MEASUREMENT OF MOISTURE TRANSPORT THROUGH PERFORATED VAPOUR BARRIERS

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SUMMARY:
In the European Standards EN 15026 and EN ISO 13788, moisture transport in building envelopes is assumed one dimensional. In fact, three-dimensional moisture transport occurs due to layer perforation or building assembly details. The article is focused on cases of flat roofs where the vapour barrier is perforated. Water vapour permeability measurement of different vapour barriers 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 barriers which are perforated. A note on setting the apparatus to measure materials with very high water vapour resistance factor is presented. Finally, based on the results we discussed new recommendations to design more efficient flat roofs and avoid future failures.

1. Introduction

Flat roof sandwich assemblies with classical order of layers (roof membrane, insulation, vapour barrier) are regularly designed and build in central and north Europe (Silarova, 2005) and also in cold regions of North America (Mehta et al., 2008). A vapour barrier is included in these assemblies to avoid excessive interstitial condensation of water vapour usually below the roofing membrane during cold seasons. Vapour barriers are designed based on calculations described in International and European Standards EN 15026 (2007) and EN ISO 13788 (2001). 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, then failure comes, the service life is shortened and the roof assembly loses its integrity.

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

- imperfect joining of material strips;
- bad connection of vapour barrier to openings;
- mechanically fastenings puncturing the roof layers;
- bad workmanship during construction;
- structure and assembly details;
- aging of sealing materials.

The main problem is with materials which have high sd-value and which are usually used for vapour barrier 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 a perforation of the vapour barrier in the roof assembly is shown in *FIG.1.* Slanina S. and Silarova S. (2006).

It is very difficult to simulate 3D moisture transport in envelope (roof) assembly Karagiozis A.N. (2001) therefore we have decided to use measurement to show how much moisture can be transported through perforated vapour barriers. Perforations can result for example from a mechanical fixing which penetrates the vapour barrier or perforation of vapour barrier due to work negligence. We focused more on flat roof assemblies where moisture transport due to convection does not occur because roofing membranes are air impermeable.

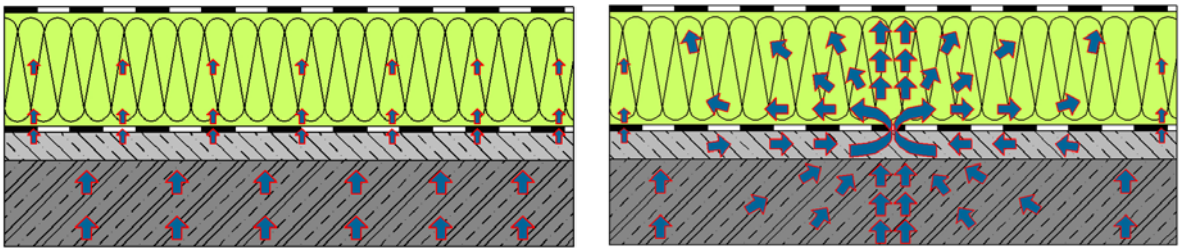

FIG. 1: 1D and 2D(3D) moisture transport in roof assembly. A diffusion bridge is demonstrated on the right.

2. Previous Work

In the past, water vapour permeability of perforated materials with high sd-value was measured by Seiffert (1960), Bauer (1965) and Mrlik F. (1985). K. Seiffert measured sd-value of 1,5 mm thick aluminium sheet with percentage of perforation from 0,01% to 0,22%. His measurements showed a significant decrease in the sd-value. W. Bauer did similar measurements. He measured sd-values of three different materials (aluminium sheet d=1mm, PVC foil, fiberglas board). The percentage of perforation for these materials was between 0,03% to 10%. His measurements show that the decrease in sd-values is greater in the case of materials with higher water vapour resistance factor (i.e. aluminium sheet). Above 1% of perforation, the sd-value does not dependent on material because all measured materials have the same sd-value with similar perforation.

The strange result of Bauer's measurement is the sd-value of aluminium sheet without any perforation because he had measured s_d = 54 m and according to standards it should be 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 Al-sheet and smaller percentage of perforation) but the result is twice higher for Bauer's aluminium sheet s_d = 5m than Seiffert's aluminium sheet s_d=2,02m. These two discrepancies make all the results uncertain.

Other similar measurements were done by F. Mrlik. He measured the sd-value of PE foil that was perforated by staples. First he measured sd-value of PE foil with staples then he pulled out the staples and measured the sd-value of PE foil again only with pinholes. A factor of 2 to 3 was found between these two measurements.

3. Measurements

3.1 Method

As we were not able to find other results and the results shown above are unclear, we had decided to perform our measurement in the laboratory of Faculty of Civil Engineering, CTU in Prague.

We use the wet-cup method as basis mechanism for our measurements. Advantages of this mechanism are: simplicity, low cost, accuracy, wet-cup method is described in several international standards (ASTM E 96/E 96M (2005), EN ISO 12572 (2001), EN 1931 (2000)), and also the conditions of the method are similar to real condition in roof assemblies. One disadvantage for the measurement is the long time period needed to get results.

The principle of the wet-cup method is to create two environments with different relative humidity (RH). RH inside a cup is 50% and RH outside the cup is 95%. Temperature is the same for both environments. Vapour flux then goes from the cup with higher RH through a sample to the environment with lower RH according to simple equation (1).

$$g_v = -\frac{\delta_a}{\mu(\varphi)} \nabla p_v \qquad (1)$$

where:

g_v water vapour flux [kgm^{-2}s^{-1}],

p_v water vapour partial pressure [Pa],

δ_a water vapour diffusion coefficient of dry air [kg Pa^{-1} s^{-1} m^{-1}],

μ water vapour resistance factor of measured material [-],which depends on moisture content.

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

$$\mu = \frac{\Delta t \; A \; \Delta p_v \; \delta_a}{\Delta m \; d} \tag{2}$$

Where:

Δt time difference between weighing with constant decrease of weight [s],

Δm weight difference between weighing with constant decrease of weight [kg],

A measured area of the sample [m^2],

d thickness of the sample [m],

δ_a water vapour diffusion coefficient in air [kg Pa^{-1} s^{-1} m^{-1}], calculated from simplified Schirmer's equation, see in WTA 6-2-0, (2004).

$$\delta_a = \frac{1{,}97 \; . \; 10^{-7} \; . \; T^{0{,}81}}{P} \tag{3}$$

where:

T absolute temperature [K],

P barometric pressure [Pa], we used constant value; P = 101325 Pa,

and

Δp_v water vapour partial pressure difference between the sides of the sample [Pa], EN ISO 13788 (2001),

$$\Delta p_v = \frac{\Delta rh}{100} \; . \; 610{,}5 \; . \; e^{\frac{17{,}269 \; . \; \theta}{237{,}3 + \theta}} \tag{4}$$

where:

Δrh different relative humidity between the sides of the sample [%],

θ constant temperature during the measurement [°C].

The equation (4) is for temperatures equal to or higher than zero degree Celsius ($\theta \geq 0$ °C). The sd-value of the sample is calculated using equation (5):

$$s_d = d \; . \; \mu \tag{5}$$

where:

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

As we measured materials with high sd-value, we assume that water vapour transfer coefficients on the both sides of the samples are insignificant and thus these coefficients are not taken into account.

Furthermore, in our calculation we did not use corrections for the sd-value calculation as are mentioned in ASTM E 96/E 96M (2005) or Mukhopadhyaya et al. (2007). These corrections are: water vapour resistance due to still air between saturated solution and specimen surface, edge mask effect and buoyancy correction. The first two corrections – water vapour resistance due to still air and edge mask effect – are insignificant in our case because the resistance due to still air is too small to compare with water vapour resistance of the samples and edge mask effect is used only for thick samples. To eliminate buoyancy effect we employed a "blind test".

3.2 Experimental set-up

The principle of 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:

1. Cup – Aluminium cups of thickness 1mm were used. The cups were painted to avoid chemical reaction with saturated solution. The surface in contact with the sample and sealing material must not be painted. Glass cups are also good but quite heavy.
2. Scale – Scale resolution 0,001g is necessary (resolution 0,0001g would be even better). A scale with resolution 0,001g was used for the results presented here.
3. Area of the sample – The area of samples should be as large as possible. Samples with measured area 0,03m^2 were used here.
4. Sealing material – The sealing material is the most important technical issue to obtain accurate measurement results as shown is several round-robin tests, e.g. Toas M. (1989) or Time B. and Uvsløkk S. (2003). Four sealing materials (silicon, bee wax, bitumen mastic and butyl mastic) were tested for half a year with help of the "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 (1mm) were used instead of samples. Butyl mastic was finally chosen from the following reasons: almost impermeable for water vapour, almost no moisture adsorbed, good adhesion, easy to fit and no chemical reactions with sample or aluminium cup.
5. Monitoring – Relative humidity and temperature outside of the cups were monitored every half an hour. RH inside of the cups was monitored only once and atmospheric pressure was monitored every time when the samples were weighed.
6. Set-up – 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. A suggestion of similar principle can be found in ASTM E 96/E 96M (2005). The final sd-value should be calculated by equation (6),

$$s_{df} = \frac{\sum s_{dn}}{n} - \frac{\sum s_{d\,i}}{i} \qquad (6)$$

where:

s_{df} final sd-value of the material [m],
s_{dn} the sd-value of each sample [m],
sd_i the sd-value of each blind test [m],
n number of samples [-],
i number of blind cups [-].

The schema of final experimental apparatus is outlined on *FIG.2* and real experimental apparatus is shown on *FIG.3*.

3.3 Procedure of Measurement

First we measured materials without any perforation. We perforated vapour barrier materials with a sharp pin after four or five weightings which had showed constant decrease of mass. Then we weighed cups with perforated samples and after four or five constant decreases of the mass per time period we perforated samples again with higher percentage of perforation and etc.

The area of the perforation was calculated from the diameter of the pin. The sample with 1, 3, 6, 12 and 24 holes were measured and sd-value was calculated. The holes evenly positioned over the surface of samples.

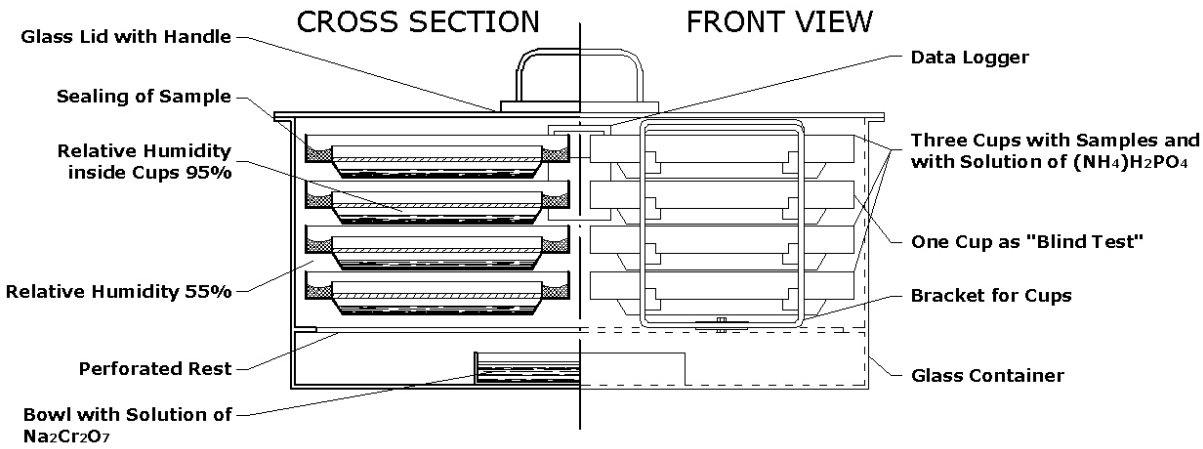

FIG. 2: Schema of experimental apparatus for water vapour permeability measurement

FIG. 3: Final experimental apparatus for water vapour permeability measurement with only one tray of cups.

4. Results of Measurement

Measurements of sd-value were made in the laboratory of Faculty of Civil Engineering, CTU in Prague on five different materials; three foil membranes and two bitumen membranes. The results of the measurement are shown in tables 1-4 and were calculated with help of equations (2)-(5).

TABLE 1: Results of the measurements, the sd-value of perforated vapour barrier – Material A

Material A: Polyethylene	Number of samples: $n = 4$	Thickness: $d = 0{,}15$ mm	Manufacturer's sd-value: $s_{dp} = 21$m
Percentage of perforation [%]	Average sd-value [m]	Standard deviation [m]	
0,0000	86,0	14,8	
0,0024	47,4	2,0	
0,0071	30,5	1,5	
0,0143	20,3	0,8	
0,0285	12,5	0,3	
0,0570	6,7	0,1	

TABLE 2: Results of the measurements, the sd-value of perforated vapour barrier – Material B

Material B: LD Polyethylene	Number of samples: $n = 3$	Thickness: $d = 0{,}22$ mm	Manufacturer's sd-value: $s_{dp} = 198$m
Percentage of perforation [%]	Average sd-value [m]	Standard deviation [m]	
0,0000	187,6	19,0	
0,0024[a]	109,2	0,9	
0,0071	49,1	4,1	
0,0143	30,2	1,6	
0,0285	16,1	0,5	
0,0570	8,5	0,2	

[a]Only two samples of Material B were calculated in this percentage of perforation

TABLE 3: Results of the measurements, the sd-value of perforated vapour barrier – Material C

Material C: LD/HD Polyethylene	Number of samples: $n = 3$	Thickness: $d = 0{,}30$ mm	Manufacturer's sd-value: $s_{dp} = 360$ m
Percentage of perforation [%]	Average sd-value [m]	Standard deviation [m]	
0,0000[a]	661,9	107,7	
0,0024	192,4	13,6	
0,0071	57,5	2,7	
0,0143	30,4	0,5	
0,0285	13,9	0,4	
0,0570	7,8	0,1	

[a]Due to lack of time only three weightings with constant decrease of mass where used to calculate the average sd-value of non-perforated Material C.

TABLE 4: Results of the measurements, sd-value of perforated roof membrane – Material D

Material D: Bitumen membrane	Number of samples: $n = 4$	Thickness: $d = 2{,}7$ mm	Manufacturer's sd-value: $s_{dp} = 130$ m
Percentage of perforation [%]	Average sd-value [m]	Standard deviation [m]	
0,0000	137,1	21,8	
0,0024[a]	181,9	26,9	
0,0056[b]	144,0	4,3	
0,0113[b]	84,4	6,9	
0,0169[b]	89,8	5,9	
0,0338[b]	64,4	7,7	
0,0675[b]	41,4	1,3	

[a]A hot pin(ø =0,975 mm) was used to perforate samples.
[b]A hot pin(ø =1,26 mm) was used to perforate samples.

Another bitumen membrane with thin Aluminium sheet was also measured. To determine the steady state of water vapour flux through the membrane was impossible during period of two months and thus the measurement was stopped.

5. Discussion of Results

The results of the measurement show a significant decrease in sd-values of materials which have high water vapour resistance factor and which are perforated. 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 in Bauer (1965).

We found very interesting that sd-values for foils (Material A,B and C) does not depend on the material for percentage of perforation higher than 0,03%; all three vapour barriers have almost the same sd-value, see in *FIG.4.*

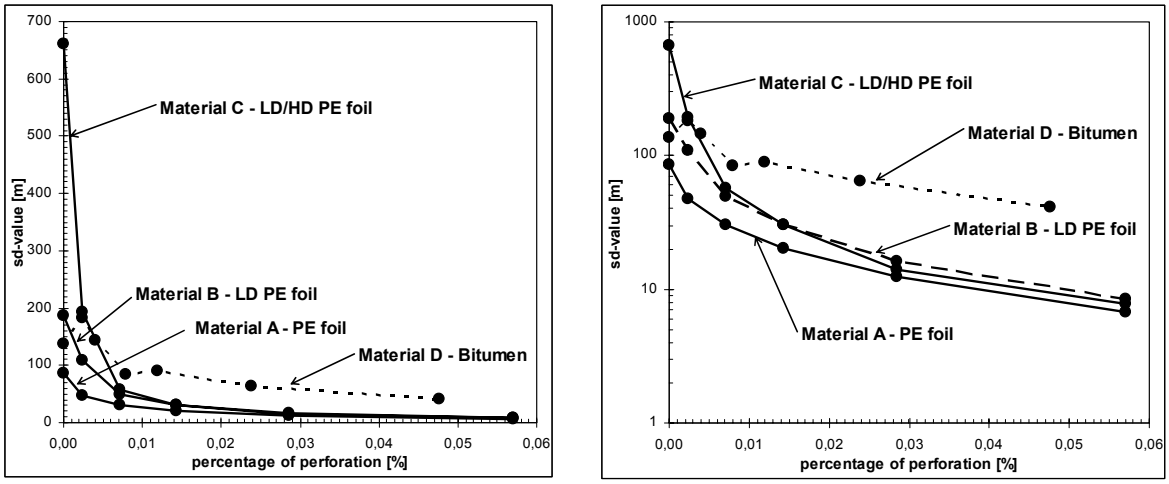

FIG. 4: Dependence of sd-value on percentage of penetration – regular, logarithmic scale

On the right side of *FIG.4* can be seen a crossing of curves (Material B and Material C). The crossing is probably due to difference in an area of pinholes. The area of pinholes has not been checked for example by a microscope.

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. Great adsorption of moisture was observed in the bitumen membranes unlike foil vapour barriers. The adsorption and the fact that to perforate bitumen membranes is more difficult – we had to use a hot sharp pin – probably caused that the curve of bitumen membrane (Material D) is not so smooth.

The results show exact measurement up to 200m of sd-value. The results above this level are varied more than 10%. Blind tests that were employed during the measurements confirmed the good sealing quality of butyl mastic. We used three blind tests with samples of Material B, C and with bitumen membrane with aluminium sheet. These blind tests ran in the same time in two glass containers showed different changes in weight. During a period of 105 days two blind tests showed increase in weight 0,07g and 0,20g and the third blind test decreased in weight 0,11g. This difference was mainly caused at the beginning of the measurement. If we look at period between 40^{th} and 105^{th} day we will find the difference in weight 0,001g, 0,037g and minus 0,077g. We assumed that the difference was caused by dirt on the surface of aluminium sheets because the sheets had been used before for testing of different sealing materials. Due to this difference we did not employ the equation (6) for final sd-values.

6. Conclusion

We described in the first part of the paper some problems with simulation of moisture transport in building envelopes and what diffusion bridges are. Some recommendations on how to measure water vapour permeability of materials with high sd-value were provided. The most important points are to use the setup of cups with samples and cups as a blind test and as the sealing to use butyl mastic.

The results of our measurement show significant increases of vapour transport through vapour barriers due to a small percentage of perforations and that is the reason why a perforation of a vapour barrier and multidimensional moisture transport must be taken in an account when a simulation of moisture transport is done in building envelope assemblies especially when it is known in advance that the multidimensional moisture transport will occur (e.g. mechanical fixing, building details).

7. Acknowledgement

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