Moisture transport through perforated vapour retarders

Petr Slanina*, Šárka Šilarová

Department of Building Structures, Faculty of Civil Engineering, Czech Technical University in Prague, Thakurova 7, 166 29 Prague, Czech Republic

ABSTRACT

Nowadays, in most cases and according to recent international standards, moisture transport in building envelopes is assumed as one-dimensional. In fact, three-dimensional moisture transport occurs due to layer perforation or building assembly details. The article is focused on cases of low-slope compact roofs with a waterproofing membrane where the vapour retarder is perforated. Water vapour permeability measurement of different vapour retarders with different degrees of perforation is done by the wet-cup method. Results are presented. A significant increase of moisture transport is found through vapour retarders although their percentage of perforation was much lower than in previous known studies. A description of setting the apparatus to measure materials with a very high water vapour resistance factor is presented. Finally, based on the results, we formulated an analytical equation that describes water vapour diffusion flux through perforated vapour retarders. A simple equation can be used in cases where only one-dimensional moisture transport is calculated, which will help building designers to determine diffusion properties of perforated vapour retarders.

© 2008 Elsevier Ltd. All rights reserved.

1. Introduction

Low-slope compact roofs topped with a waterproofing membrane are regularly designed in North America [1] and Europe [2]. In cold-climate parts of these regions only, a vapour retarder is included into the roof assemblies [3,4] to control water vapour diffusion flux and to avoid excessive interstitial condensation of water vapour usually below a roofing membrane during cold seasons. The water vapour transfer due to air movement in this type of assemblies seldom occurs because the waterproofing membrane is very resistant to air leakage [4].

Vapour retarders are designed based on calculations described in International and European Standards EN 15026 [5] and EN ISO 13788 [6]. In these standards, moisture transport in building envelopes is assumed to be one-dimensional. This is correct when each roof layer is homogeneous, without any perforation, and when the roof assembly is truly planar. However, under certain circumstances, three-dimensional transport of moisture may occur in the roof assembly and then the calculations – according to the standard method – are not realistic. Thus, in certain cases, failure may come, the service life may be shortened and the roof assembly may loose its integrity.

Three-dimensional moisture transport occurs in roof (envelope) assemblies due to several reasons:

- imperfect joining of material strips;
- bad connection of vapour retarder to openings;
- mechanical fasteners puncturing roof layers;
- bad workmanship during construction;
- structure and assembly details;
- aging of sealing materials.

The main problem with three-dimensional moisture transport is with materials which have a high diffusion resistance factor and which are usually used for vapour retarder layers. We name a place of imperfection or perforation of an envelope layer a "diffusion bridge" because moisture transport noticeably increases in this place and because of similarity with the term "thermal bridge". A diffusion bridge in the case of perforation of the vapour retarder in the roof assembly is shown in Fig. 1 [7]. The calculation of moisture transport in the case where a vapour retarder is perforated will be according to the standards only in one-dimensional Fig. 1. left. However, two or three-dimensional moisture transport occurs due to the perforation and moisture transport through the vapour retarder can be greater Fig. 1. right.

It is generally known that water vapour transport significantly increases due to perforation of a building layer, especially if the layer has a great diffusion resistance. However, only four results [8–11] of water vapour permeability measurements of perforated building products can be found in literature. The results of the measurements are discussed in detail in the following section. These previous experimental measurements were done only for few products that are used as vapour retarders. According to Refs.

* Corresponding author. Tel.: +420 605 211694.
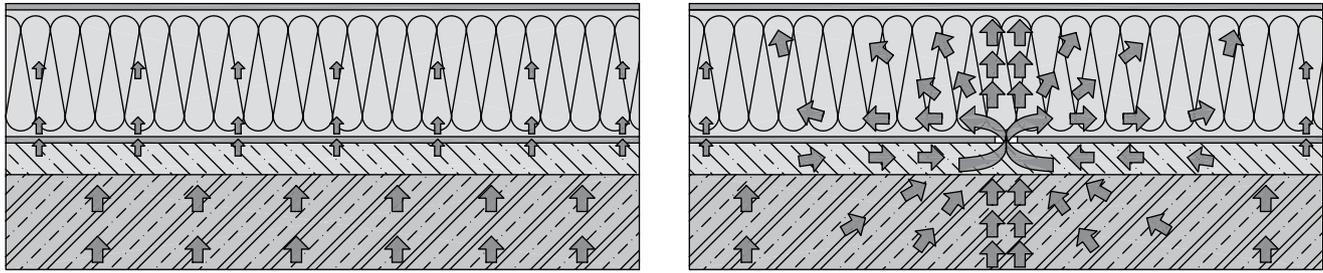 E-mail address: petr.slanina@fsv.cvut.cz (P. Slanina).

Fig. 1. 1D and 2D(3D) moisture transport in a roof assembly. A diffusion bridge is demonstrated on the right, where a vapour retarder is perforated [7].

[1] and [2], vapour retarders with greater diffusion resistance are commonly used in compact membrane roofs. Also, the percentage of perforation in previous measurements in most cases was higher than 0.01% but in real assemblies, it can be much lower.

The lack of results and their inaccuracies led to a decision to do our own experimental measurement. Our goal was to focus on water vapour permeability measurements of commonly used and perforated vapour retarders; especially if the percentage of their perforation is lower than 0.01% (i.e. less than in previous measurements) and the diffusion resistance of the products will be higher than in known cases of similar measurements.

2. Nomenclature

First of all, a note about quantities and units that describe diffusion properties of materials and products shall be done.

In Europe, diffusion properties of thin products (e.g. waterproof membranes, vapour retarders) are most commonly described with the help of the equivalent vapour diffusion thickness of a product (sd-value), s_d [m]. The sd-value is defined as follows

$$s_d = \mu d \qquad (1)$$

where μ is the water vapour resistance factor of a product material [–], and d is the thickness of the product [m]. The water vapour resistance factor of a material is defined as the ratio between the vapour permeability of stagnant air δ_a [kg/(Pa m s)] and the vapour permeability of the material δ_p [kg/(Pa m s)] under identical thermodynamic conditions (same temperature and pressure), see equation (2).

$$\mu = \frac{\delta_a}{\delta_p} \qquad (2)$$

In North America, the water vapour permeance, δ_1 [kg/(Pa s m^2)] more often written as [ng/(Pa s m^2)] is usually used for membranes and composite materials. The water vapour permeance is defined as follows.

$$\delta_1 = \frac{\delta_p}{d} \qquad (3)$$

Sometime, the water vapour permeance is expressed in perms (inch-pound units). One perm is defined as [grain/(h ft^2 in Hg)] and the conversion between IP units and SI can be written as

$$1 \text{ perm} = 57.2 \text{ ng/(Pa s m}^2) \qquad (4)$$

The conversion equation (4) applies only for a temperature equalled to 0 °C [12].

3. Previous work

In the past, water vapour permeability of perforated materials with high sd-value was measured by Seiffert [8], Bauer [9], Mrlík

[10], and Suprenant and Malisch [11]. Seiffert measured sd-values of 1.5 mm thick aluminium sheet with percentage of perforation from 0.01% to 0.22% Table 1. His measurement showed significant decrease in the sd-value.

Bauer made similar measurements. He measured sd-values of three different materials (aluminium sheet $d = 1$ mm, PVC foil, fibreglass board). The percentage of perforation for these materials varied between 0.03% and 10%. His measurements show that the decrease in sd-values is greater in the case of materials with a higher water vapour resistance factor (i.e. aluminium sheet). Above 1% perforation, the sd-value does not depend on the material because all measured products have the same sd-value with similar perforation, Table 2.

Bauer measurement results can be questioned as he reported the sd-value of aluminium sheet without any perforation of $s_d = 54$ m. According to standards the value should be infinity or at least 1500 m. Also Bauer's and Seifert's measurements vary in sd-values of aluminium sheet for percentage 0.03% and 0.0275%. The sd-value should be higher for Seifert (greater thickness of aluminium sheet and smaller percentage of perforation) but the result is twice higher for Bauer's aluminium sheet $s_d = 5$ m than Seiffert's aluminium sheet $s_d = 2.02$ m. These two discrepancies make all the results uncertain.

Similar measurements were made by Mrlík. He measured the sd-value of PE foil that was perforated by staples. First he measured sd-values of PE foil with staples, then he pulled out the staples and measured sd-values of PE foil again only with pinholes. The sd-value factor of 2–3 was found between these two measurements, see Table 3. The disadvantage of Mrlík's measurement is that the area of pinholes is unknown, and therefore the results of the measurement cannot be compared with other results of similar measurements.

In the USA, water vapour permeability measurements of perforated PE foils with two different thicknesses were done by Suprenant and Malisch [11]. The authors used the calcium chloride cup test. The results of their measurements showed significant water vapour transport through retarders with very large holes (ø3.2 mm and ø15.9 mm) but the authors were not able to distinguish the water vapour flow through non-perforated PE foils with two different thicknesses, therefore the results are unclear.

Another source of information is a large-scale investigation of moisture and heat transport in a wood frame wall assembly with

Table 1
Seiffert water vapour permeability measurement of perforated aluminium sheet [8].

Material: aluminium sheet	Thickness: $d = 1.5$ mm
Percentage of perforation [%]	sd-value [m]
0.014	9.30
0.0275	2.02
0.055	0.915
0.11	0.515
0.22	0.246

Table 2
Bauer water vapour permeability measurement of three perforated materials (aluminium sheet, PVC foil, fibreglass board) [9].

Material:	Aluminium sheet	PVC foil	Fibreglass board
Thickness:	$d = 1$ mm	$d = 0.16$ mm	$d = 4.1$ mm
Percentage of perforation [%]	sd-value [m]	sd-value [m]	sd-value [m]
0	54.00	14.24	0.45
0.03	5.00	3.00	0.44
0.3	0.60	0.40	0.34
0.5	0.47	0.33	0.31
1	0.27	0.27	0.27
1.5	0.24	0.24	0.24
2	0.22	0.22	0.22
3	0.19	0.19	0.19
5	0.15	0.15	0.15
10	0.08	0.08	0.08

a perforated vapour retarder which was performed by Zarr et al. [13]. The same wall specimen was investigated with and without a vapour retarder and with the vapour retarder with a hole of 11.5 mm diameter. The relative humidity (RH) measurements for the case with the hole fall between the cases with and without vapour retarder.

Finally, further investigations of moisture transport in roof assemblies were performed by Hens et al. [14]. Four-year measurements of compact low-slope roof assemblies on heavy-weight decks were compared. One case had a perfect vapour retarder while the other had open joints to simulate poor workmanship. The results showed that there was no condensation deposit after the first winter for the roof with a high-quality vapour retarder. The roof with the open joint vapour retarder had condensation deposit after the first winter in the amount of 0.5 kg/m^2. Hens concluded that moisture control depends on the condition that a perfect vapour and airflow retarder is mounted just below the thermal insulation.

4. Measurements

4.1. Method

As we were not able to find other results and the results shown above are insufficient to describe clearly the phenomenon, we decided to perform more measurement in the laboratory of the Faculty of Civil Engineering, CTU in Prague.

We used the wet-cup method as the experimental approach for our measurements. Advantages of this method are simplicity, low cost, and accuracy. In addition the wet-cup method is described in several international standards [12,15,16]; also the conditions of the method match well with real conditions in roof assemblies. One disadvantage of the measurement is the long time period needed to get results.

Table 3
Mrlík water vapour permeability measurement of perforated PE foil with stapes and with pinholes ones staples were removed [10].

Material:	PE foil with staples	PE foil only with holes
Thickness:	$d = 0.085$ mm	$d = 0.085$ mm
Number of staples [items/m^2]	sd-value [m]	sd-value [m]
0	28.74	28.74
100	14.35	5.00
200	3.60	1.92
300	2.20	1.40
400	2.07	1.25
500	2.00	1.20
1000	1.60	0.74
1500	1.12	0.50
2000	0.70	0.30

The principle of the wet-cup method is to create two environments with different relative humidity. The RH inside a cup is 95% and the RH outside the cup is 50%. The RH is constant due to saturated soil solutions that are placed inside cups and glass containers. Temperature is the same for both environments. The vapour flux then goes from the cup where RH is higher, through a sample, to the environment with lower RH according to the simple equation (5),

$$g_v = -\frac{\delta_a}{\mu(w)}\nabla p_v \tag{5}$$

where g_v is water vapour flux [kg/(m^2 s)], p_v is water vapour partial pressure [Pa], δ_a is water vapour diffusion coefficient of dry air [kg/(Pa s m)] and μ is water vapour resistance factor of measured material [–], which depends on moisture content w inside a material [kg/m^3].

The cup with the sample is weighed at regular time intervals. When the vapour flux reaches steady state (decrease of mass is constant per time period), a minimum of four additional weighings are done. Then the sd-value of the sample is calculated using the following equations;

$$\mu = \frac{\Delta t A \Delta p_v \delta_a}{\Delta m d} \tag{6}$$

where Δt is the time difference between weighing with constant decrease of weight [s], Δm is the mass difference between weighing with constant decrease of mass [kg], A is the effective area of the sample [m^2], d is the thickness of the sample [m] and δ_a is water vapour permeability of still air [kg/(Pa s m)], calculated from the simplified Schirmer's equation [17],

$$\delta_a = \frac{1.97 \times 10^{-7} \times T^{0.81}}{P} \tag{7}$$

where T is the absolute temperature [K], P is the barometric pressure [Pa]; assumed constant at $P = 101,325$ Pa, and Δp_v is the water vapour partial pressure difference across the sample [Pa], [6]

$$\Delta p_v = \frac{\Delta rh}{100}610.5 \times e^{17.269\theta/237.3+\theta} \tag{8}$$

where ΔRH is the relative humidity difference across the sample [%] and θ is the temperature [°C]. Equation (8) is for temperatures equal to or higher than 0 °C. The sd-value of the sample is calculated using equation (9),

$$s_d = d\mu \tag{9}$$

where s_d is the water vapour diffusion-equivalent air layer thickness (sd-value) [m].

As we measure materials with high sd-value, we assume that water vapour surface coefficients on the both sides of the samples are insignificant and thus these coefficients are not taken into account, i.e. [18].

Furthermore, in our calculation we did not use corrections for the sd-value as mentioned in standard [15] or for example in Ref. [19]. These corrections are

1. water vapour resistance due to still air between saturated solution and specimen surface,
2. edge mask effect,
3. buoyancy correction.

The first correction – water vapour resistance due to still air – is insignificant in cases where the sd-value of materials is higher than 1.74 m or permeance is lower than 114 ng/(Pa m^2 s) (2 perm inch-pound) according to Ref. [12]. Slightly different values are in Ref.
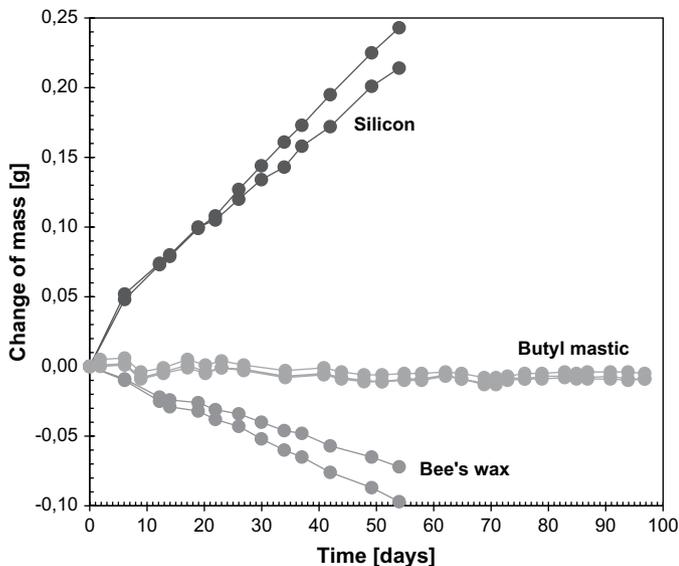
Fig. 2. Testing sealing materials with help of blind tests (small cups) – change of cup mass from the beginning of the measurement. (Mass decreases above zero and increases below zero).

[20]. As the sd-values of our samples are much higher than these values, we neglected the resistance due to still air layers.

We also did not employ the edge mask effect because this effect plays an important role only for thick samples where multidimensional water vapour flux occurs [21].

The buoyancy correction [22] is due to varying in atmospheric pressure that affects all gravimetric data. To eliminate buoyancy effect, we employed a "blind test".

4.2. Experimental set-up

The principle of the wet-cup method is simple but special care is required to measure materials with very high μ-factor. The apparatus needed improvement. After three years of measurement, we can recommend the following:

4.2.1. Cup
Aluminium cups of thickness 1 mm were used. The cups were painted to avoid chemical reaction with saturated solutions. The surface in contact with the sample and sealing material must not be painted. Glass cups are also good but quite heavy for exact scales.

4.2.2. Scale
Scale resolution of 0.001 g is necessary (resolution 0.0001 g would be better). A scale with resolution 0.001 g was used for the results presented here.

4.2.3. Area of the sample
The area of samples should be as large as possible. At the beginning we used cups with effective diameter of 50 mm (area 0.002 m^2), but results of measurements proved that cups with larger effective area were necessary. Later, these small cups were used only to find out the best sealing material. The cups with effective area 0.03 m^2 were finally used to measure the sd-values of the samples.

4.2.4. Sealing material
The sealing material is the most important technical issue to obtain accurate measurement results for products with very high

sd-value. Kumaran in Ref. [23] emphasized the influence of the method of sealing the specimen to the mouth of the cup. In a round-robin test [24], only three laboratories out of twelve were judged to be skilled in sealing. In another round-robin test [25], 40 μm polyethylene foil was measured by ten laboratories. The mean sd-value of the foil was measured as $s_d = 15.3$ m but the 95% confidence interval was as large as ±13.7m! In Ref. [26], six laboratories measured 0.25 mm polyethylene foil and the results of the measurements were similar. The average sd-value of the foil was measured as $s_d = 101$ m. However, the standard deviation among laboratories was ±45 m (44%).

Taking into account the difficulties reported above, we decided to test first the sealing materials. Four sealing materials (silicon, bee's wax, bitumen mastic and butyl mastic) were tested for half a year with the help of "blind tests". The blind test is a measurement where the sample is replaced by the material from which the cup is made. In this case, aluminium sheets (1 mm) were used. The results from blind test measurements are presented in Fig. 2 (cups ø50 mm) and Fig. 3 (cups ø200 mm).

The test showed that silicon and bee's wax are not perfect sealing materials. A silicon sealant was too permeable for water vapour flux. Bee's wax adsorbed too much moisture in the small cup. Only cups with butyl mastic sealing had almost constant mass over time. Similar results are shown in Fig. 3. where cups of ø200 mm were used. In this case bee's wax sealant shrank and water vapour leakage appeared. Silicon and bitumen mastic sealants showed almost similar permeance. Again, only butyl mastic sealant had almost constant mass over time (varies ±0.01 g during period of 42 days). Butyl mastic was finally chosen for following measurements as sealant because of the following properties: almost impermeable for water vapour, almost no moisture adsorbed, good adhesion, shapeable and no chemical reactions with sample or with aluminium cup.

4.2.5. Monitoring
Relative humidity and temperature outside of the cups were monitored every half an hour. The RH inside of the cups was monitored only once and atmospheric pressure was monitored every time when the samples were weighed.
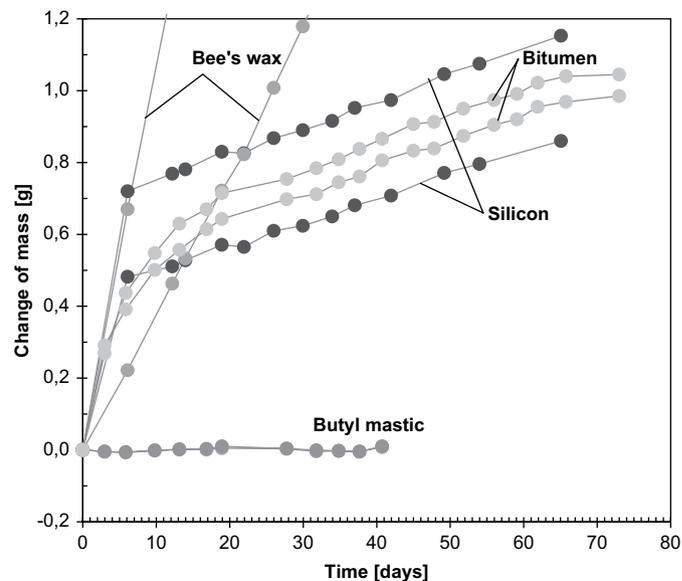

Fig. 3. Testing sealing materials with help of blind tests (large cups) – change of cup mass from the beginning of the measurement. (Mass decreases above zero and increases below zero).
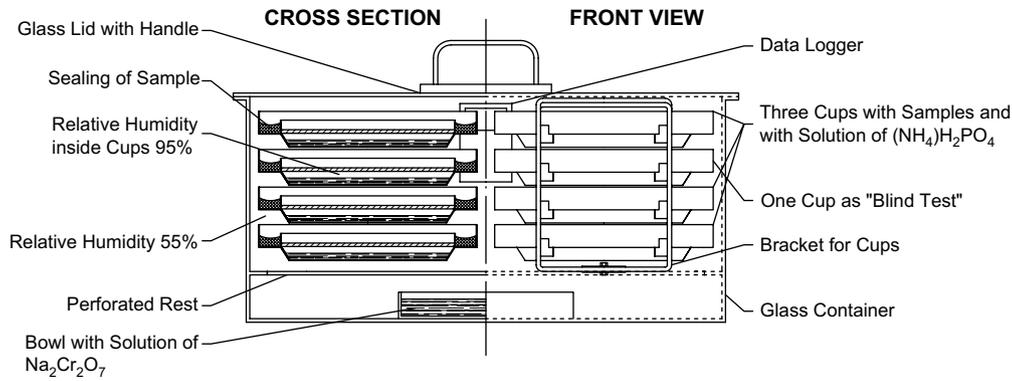
Fig. 4. Experimental apparatus for water vapour permeability measurement of low-permeable materials.

4.2.6. Set-up

For each set of measurements three or four cups with samples and one cup as the blind test were used in the same time period. The blind test was used to compensate for leakage and varying atmospheric pressure. The schema of the final experimental apparatus is shown in Fig. 4.

The advantages of the apparatus in contrast to common experimental measurements [12,15] are

1. The blind test shows how tight a sealing system is because the change in mass for blind tests should be zero during the whole time period of a measurement. This is extremely important if products with great diffusion resistance are measured.
2. If the blind test cups are weighed together with regular cups with samples the buoyancy effect is eliminated due to applying the following equation into equation (6),

$$\Delta m = \Delta m_s - \Delta m_b \qquad (10)$$

where Δm is the change of the mass [kg], that will be used in equation (6), Δm_s is the change of the mass [kg] for cups with samples, and Δm_b is the change of the mass [kg] for blind tests. Equation (10) would be also used in the first point if a sealing system is not totally vapour tight.
3. The previous two points reduce a time period needed to get results from the measurement.

4.3. Measurement procedure

1) The saturated salt solution was carefully poured into the aluminium cup and then the samples or aluminium sheets (for blind tests) were placed into cup mouths and properly sealed by butyl mastic. The cups with samples and blind test cups were weighed, their weight was registered and then they were placed into glass containers.
2) The cups with samples and blind tests were weighed in regular time periods. The time period lasted from two till five days. During weighing, the cup was removed from the glass container (control environment), placed onto the scale, its weight was registered, and then it was placed back into the glass container. The time period, when the cup with the sample was out of the control environment, should be as short as possible. The RH inside the glass containers degreased approximately for 30 min below the constant level according to monitoring systems.
3) The steady state occurs when the four or five weighings showed a constant decrease of the mass. The constant decrease of the mass was recognised from the graph where the change of the mass per time was plotted, Fig. 5. When the steady state was reached each sample was punctured by a sharp pin. The sharp pin with diameter of 0.68 mm was used for foil samples. Bitumen samples were punctured with the same sharp pin but no change in the mass was observed. Later, a hot pin with diameter of 1.26 mm had to be used only to puncture bitumen
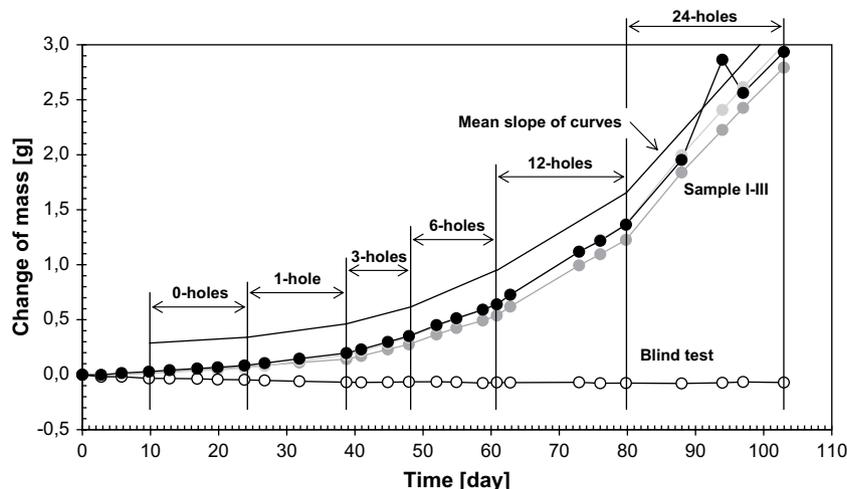

Fig. 5. Mass change per time for cups with samples and for one blind test during the whole time of the measurement. (Mass decreases above zero and increases below zero).

Table 4
Properties of measured products.

Material	Thickness [mm]	Number of samples	Number of blind tests	Manufacturer's sd-value [m]
PE	0.15	4	0	21
LD PE	0.22	3	1	198
LD/HD PE	0.3	3	1	360
Bitumen membrane	2.7	4	0	130
Bitumen + Al membrane	4.0	3	1	800

samples so that the sealing system of the cup was not destroyed. The sample remained sealed in the mouth of the cup during puncturing. The samples were step by step punctured after the steady state occurred with 1, 3, 6, 12 and 24 holes, Fig. 5. The pinholes were evenly positioned over the surface of the samples. After water vapour permeability measurements were finished, the area of holes in foil samples was measured by a microscope. The mean area for one pinhole was determined as 0.049 mm^2 with standard deviation as 0.004 mm^2. The area of holes in bitumen samples was calculated from the diameter of pins. The sd-value of the samples was calculated with the help of equations (6)–(9).

5. Results of measurement

Five different materials, three foil membranes and two bitumen membranes (see Table 4), were measured in the laboratory of the Faculty of Civil Engineering, CTU in Prague.

Table 5
Results of the measurements, sd-value [m], permeance [ng/(Pa s m^2)] and permeance [perm (inch-pound)] of perforated PE foil.

Product – PE foil						
Percentage of perforation [%]	sd-value [m]		Permeance [ng/(Pa s m^2)]		Permeance [perm IP][a]	
	Sample 1–4	Mean (SD)	Sample 1–4	Mean (SD)	Sample 1–4	Mean (SD)
0.00000	101.8	86.0 (±14.8)	1.93	2.35 (±0.40)	0.0338	0.0410 (±0.0070)
	99.8		1.96		0.0343	
	72.9		2.68		0.0468	
	69.5		2.81		0.0492	
0.00016	47.5	47.4 (±2.0)	4.12	4.14 (±0.18)	0.0720	0.0724 (±0.0031)
	48.8		4.01		0.0700	
	49.1		4.00		0.0699	
	44.1		4.44		0.0776	
0.00047	31.5	30.5 (±1.5)	6.23	6.48 (±0.36)	0.1088	0.1132 (±0.0063)
	32.3		6.05		0.1057	
	29.8		6.67		0.1166	
	28.3		6.97		0.1218	
0.00094	21.2	20.3 (±0.8)	9.28	9.70 (±0.39)	0.1622	0.1695 (±0.0067)
	20.8		9.43		0.1648	
	20.0		9.81		0.1715	
	19.1		10.28		0.1796	
0.00187	12.7	12.5 (±0.3)	15.53	15.78 (±0.41)	0.2715	0.2759 (±0.0072)
	12.9		15.25		0.2666	
	12.2		16.10		0.2815	
	12.1		16.25		0.2841	
0.00374	6.7	6.7 (±0.1)	29.24	29.47 (±0.54)	0.5111	0.5152 (±0.0094)
	6.9		28.82		0.5038	
	6.7		29.55		0.5166	
	6.5		30.28		0.5294	

[a] permeance in [perm (inch-pound)] was calculated as 1 perm [grains/(h ft^2 in·Hg)] = 57.2 ng/(Pa s m^2).

Measurement results are found below for each material at different percentages of the perforation. Table 5 is for PE foil, Table 6 for LD PE foil, Table 7 for LD/HD PE foil, and Table 8 for bitumen membrane. As for the last product, bitumen membrane with aluminium sheet, the equilibrium water vapour flux through the samples could not be determined; the measurements were stopped after 100 days.

6. Analytical modelling of results

Measurements were performed only for four different membrane products with percentage of the perforation going from 0.00016% to 0.0037%. In the cases of other products or wider range of the perforation, a simple mathematical equation is needed.

In literature, a few attempts can be found. For example [27], an analytical solution for a perforated foil between two nearby layers is described. The final equation is without a material constant that should be used in the place of the perforated foil. In Ref. [28], the results of Seiffert [8] and Bauer [9] measurements of perforated products were compared but no solution was found. Otherwise, the simple equation has been used for thin low-permeable products (steel rib decks) with joints Mrlík [10]. The equation is written as parallel circuit of diffusion resistances,

$$\frac{A_{\text{tot}}}{Z_{\text{ekv}}} = \frac{A}{Z} + \frac{A_{\text{j}}}{Z_{\text{j}}} \tag{11}$$

where A_{tot} is the total area of a layer (product), which is the sum of A (area of homogeneous layer) and A_{j} (area of a joint) all of them in [m^2]. Z_{eqv} is the equivalent diffusion resistances for the layer (product) with the joint, Z is the diffusion resistance for the homogeneous layer and Z_{j} is the diffusion resistance for the joint, all in [m/s]. The diffusion resistance for joints Z_{j} is experimentally measured for each product and a type of joints (open or sealed).

As we wanted to express the sd-value of perforated products with low permeance with help of a simple equation, we plotted all

Table 6
Results of the measurements, sd-value [m], permeance [ng/(Pa·s m^2)] and permeance [perm (inch-pound)] of perforated LD PE foil.

Product – LD PE foil						
Percentage of perforation [%]	sd-value [m]		Permeance [ng/(Pa·s·m^2)]		Permeance [perm IP][a]	
	Sample 1–3	Mean (SD)	Sample 1–3	Mean (SD)	Sample 1–3	Mean (SD)
0.00000	161.4	187.6 (±19.0)	1.23	1.09 (±0.10)	0.0214	0.0191 (±0.0017)
	205.8		1.04		0.0181	
	195.7		1.01		0.0177	
0.00016	–	109.2 (±0.9)	–	1.83 (±0.03)	–	0.0319 (±0.0005)
	108.3		1.85		0.0324	
	110.0		1.80		0.0315	
0.00047	54.7	49.1 (±4.1)	3.61	4.05 (±0.32)	0.0631	0.0708 (±0.0056)
	45.2		4.37		0.0764	
	47.4		4.17		0.0729	
0.00094	32.3	30.2 (±1.6)	6.07	6.51 (±0.32)	0.1061	0.1139 (±0.0056)
	28.7		6.82		0.1192	
	29.5		6.65		0.1162	
0.00187	16.8	16.1 (±0.5)	11.63	12.13 (±0.36)	0.2034	0.2121 (±0.0063)
	15.7		12.47		0.2180	
	15.9		12.29		0.2149	
0.00374	8.6	8.5 (±0.2)	22.67	23.01 (±0.45)	0.3964	0.4022 (±0.0079)
	8.2		23.64		0.4133	
	8.6		22.70		0.3969	

[a] permeance in [perm (inch-pound)] was calculated as 1 perm [grains/(h ft^2 in·Hg)] = 57.2 ng/(Pa s m^2).

Table 7
Results of the measurements, sd-value [m], permeance [ng/(Pa s m²)] and permeance [perm (inch-pound)] of perforated LD/HD PE foil.

Product – LD/HD PE foil						
Percentage of perforation [%]	sd-value [m]		Permeance [ng/(Pa·s·m²)]		Permeance [perm IP]ᵃ	
	Sample 1–3	Mean (SD)	Sample 1–3	Mean (SD)	Sample 1–3	Mean (SD)
0.00000	571.6 813.2 601.0	661.9 (±107.7)	0.35 0.24 0.33	0.31 (±0.05)	0.0060 0.0042 0.0057	0.0053 (±0.0008)
0.00016	173.4 204.4 199.3	192.4 (±13.6)	1.13 1.00 1.05	1.06 (±0.05)	0.0197 0.0175 0.0184	0.0186 (±0.0009)
0.00047	56.3 55.0 61.2	57.5 (±2.7)	3.46 3.55 3.20	3.41 (±0.15)	0.0605 0.0621 0.0560	0.0595 (±0.0026)
0.00094	30.9 29.6 30.6	30.4 (±0.5)	6.35 6.62 6.38	6.45 (±0.12)	0.1110 0.1157 0.1116	0.1128 (±0.0021)
0.00187	14.5 13.4 13.9	13.9 (±0.4)	13.45 14.62 14.07	14.05 (±0.48)	0.2352 0.2556 0.2460	0.2456 (±0.0083)
0.00374	7.9 7.8 7.8	7.8 (±0.1)	24.50 24.87 24.83	24.74 (±0.17)	0.4283 0.4349 0.4341	0.4324 (±0.0029)

ᵃ permeance in [perm (inch-pound)] was calculated as 1 perm [grains/(h ft² in·Hg)] = 57.2 ng/(Pa s m²).

Table 8
Results of the measurements, sd-value [m], permeance [ng/(Pa s m²)] and permeance [perm (inch-pound)] of perforated bitumen membrane.

Product – bitumen membrane						
Percentage of perforation [%]ᵃ	sd-value [m]		Permeance [ng/(Pa·s·m²)]		Permeance [perm IP]ᵇ	
	Sample 1–4	Mean (SD)	Sample 1–4	Mean (SD)	Sample 1–4	Mean (SD)
0.0000	111.6 122.2 167.8 146.7	137.1 (±21.8)	1.81 1.70 1.46 1.35	1.58 (±0.18)	0.0317 0.0297 0.0255 0.0236	0.0276 (±0.0032)
0.0012	172.3 152.3 225.6 177.2	181.9 (±26.9)	1.15 1.30 0.88 1.12	1.11 (±0.15)	0.0201 0.0228 0.0154 0.0196	0.0195 (±0.0026)
0.0040	138.2 142.0 145.8 149.9	144.0 (±4.3)	1.51 1.47 1.50 1.36	1.46 (±0.06)	0.0264 0.0257 0.0262 0.0237	0.0255 (±0.0010)
0.0079	83.8 77.9 80.2 95.7	84.4 (±6.9)	2.43 2.57 2.53 2.10	2.41 (±0.19)	0.0425 0.0450 0.0443 0.0367	0.0421 (±0.0033)
0.0119	86.9 81.5 94.0 96.6	89.8 (±5.9)	2.29 2.45 2.16 2.07	2.24 (±0.14)	0.0401 0.0428 0.0378 0.0361	0.0392 (±0.0025)
0.0238	71.0 62.2 52.7 71.7	64.4 (±7.7)	2.79 3.22 3.77 3.07	3.21 (±0.36)	0.0488 0.0563 0.0659 0.0537	0.0562 (±0.0062)
0.0476	43.5 40.9 40.0 41.4	41.4 (±1.3)	4.50 4.92 4.98 4.73	4.78 (±0.19)	0.0787 0.0860 0.0871 0.0827	0.0836 (±0.0032)

ᵃ The area of perforation is calculated from diameter of pins.
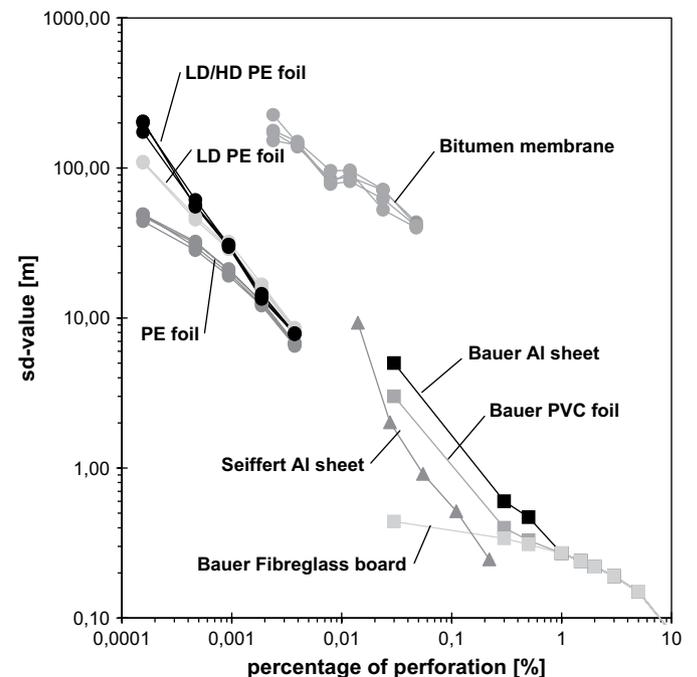ᵇ Permeance in [perm (inch-pound)] was calculated as 1 perm [grains/(h ft² in Hg)] = 57.2 ng/(Pa s m²).

our results with results from previous measurements into a logarithmic graph (Fig. 6) to see if there is some relationship.

The results show that three foils have the same curve pattern in contrast to the curves made by bitumen membranes. The curves of Bauer's measurements have very similar pattern like the foil curves only moved to the right. We outlined the curve pattern in Fig. 7, where f_1–f_4 are functions for four products with sd-values without any perforation s_{d1}–s_{d4}. The function f_t is for an impermeable product, for example aluminium sheet. The explanation of these functions can be written as follow:

$$s_{df} = \frac{1}{\left(\left(1 - f_{Ap}\right)/s_d\right) + \left(f_{Ap}/s_{da}\right)} \tag{12}$$

where s_{df} is the final sd-value for perforated product in [m], s_d is the sd-value of the product without any perforation in [m], s_{da} is the sd-value for holes (perforation) in [m] and the value is unknown and f_{Ap} is the area factor [-] that equals to:

$$f_{Ap} = \frac{A_p}{A_{tot}} \tag{13}$$

where A_p is the perforated area [m²] and A_{tot} is the total area in [m²].

In equation (12), which is an alternative expression of equation (11), the unknown is the sd-value of the perforated area s_{da} [m]. We determined this coefficient by least square regression with our results of measurements (only foils) and we got

$$s_{da} = 0.000292 \text{ m} \tag{14}$$

If we substitute equation (14) into equation (12) and compare this with the results of the measurements, the mean square correlation coefficient will be $r^2 = 0.98$ for all ten foil samples and $r^2 = 0.99$ for eight foil samples if we exclude two samples of PE foil with higher sd-values.

Fig. 6. Dependence of the sd-value on percentage of perforation. Comparison of measurement results and results from Bauer and Seiffert.
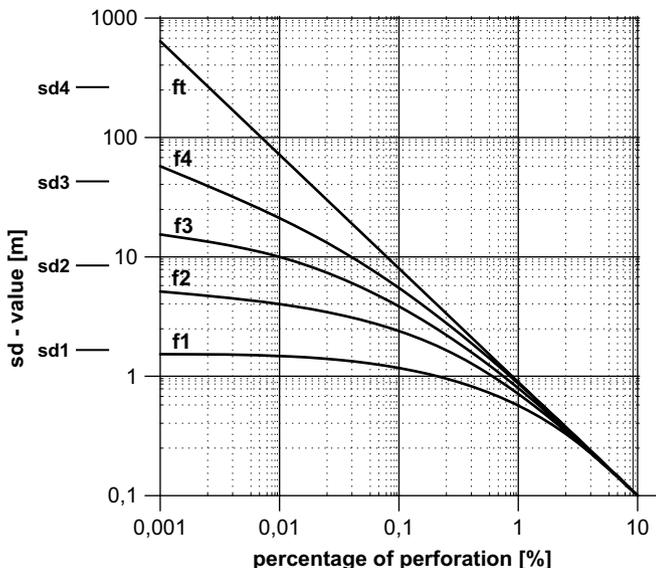
Fig. 7. Dependence of the sd-value on percentage of perforation. Curve patterns for five different materials f_1–f_t with percentage of perforation 0.001–10%.

Fig. 9. Dependence of the sd-value on percentage of perforation. Comparison of measurements and calculations (regular scale).

The comparison of measurement results with equation (12) is shown in Fig. 8 with logarithmic scales and with regular scale in Fig. 9.

7. Discussion

The results of the measurement on materials with a high water vapour resistance factor show a significant decrease in sd-values with increased perforation percentage. The decrease in the sd-value is greater for materials with higher value of water vapour resistance factor. This result is in accordance with the measurements done by Bauer [9].

We found very interesting that sd-values for the foils does not depend on the material for the percentage of perforation higher than 0.001%; all three vapour retarders (PE, LDPE, and LD/HD PE
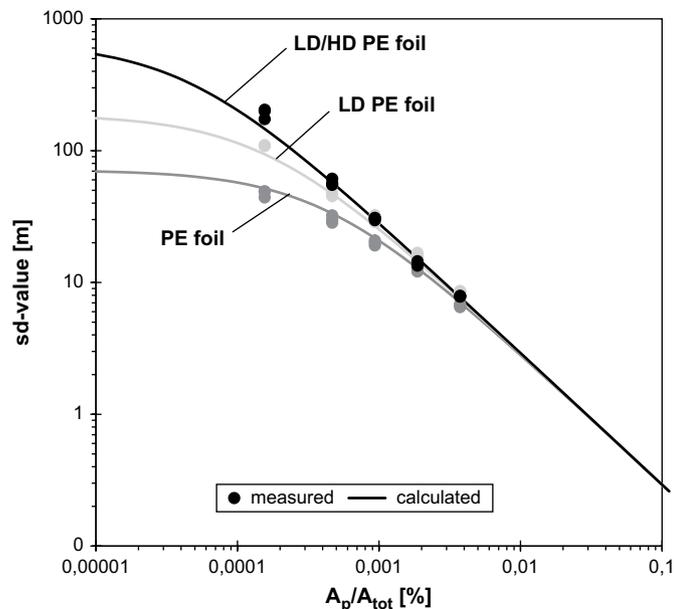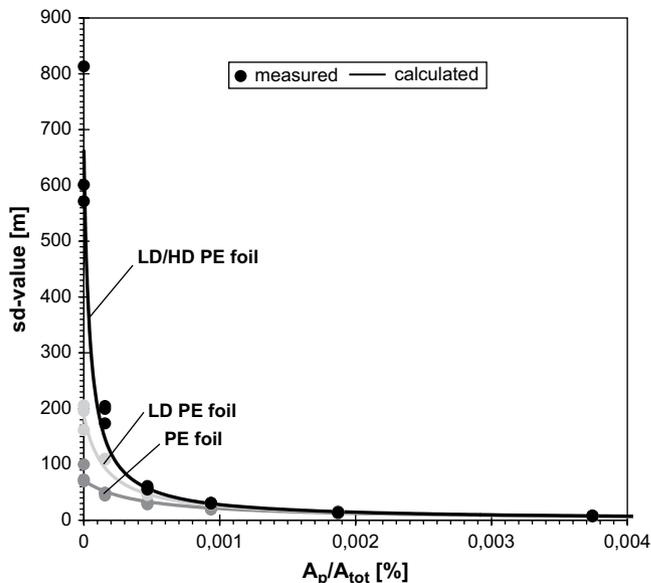
foils) have almost the same sd-value as shown in Fig. 6. On the figure, a crossing of curves (LD PE foil and LD/HD foil) can be seen. The crossing is probably due to difference in an area of pinholes. The area of pinholes (foil samples) was calculated from the average measured value for one pinhole. The measurement of the area was made, when water vapour permeability measurements finished, with the help of a microscope. The area of pinholes in bitumen samples was calculated from the diameter of the pin. In this case, the microscope could not be used because of a great thickness of samples.

The decrease in the sd-value is greater for foil membranes than for bitumen membrane. We assume that this is due to a contraction of the pinholes after perforation, but other measurements are needed. Greater adsorption of moisture was observed in the bitumen membranes compared to foil vapour retarders.The curve shape of bitumen samples varies from the curve shape of foil products probably due to the following reasons: greater adsorption of moisture, different determination of the area of pinholes or due to different contraction of pinholes.

The experimental results indicate that the test set-up provides very accurate measurements up to the sd-value of 200 m, over which the results vary more than 10% within each product. We were not able to determine the sd-value of bitumen membrane with aluminium sheet because the membrane was adsorbing more moisture than the amount of moisture being released through the samples during a time period of 100 days. Then we stopped the measurement.

The measurement results can be affected so that the cups with samples were removed from the control environment with a constant relative humidity during weighing. This process lasted approximately 60 s. This time period appears very short in contrast to the fact that the cups with the samples were place in a control environment between two weighings from 2 to 5 days, and therefore we assume this influence on the results will be insignificant.

Blind tests, which were employed during the measurements, confirmed the good sealing qualities of butyl mastic. We used three blind tests with samples of LD and LD/HD PE foils and with bitumen membrane with aluminium sheet. These blind tests ran at the same time in two glass containers showing different changes in mass. During a period of 105 days two blind tests showed increases in
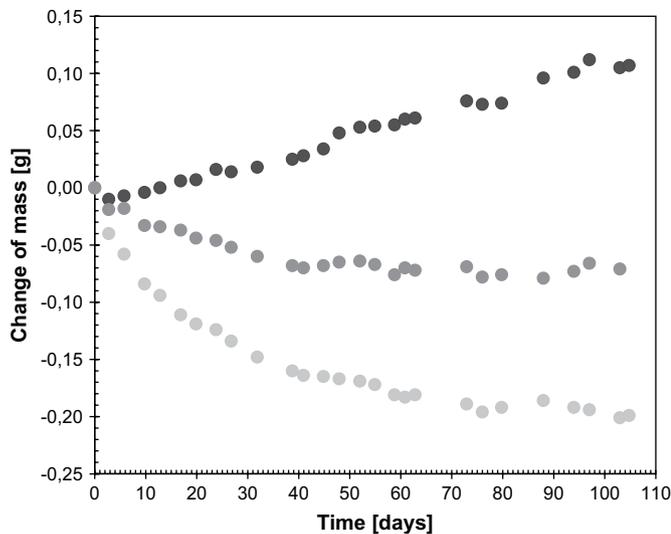

Fig. 8. Dependence of the sd-value on percentage of perforation. Comparison of measurements and calculations (logarithmic scale).

Fig. 10. Three blind tests during the measurements. Change of cup mass from the beginning of the measurement. (Mass decreases above zero and increases below zero).

mass of 0.07 g and 0.20 g and the third blind test decreased in mass by 0.11 g. This difference occurred mainly at the beginning of the measurement, Fig. 10. If we look at period between 40th and 105th day we will find the difference in mass of 0.001 g, 0.037 g and −0.077 g.

We assumed that the negative difference might be caused by a leakage and two positive differences could be caused by dirt on the surface of aluminium sheets because they had been used before for testing different sealing materials and although the sheets were cleaned, some little amount of a sealing material (bee's wax) could have remained on the surface. Due to this difference and because we did not use the blind test with each product measurement, we did not employ equation (10) for final sd-values. If we apply equation (10), for example for the LD PE foil, the results will vary mainly for no perforated samples or samples with a small percentage of perforation as can be seen in Table 9.

Due to our experience with water vapour permeability measurements of materials with great diffusion resistance, we strongly recommend to use the blind tests simultaneously with regular samples and apply equation (10) to eliminate the uncertainties of bad sealant and the buoyancy effect.

Analytical equation (12) with constant equation (14) fits very well to results of our measurements. The equation can be used to calculate the equivalent sd-value of thin low-permeable products (i.e. polyethylene foils or aluminium sheets) with perforations as holes or joints. If we compare analytical equation (12) and constant equation (14) with the results of Bauer's measurements, we will get a very good agreement (the mean square correlation coefficient is

$r^2 = 0.99$ for aluminium sheet and $r^2 = 0.97$ for PVC foil) although the sd-value of Bauer's aluminium sheet without any perforation is much lower than it should be. We assume that the low sd-value of aluminium sheet was caused by a leakage. Then, we can compare the results only based on an assumption that Bauer's aluminium sheet has diffusion properties like a product with lower sd-value.

However, the results of our measurements were done for products where air is on both sides of samples. Usually in roof assemblies, a vapour retarder is placed between two other layers. Material of these layers has lower water vapour permeability than still air and therefore the impact of the penetration will be reduced [28]. On the other hand, if a movement of air occurs in the roof assembly, the water vapour transport will be higher than the transport due to diffusion and the impact of the penetration will play more important role.

8. Conclusion

In the first part of the paper, we described some problems with simulations of moisture transport in building envelopes and what diffusion bridges are. Several improvements of the water vapour permeability measurement of products with great diffusion resistance were suggested. The most important issues are to employ simultaneously during the measurement blind tests and cups with product samples, and to use butyl mastic as the sealant.

The results of our measurement show significant increases of vapour transport through vapour retarders due to its perforation. That is the reason why perforations of a vapour retarder or diffusion bridges must be taken into account when hygrothermal behaviour of building envelope assemblies is simulated.

The analytical equation that facilitates to calculate diffusion flux through perforated low-permeable products was presented. This equation fits very well with results of the measurements and can indicate how much moisture will be transported through perforated low-permeable thin layers in real compact roof assemblies.

Acknowledgement

References

[1] Griffin CW, Fricklas RL. Manual of low-slope roof systems. New York: McGraw-Hill; 2006.
[2] Šilarová Š. Jednoplášťové střechy (Compact roofs). In: Hanzalová L, Šilarová Š, editors. Ploché střechy (Flat roofs). Prague: Informacni centrum CKAIT; 2005. p. 100–16. [in Czech].
[3] Chapter 24 – thermal and moisture control in insulated assemblies – applications, ASHRAE handbook, fundamentals. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2005.
[4] Tobiasson W. General considerations for roofs. In: Trechsel HR, editor. Moisture control in buildings. Philadelphia: ASTM; 1994. p. 291–320.
[5] EN 15026: 2007 Hygrothermal performance of building components and building elements – assessment of moisture transfer by numerical simulation. CEN; 2007.
[6] EN ISO 13788: 2001 Hygrothermal performance of building components and building elements – internal surface temperature to avoid critical surface humidity and interstitial condensation – calculation methods. CEN; 2001.
[7] Slanina P, Silarova S. Difuzni mosty (Diffusion bridges). Strechy, fasady, izolace 2006;13(4):66–7 [in Czech].
[8] Seiffert K. Messungen vom diffusionswiderstandsfaktoren (Measurements of diffusion resistance factors). Kaltetechnik 1960;12(7):187–90 [in German].
[9] Bauer W. Influence of holes on water-vapor permeability of vapor-checking surface layers. In: Symposium moisture problems in buildings. Helsinki: RILEM-CIB; 1965.
[10] Mrlík F. Vlhkostné problémy stavebných materiálov a konštrukcií (Moisture problems of building materials and structures). Bratislava: Alfa; 1985 [in Slovak].
[11] Suprenant BA, Malisch WR. Don't puncture the vapor retarder. Aberdeen's Concrete Construction 1998;43:1071–5.

Table 9
Example of applying the blind test correction due to equation (10), sd-values of perforated LD PE foil with and without the correction and relative differences of the results.

Percentage of perforation [%]	sd-value [m] without the correction		sd-value [m] with the correction		Relative differences [%]
	Mean	Standard deviation	Mean	Standard deviation	
0.00000	187.6	±19.0	168.0	±15.6	11.7
0.00016	109.2	±0.9	90.0	±0.7	21.3
0.00047	49.1	±4.1	49.5	±4.2	0.8
0.00094	30.2	±1.6	30.1	±1.5	0.3
0.00187	16.1	±0.5	15.8	±0.5	1.9
0.00374	8.5	±0.2	8.5	±0.1	0.0

[12] ASTM E 96/E 96M – 05. Standard test methods for water vapor transmission of materials. West Conshohocken: ASTM International; 2005.

[13] Zarr RR, Burch DM, Fanney AH. Heat and moisture transfer in wood-based wall construction: measured versus predicted. In: NIST building science series 173. National Institute of Standards and Technology; 1995.

[14] Hens H, Janssens A, Zheng R. Zinc roofs: an evaluation based on test house measurements. Building and Environment 2003;38:795–806.

[15] EN ISO 12572: 2001 Hygrothermal performance of building materials and products – determination of water vapour transmission properties. CEN; 2001.

[16] EN 1931: 2000 Flexible sheets for waterproofing. Bitumen, plastic and rubber sheets for roof waterproofing. Determination of water vapour transmission properties. CEN; 2000.

[17] WTA 6-2-01. Simulation of heat and moisture transfer. Munchen: WTA Publicatons; 2004.

[18] Kumaran MK, Lackey JC, Normandin N, van Reenen D. Vapor permeances, air permeances, and water absorption coefficients of building membranes. Journal of Testing and Evaluation 2006;34(3):241–5.

[19] Mukhopadhyaya P, Kumuran MK, Lackey JC, van Reenen D. Water vapor transmission measurement and significance of corrections. Journal of ASTM International 2007;4(8):1–12.

[20] Lackey JC, Marchand RG, Kumaran MK. A logical extension of the ASTM standard E96 to determine the dependence of water vapour transmission on relative humidity. In: Graves RS, Zarr RR, editors. Insulation materials: testing and applications, vol. 3. Philadelphia: ASTM STP; 1997. p. 456–70.

[21] Joy FA, Wilson AG. Standardization of the dish method for measuring water vapour transmission. In: Proceedings of the international symposium on humidity and moisture, vol. 4. Washington, DC; 1963. p. 259–70.

[22] McGlashan ML. Physicochemical quantities and units. London: Royal Institute of Chemistry; 1971.

[23] Kumaran MK. Interlaboratory comparison of the ASTM standard test methods for water vapor transmission of materials (E96-95). Journal of Testing and Evaluation 1998;26(2):83–8.

[24] Toas M. Results of the 1985 round-robin test series using ASTM E96-80. In: Trechsel HP, Bomberg M, editors. Water vapor transmission through building materials and systems. Mechanisms and measurement. Philadelphia: ASTM STP; 1989. p. 73–90.

[25] Hansen KK, Bertelsen NH. Results of a water vapor transmission round-robin test using cup methods. In: Trechsel HP, Bomberg M, editors. Water vapor transmission through building materials and systems. Mechanisms and measurement. Philadelphia: ASTM STP; 1989. p. 91–100.

[26] Time B, Uvsløkk S. Intercomparison on measurement of water vapour permeance. Oslo: Norges byggforskningsinstitutt; 2003.

[27] van der Spoel W. Water vapour transport through perforated foils. In: Carmeliet J, Hens H, Vermeir G, editors. Research in building physics: proceedings of the 2nd international conference on building physics. Leuven: Lisse, Exton, PA: A.A. Balkema; 2003. p. 207–15.

[28] Schule W, Reichardt I. Wasserdampfdurchgang durch Öffnungen (Moisture flux through holes). Sonderausgabe. Zeitschrift fur Warmeschutz. Kalteschutz, Brandscutz, WKSB; 1980 August 12–16 [in German].