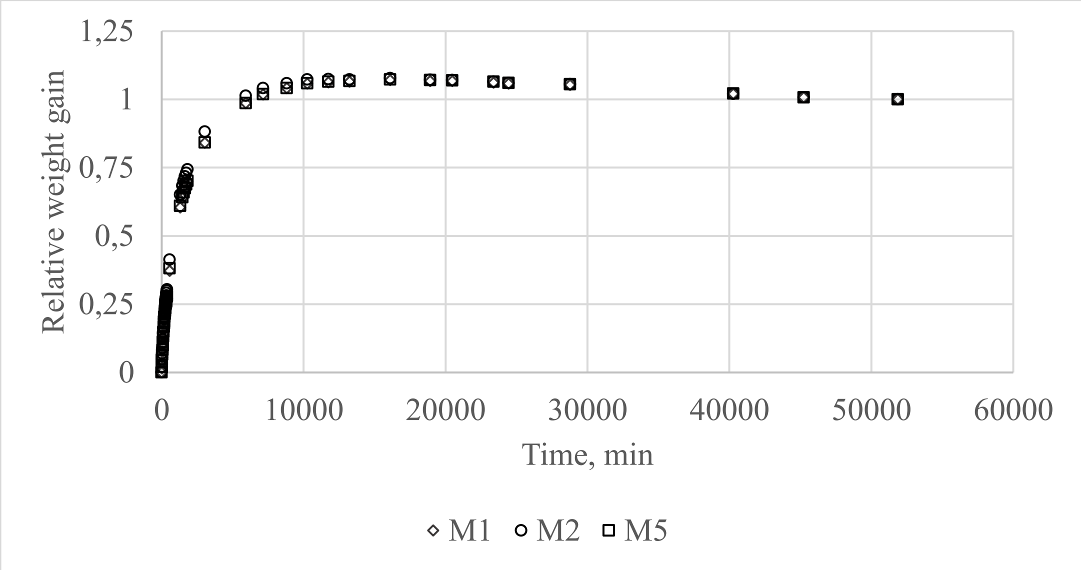

Figure 6. Relative weight gain over time – soft wool, RH range 45 to 90%

Due to the specificity of the measurement methods, the moisture diffusion coefficient values obtained from different methods can differ considerably [3–4], [7–9]. The authors of the paper [9] stated that the values of the moisture diffusion coefficient results can differ by as much as 4 orders of magnitude for the results obtained for studies with different methods. In the case of the present study, the results from the two analytical methods differed by a maximum of almost 1 order of magnitude, with the largest discrepancies obtained for soft wool in the range of higher relative humidities.

CONCLUSIONS

In this study, the moisture diffusion coefficient of wood wool samples was determined for two different ranges of relative humidity – from 0 to 45%, and then from 45 to 90%. The analyses carried out lead to the following conclusions:

1. For the materials examined, the value of the moisture diffusion coefficient decreases as the humidity of the air in the chamber increases. For hard wool, the average moisture diffusion coefficient in the relative humidity range from 45 to 90% was lower than in the range from 0 to 45% by 73.76% and 74.07%, respectively, from results obtained by Crank's method and from results obtained by Liu's method. For soft wool, the average moisture diffusion coefficient in the relative humidity range from 45 to 90% was lower than in the range from 0 to 45% by 88.17% and 73.86%, from results obtained by Crank's method and from results obtained by Liu's method, respectively.
2. The values of the moisture diffusion coefficient obtained from different methods may differ from each other. When determining the moisture diffusion coefficient using the Liu's method, it is important to take the measurement at a time as close to half time (the time at which the sample reached half of its maximum weight gain under the given conditions) as possible. Otherwise, the calculation results may be inaccurate. A larger number of measurements are taken into account to determine the moisture diffusion coefficient by Crank's method; therefore, some researchers believe it to be more accurate [4, 8].

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