Laboratory exercise No. 4 – Water vapor and liquid moisture transport

Water vapor transport in porous materials

Due to the thermal conductivity of water and other unfavourable properties and effects in porous materials, the thermal isolation problem of buildings is also connected with the building construction stability with respect to moisture and water vapor condensation inside a construction. Water vapor contained in the air diffuses through a porous material from places with a higher partial pressure to places with a lower partial pressure. The driving force of water vapour transport in porous material is the gradient of partial pressure that is related to the partial density of the water vapour flux according to the equation

$$J = -\delta \,\mathrm{grad}\, p \,,$$

where δ is the water vapor diffusion permeability [s] that expresses the possibility of a particular material to transport water vapor by diffusion and its value is equal to the density of the water vapor flux within the partial water vapor pressure gradient 1 Pa m^{-1}.

The most often used parameter describing the water vapor transport in a building practice is the water vapor diffusion coefficient which is defined by the formula

$$D = \frac{\delta R T}{M}, \qquad [\mathrm{m}^2.\mathrm{s}^{-1}]$$

where R is the universal gas constant [8.314 J $\mathrm{mol}^{-1}\mathrm{K}^{-1}$], T is the absolute temperature [K] and M is the molar mass of water [0.018 kg mol^{-1}]. In building practice the water vapor resistance factor is also used,

$$\mu = \frac{D_a}{D}, \qquad [-]$$

where $D_a = 2.3 \times 10^{-5}\ \mathrm{m}^2.\mathrm{s}^{-1}$ is the diffusion coefficient of water vapor in the air.

From the practical point of view the knowledge on water vapor diffusion can be applied on water vapor condensation in a construction during winter time. In this case it is necessary that the vapor flux in the construction is minimal. So, it is necessary that the internal surface of a wall in wet rooms is covered by a layer with a high diffuse resistance and the external side of the wall by a layer with a small diffusion resistance and a high thermal resistance.

The measurement of the water vapor diffusion permeability by the method with no temperature gradient is based on one-dimensional diffusion of water vapor through a sample and consists in the measurement of the water vapor diffuse flux passing through the sample, knowing the partial water vapor pressure in the air over and under the measuring surface of the sample. The sample is fixed in an airtight way in a bowl full of water. The mass of the bowl with the sample is periodically measured and the obtained mass losses are plotted against the measured time. When the measured curve becomes linear, the measurement is considered to be finished. The water vapor diffusion permeability δ is calculated from the equation

$$\delta = \frac{\Delta m\, d}{S \tau\, \Delta p_p} \quad \text{[s]},$$

where Δm is the amount of water vapour diffused through the sample [kg], d is the sample thickness [m], S is the surface of the sample [m^2], τ is the period of time corresponding to the mass transport of water vapour Δm [s] and Δp_p is the difference between the partial vapor pressure in air over and under the specific surface of the sample [Pa]. The latter is calculated from table data for the corresponding temperature and moisture.

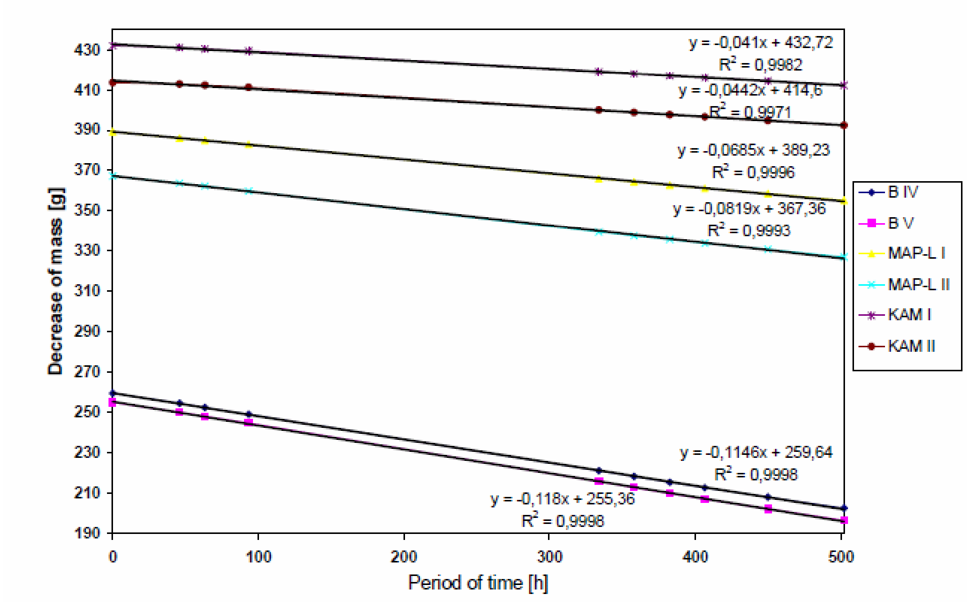

Fig.1 – Example of the course and evaluation of water vapor transport in porous materials

Task 1: Measure water vapor transport in a given material by the bowl method with no temperature gradient and calculate the water vapour diffusion permeability.

Water vapor diffusion in a construction

Water vapor can penetrate into a construction in two ways: either together with air flowing through leaks in the construction or by diffusion.

Diffusion is a mass transport which results from a statistical behavior of molecules, in our case water vapor molecules which are in the air. These molecules in the air are in a spontaneous, chaotic motion in the all directions. Naturally, more molecules move from places with a high water vapor concentration to the surroundings than from places with a lower concentration. This leads to spontaneous balancing of different concentrations in different places. After the concentrations are equilibrated, the molecular motion does not stop, only mass flows are compensated: the same amount of vapor molecules which flow out of a certain volume also flows into the volume from its surroundings. This movement is no longer considered to be a diffusion.

Water vapor diffusion and driving forces

If we are talking about water vapor diffusion in civil engineering, we only mean a water vapor molecules transport in the air or in those pores and channels in building materials filled with air. In calculations we usually do not work with concentrations but the partial water vapor pressure (the pressure which vapor molecules would cause on walls of a reservoir if only these molecules are in the reservoir, without other atmospheric gases). Suppose that two media that are adjacent to each other have different initial partial water vapor pressures. Usually, we are interested in the cases when the two media are the inside and outside air separated by an enclosure wall. Then molecules with a higher partial pressure move to the surroundings in a greater rate than the molecules with a lower partial pressure, until the partial pressures are equilibrated. The thicker the wall is and the lower the diffusion coefficient the wall has, the greater the obstacle to the molecular motion the wall represents; this is an analogy to heat transfer coefficient.

Although the molecules “do not feel” that they are forced to move somewhere and they move in a completely chaotic way, from the macroscopic point of view the driving force of the water diffusion transport is the difference of partial water vapor pressures (divided by the distance of places with different partial pressures). This force and also the diffusion cease to exist once the partial pressures are equilibrated. In the case of water vapor – in contrast to most common gases – the transport can be complicated by water vapor condensation.

Dew point

Water vapor has the property that at normal temperatures acceptable for life its partial pressure in air can increase form zero only to the value of the partial pressure of saturated vapor. Additional amounts of water vapor at an unchanged temperature only condensate, but they do not increase the water vapor content in the air. The partial pressure depends on temperature exponentially.

If the partial water vapor pressure in the air is equal to the partial saturated vapor pressure, we say that the air has the relative humidity of 100 %. For example, an air with the temperature 20 °C and the partial water vapor pressure 2336.74 Pa has (for the temperature 20 °C) a maximal possible humidity and, thus, its relative humidity is 100 %. If the water vapor pressure at the same temperature is only 1168.37 Pa, the air has the relative humidity 50 %. The air with the temperature 25 °C and the partial water vapor pressure 2336.74 has the relative humidity 73.83 %. The dew point (rather, the dew point temperature) of this air is 20 °C because condensation starts when it is cooled to this temperature.

Serious consequences follow from the exponential dependence of the saturated vapor pressure on temperature. Even if it is dry at home and the outside air is wet, vapor intensively diffuses outside from the inside due to a high internal temperature. In fact, if it is –15 °C in winter and the relative humidity is 100 %, than the partial vapor pressure is 165 Pa. If the temperature inside is 20 °C and the relative humidity is 50 % (dry), than the partial saturated vapor pressure is 1168.37 Pa. The pressure difference is 1003 Pa. If the thickness of an enclosure wall is 0.45 m, the generalized force driving the diffusion of water vapor outside from the inside is 1003/0.45 Pa/m = 2229 Pa/m.

Condensation zone

If temperatures in a construction – especially the temperature in an isolation layer – decrease faster than the dew point temperature, which often happens in winter, a dew point could be create in the construction at first, and later the place where vapor starts to condense becomes a region of a final thickness called a condensation zone. In a very cold weather the condensation zone with a varying thickness is created in a certain depth from the internal surface in practically all types of constructions (with one or several layers). In a warm weather most of the condensed water evaporates away.

Multilayer walls with a wide layer of thermal isolation have least tendency for the creation of a condensation zone from the external size in case the internal walls are only little permeable to water vapor and the external layer of isolation leak is substantially more permeable to water vapor than the external layers and is vented.

An inverse solution is also considered to be satisfactory (from the diffusion viewpoint) when a thick layer of thermal isolation from an external side is very little permeable to vapor but isolates thermally so well that no significant temperature decrease is created in the main internal layer in winter. Because of this possible condensation may occur only in the isolation, but its amount is so small (due to a small diffusive permeability of the isolation) that this solution is considered to be durable and safe.

Liquid moisture transport

Moisture transport through a porous material is described by the non-linear diffusion equation

$$\frac{\partial w}{\partial t} = div(\kappa \, grad \, w),$$

where w is the moisture content and κ the moisture diffusivity coefficient [$m^2.s^{-1}$].

Samples for absorption measurements are isolated along circumference (to ensure a one-dimensional moisture transport) and the non-isolated bottom side is immersed 1-2 mm under a water level. A constant water level is kept with the help of a bottle filled with water into which two capillaries are immersed; one capillary has the internal diameter of

2 mm and is under the water, while the other capillary has the internal diameter of 5 mm is above the water level. The sample hangs on automatic digital scales that record the mass of the sample. From a known value of the moisture flow into the sample during sorption, the moisture diffusivity coefficient is calculated. The experiment can be performed also manually when in specific time intervals the mass of the sample is measured.

The apparent moisture diffusivity coefficient can be calculated from the equation

$$\kappa = D_w \approx \left(\frac{A}{w_{cap}} \right)^2 \qquad [\mathrm{m^2.s^{-1}}],$$

where A is the water absorption coefficient [kg.m^{-2}.s$^{-1/2}$] and w_{cap} is the capillary saturated moisture content [kg.m^{-3}].

The absorption coefficient of water is determined directly from the initial linear dependence of the water mass per unit material surface [kg.m^{-2}] and the square root of time [s$^{1/2}$].

The value of the capillary saturated moisture content is calculated from the equation

$$w_{cap} = \frac{m_{cap} - m_0}{V}, \qquad [\mathrm{kg.m^{-3}}]$$

where m_{cap} is the mass of the sample corresponding to capillary absorption, m_0 the mass of a dry sample, and V the volume of a measured sample.

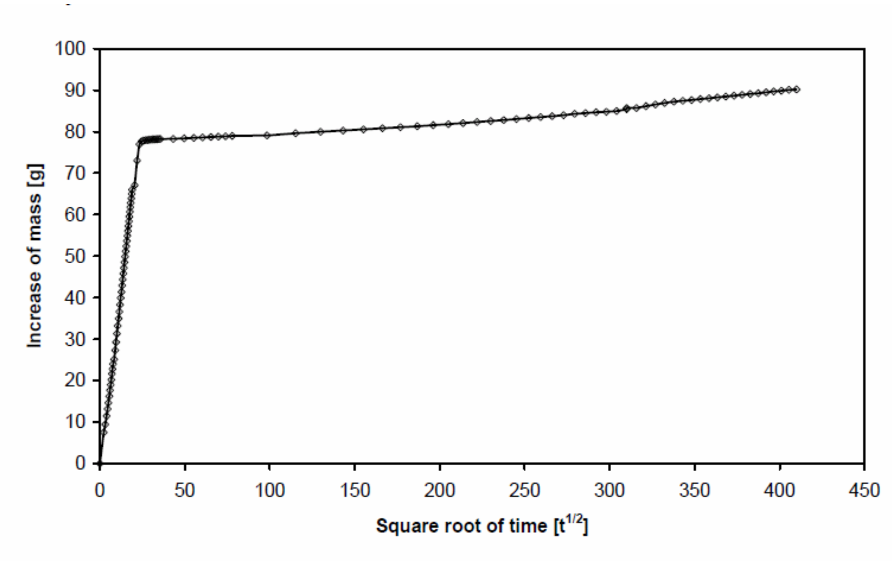

Fig.2 – A typical curve of absorption.

Task 2: Measure the water suction curve of several materials, determinate the water absorption coefficient A, and then calculate the apparent moisture diffusivity coefficient κ.

Laboratory protocol:

Title page: Title of experiment
Student’s name (or the members of a study group)
Date
Protocol: Short description of the studied materials
Description of applied experimental methods
List of used devices, tools and meters
Measured values and used constants
Intermediate and final results
Evaluation and data interpretation, conclusions

Table 1 – Density of water vapor and water vapor saturation pressure

t / °C	**ρ / g.m^{-3}**	**p / Pa**
10	9.40	1227
11	10.01	1312
12	10.66	1401
13	11.35	1497
14	12.06	1597
15	12.82	1704
16	13.63	1817
17	14.48	1937
18	15.36	2062
19	16.29	2196
20	17.29	2337
21	18.32	2486
22	19.41	2642
23	20.57	2809
24	21.78	2984
25	23.04	3168
26	24.37	3361
27	25.76	3565
28	27.23	3780
29	28.75	4005
30	30.35	4242