A novel and flexible test setup to measure the vapour diffusion resistance of building materials and wall components

Evy Vereecken^{1,*}, Wouter Van De Walle¹, and Staf Roels¹

¹KU Leuven, Department of Civil Engineering, Building Physics Section, Kasteelpark Arenberg 40, 3001 Leuven, Belgium

Abstract. A novel test setup and procedure to measure the vapour diffusion resistance of building materials and components are presented. In this test setup, a vapour flux across the test sample is induced by cooling down one of the sample's surfaces by a cooling plate. The cooling plate also acts as a vapour tight plane and hence condensation is created. The vapour diffusion resistance is, via a Glaser-based calculation, inferred from the mass of condensation. Benefits of the novel procedure are its applicability to building components such as masonry, CLT, etc., and its larger flexibility in respect to the boundary conditions. The non-isothermal approach allows the induction of a large (and thus measurable) vapour flux while a quasi-constant relative humidity across the sample can be imposed. In the paper, the novel method is validated based on a bituminous impregnated fibreboard with known diffusion resistance. Thereafter, the method is applied to a masonry wall, showing the importance of diffusion measurements on the component level.

1 Introduction

The vapour diffusion resistance of building materials plays a key role in the moisture balance of building components as it determines the risk on interstitial condensation, the drying rate of the building envelope, etc. Hence, a reliable moisture evaluation requires the determination of this material property. Traditionally, the vapour diffusion resistance of porous materials is measured by the cup test specified in European and American standards [1,2]. In those measurements, the test sample acts as the lid of a cup positioned in a chamber at a constant temperature (standard equal to 23°C) and a fixed pre-defined relative humidity. By use of a saturated salt solution, another relative humidity is created in the cup, imposing a vapour pressure difference across the test sample. The vapour flux through the test sample is measured over time by weighing at discrete time steps the mass in-or decrease of the cup with inclusion of the test sample. This way, the vapour diffusion resistance of the test sample can be inferred based on Fick's first law of diffusion.

Although applied in many projects [3,4], the cup test has a number of drawbacks. For instance, when measuring more bulky samples such as masonry or Cross Laminated

* Corresponding author: Evy.Vereecken@kuleuven.be

Timber, the cups are too small. Using larger cups is possible; though, this would have a negative impact on the accuracy. Therefore, this paper presents a novel and flexible test setup and procedure, further referred to as the condensation method, that can be applied to measure the diffusion resistance of larger samples. The paper is organised as follows. Section 2 first presents the test setup and procedure. Next, in Section 3 the method is validated for a bituminous impregnated fibreboard with known vapour diffusion resistance. Here, also the benefits of a.o. the method's non-isothermal character, making the method also of use for homogeneous building materials, are explained. In Section 4, the method is applied for the determination of the vapour diffusion resistance of a masonry wall. Finally, in Section 5, the main conclusions are drawn.

2 Test setup and procedure

2.1 Test setup

The novel test setup consists of (1) a frame that holds the test sample in place, (2) a hot box and (3) a cooled plate fixed to a second box (Figure 1). In the hot box (Figure 1b), the temperature is controlled by use of a 60W infrared bulb. The relative humidity is controlled by use of saturated salt solutions. A small fan in the hot box ensures the mixing of air. At the other side of the test sample (Figure 1c), an aluminium plate is cooled down by two Peltier elements and in this way a reduced surface temperature is imposed (Figure 1d). This plate also acts as a vapour tight plane and hence condensation is created. For reasons of stability and ease of use the cooled plate is fixed to a second box. On top of the cooled plate a plexiglass cup is glued by use of a heat sink compound. A blotting paper is folded in the shape of this cup and filled with a layer of mineral wool (Figure 1e). Next, blotting paper and mineral wool are positioned in the plexiglass cup (Figure 1f). This way, the blotting paper can buffer the condensation, while the layer of mineral wool between blotting paper and test sample avoids condensation in the test sample. To minimize heat and vapour leakages from and to the laboratory, sealing strips and a layer of mineral wool are provided next to the cooled aluminium plate (Figure 1d,f). Similarly, sealing strips are applied at the end faces of the plexiglass cup. To check the efficiency of those strips and to reckon the impact of potential leakages, a calibration measurement was performed by replacing the test sample by a vapour tight plexiglass sample. For a temperature of 1.5°C at the cooled plate,

Fig. 1. Schematic view of the test setup with a real view of (a) the closed test setup, (b) the hot box, (c) the test sample, (d) the cooled plate, (e) the blotting paper, (f) the plexiglass cup with mineral wool layer and blotting paper.

an additional condensation flow of 0.46 g per day was measured.

To log the conditions in the hot box, at the sample's surface and at the cooled plate, relative humidity sensors and thermocouples are used. At regular time steps, the test frame together with the hot box can be shifted backwards to get access to the blotting paper. This way, the mass increase of the blotting paper - and thus the mass of condensation induced during the measurement - can be measured.

2.2 Glaser principle

To infer the vapour diffusion resistance, the Glaser principle can be applied. The Glaser diagram for a typical measurement with the test setup (with a mineral wool layer) as described in Section 2.1 is schematically shown in Figure 2. The condensation plane is obtained between the mineral wool and the cooled plate. For steady-state boundary conditions, without the initial hygroscopic (un)loading of the test sample, the condensation flow g_c (kg/m²s) can be calculated as:

$$g_c = \frac{p_{HB} - p_{sat,c}}{\frac{1}{\beta_{HB}} + Z_{sample} + Z_{MW}} \quad (1)$$

with p_{HB} the vapour pressure in the hot box (Pa), $p_{sat,c}$ the saturated vapour pressure at the condensation surface (Pa), β_{HB} the moisture transfer coefficient at the warm side of the test sample (s/m), Z_{sample} the diffusion resistance of the test sample (m/s) and Z_{MW} the diffusion resistance of the mineral wool layer (m/s) (if present). Here, $Z_{MW/sample}$ is equal to:

$$Z_{MW/sample} = \mu_{MW/sample} \cdot N \cdot d_{MW/sample} \quad (2)$$

with μ the vapour diffusion resistance (-), N the diffusion constant ($\approx 5.4 \cdot 10^{-9} \text{ s}^{-1}$) and d the thickness (m). By rewriting Eq.(1), the diffusion resistance of the sample can be inferred as:

$$Z_{sample} = \frac{p_{HB} - p_{sat,c}}{g_c} - Z_{MW} - \frac{1}{\beta_{HB}} \quad (3)$$

Fig. 2. Glaser diagram for a test sample in the test setup when a mineral wool layer is applied.

3 Validation

3.1 Test sample and conditions

To validate the test method, the diffusion resistance of a bituminous impregnated fibreboard was determined and compared to the results obtained via the standard cup test. A bituminous impregnated fibreboard was chosen because of its rather low moisture capacity and therefore rather constant vapour diffusion resistance. The condensation measurement will be described below; for the KU Leuven cup test assembly the reader is referred to [5].

The condensation measurement was performed for three sets of boundary conditions (see Table 1) in order to determine the vapour diffusion resistance in different relative humidity ranges. The test was performed on a 44 cm by 44 cm test sample composed of 2 fibreboards with a thickness of 18 mm each. The choice to work with a combination of two samples was made in order to reduce the mass of condensation expected in the blotting paper, and in this way, to avoid that the moisture buffer capacity of the blotting paper would be inadequate for more severe test conditions with a large condensation flow. Though, for less severe conditions a smaller thickness could have been beneficial, as a low mass of condensation might result in a larger impact of air leakages or other inaccuracies.

The test sample was hold in place by four slats with a width of 1 cm. The exposure surface of the test sample hence measured 42 cm by 42 cm. The edges were sealed with a vapour tight tape to avoid additional air and vapour paths from the hot box to the cooled plate. Between the test sample and the cooled plate a mineral wool layer with a thickness of 2.5 cm was placed.

Table 1. Boundary conditions and mean relative humidity in the test sample in the validation test.

	T_{HB} (°C)	RH_{HB} (%)	T_{CP} (°C)	p_{HB} (Pa)	p_{CP} (Pa)	$p_{HB}-p_{CP}$ (Pa)	Mean RH sample (%)
Test 1	31.8	38.5	6.1	1812.8	942.7	870.1	49.1
Test 2	35.0	54.0	2.0	3040.4	706.1	2334.3	58.3
Test 3	19.5	81.4	11.1	1848.7	1323.5	525.2	86.3

3.2 Experimental output

Figure 3a shows the mass of condensation weighed at the different measurement times. The slope of the regression line of the data points during steady-state behaviour indicates the mass of condensation per day, and is proportional with the difference in vapour pressure between the hot box and the cooled plate (see Table 1). This condensation flow was (after conversion in kg/m²s) used in Eq.(3) to determine the vapour diffusion resistance. For the mineral wool layer, μ_{MW} was assumed to be equal to 1.2 and the moisture transfer coefficient β_{HB} was calculated via $[27+0.73(T_{HB}-T_{si})]\cdot10^{-9}$ with T_{si} the surface temperature at the warm side of the test sample, as given in [6]. A correction of the masked edge was made as described in [1]. The calculated μ -values are shown in Figure 3b, and this as a function of the mean relative humidity in the test sample. In the low relative humidity range, the vapour diffusion resistance is expected to be constant. Hence, the results obtained at a relative humidity around 50% can be compared to those at 33%. For Test 1 (see Table 1), a good agreement with the results of the cup test is found in this range. For

Test 2 (see Table 1), a μ -value in the same order of magnitude is achieved. This result is expected to be more plausible than the μ -value measured by the cup test at $RH_{\text{mean}} = 72\%$, as an increase of the μ -value with increasing relative humidity is physically unrealistic. For Test 3 (see Table 1), again a good agreement with the results of the cup test is obtained.

In addition to the μ -values, error bars in Figure 3b indicate the range in relative humidity across the test sample. As can be observed, the range in relative humidity across the test sample in the condensation measurements is smaller than in the standard cup tests. And this, while the driving force in the condensation method, i.e. the difference in vapour pressure (see Table 1), is in general larger for the condensation measurements. In the cup test, the vapour flux through the test sample is induced by the difference in relative humidity at both sides of the sample only. Hence, the gradient in relative humidity in the standard cup test is needed to obtain a measurable vapour flux. However, for samples with a μ -value that is highly moisture-dependent, such a gradient can induce inaccuracies when simply assigning the measured μ -value to the sample's mean relative humidity. In the condensation method, this problem can be avoided, as a large (and thus measurable) condensation flow can be induced while the test sample is exposed to a (nearly) constant relative humidity. This (nearly) constant relative humidity can be achieved due to the more flexible boundary conditions in the test method, i.e. the non-isothermal character (not only the relative humidity in the hot box, but also the temperature in the hot box and of the cooled plate can be adjusted) and the possibility to include an insulation layer between the test sample and the cooled plate. Additionally, this higher flexibility in respect to the boundary conditions makes it possible to enlarge the condensation flow and thus to reduce the measurement time. This way, the condensation method becomes also of use to measure the vapour diffusion resistance of homogeneous building materials.

Fig. 3. Experimental output for the bituminous impregnated fibreboard: (a) mass of condensation at the different measurement steps, (b) μ -value as a function of relative humidity. The boundary conditions in the three condensation tests are given in Table 1.

4 Application: diffusion resistance of a masonry composite

4.1 Test sample and conditions

In a next step, the test procedure is applied to measure the diffusion resistance of a 1.5-stone thick masonry composite with a thickness of 29.5 cm. The test wall was composed of Vandersanden Robusta bricks (209 mm x 101 mm x 51 mm) and lime mortar (ratio: 10 liter H_2O , 12.5 kg lime St. Astier NHL3.5 and 50 kg River sand 0/2). The μ -value of the brick as

measured in an in-house cup test ranged between 9 (wet cup value at $RH_{\text{mean}} = 90\%$) and 13 (dry cup value at $RH_{\text{mean}} = 33\%$). For the (mould cured) mortar, values between 9.6 (wet cup value at $RH_{\text{mean}} = 90\%$) and 15.6 (dry cup value at $RH_{\text{mean}} = 33\%$) were obtained. The masonry test sample had a height and width of 44 cm. The sides were sealed with 1 cm tape, resulting in an exposure surface of $42 \times 42 \text{ cm}^2$. The mortar joints had a width of 1 till 1.2 cm. A 2.5 cm mineral wool layer was placed between the test sample and the cooled plate. In the hot box, a relative humidity of approximately 64% was imposed. The temperature in the hot box and at the cooled plate were respectively set at 30°C and 1.6°C .

4.2 Experimental output

The vapour diffusion resistance was determined as described in Section 3.2. Across the masonry wall a relative humidity between 40.7% and 78.8% was obtained. The μ -value obtained via Eq.(3) was 3.24, and thus lower than measured for the individual brick and mortar. Air voids and compaction pores near the brick-mortar interface possibly lie at the basis of this behaviour.

5 Conclusions

A test setup and procedure to measure the vapour diffusion resistance of building components is presented. In the method, the vapour diffusion resistance is, via a Glaser-based calculation, inferred from the induced mass of condensation. For a bituminous impregnated fibreboard, in general, the results obtained via the condensation method were in good agreement with results obtained via a standard cup test. Moreover, the more flexible boundary conditions in the condensation method made it possible to reduce the range in relative humidity across the test sample and for the range around 70% relative humidity a more realistic outcome was achieved than measured with the cup test. From this point of view, the method is also of use for the determination of the vapour diffusion resistance of homogeneous building materials. In a next step, the method was applied to a masonry test wall. For this wall, the vapour diffusion resistance was found to be lower than measured for the individual brick and mortar materials. This shows the importance of diffusion measurements on the component level.

Evy Vereecken is a postdoctoral fellow of the Research Foundation (FWO) - Flanders, Belgium (FWO project 12J5219N). This financial support is gratefully acknowledged.

References

1. EN ISO 12572:2001.
2. ASTM E 96-05. American Society for Testing and Materials, Vol. 14.06 (2005).
3. S. Roels, J. Carmeliet, H. Hens, O., et al., *J Thermal Env Bldg Sci* **27**, 307-325 (2004).
4. L. Kuishan, Z. Xu, G. Jun, *J Build Phys* **32**, 355-370 (2009).
5. S. Roels (ed.), *Annex 41 MOIST-ENG Subtask 2: Experimental analysis of moisture buffering*, ISBN 978-90-334-7058-5 (2008).
6. H. Hens, *Building Physics – Heat Air and Moisture: Fundamentals and Engineering Methods with Examples and Exercises*. Wiley, Ernst & Sohn, Second Edition (2012).