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by

Hicham Johra

July 2023

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1. Foreword

The aim of this lecture note is to present the first prototype of an air permeameter for porous building material built at Aalborg University, Department of the Built Environment. This air permeameter setup is primarily intended for porous insulation materials but could be used for all types of materials fitting the sample frame.

This lecture note also provides guidelines to operate this air permeameter and perform a state-of-the-art measurement of the effective air permeability.

2. Introduction: the effective air permeability

For porous materials, the effective air permeability [m^2] is the ability of a medium to allow the flow of air through it when a pressure difference is applied on both sides of that medium. The higher the effective air permeability, the higher the flow of air through the material for a given pressure difference.

The effective air permeability is related to the porosity and tortuosity of the pores in a material. For building materials, the effective air permeability will typically decrease when the density of the material increases (see **Figure 1**).

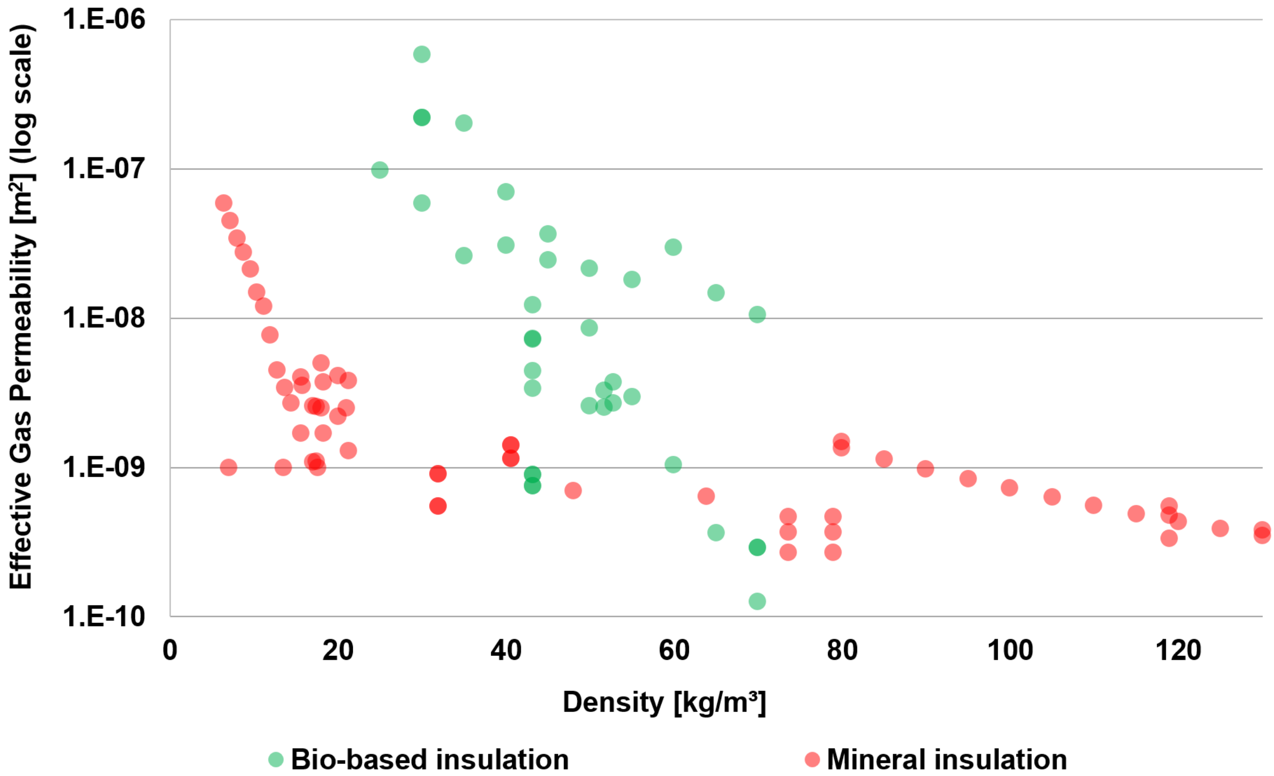

Figure 1: *Effective gas (air) permeability as a function of density for porous insulation building materials [1].*

The effective air permeability can be directly measured with an air permeameter by measuring the pressure difference across a test sample as a function of the airflow through the latter. The effective air permeability (commonly denoted "K" [m^2]) can then be calculated with the following equation that derives from Darcy's law:

$$K = \frac{\dot{V} \cdot \mu \cdot L}{A \cdot \Delta p}$$

Where:
K: Effective air permeability [m^2].
$\dot{V}$: Volumetric airflow rate [m^3/s].
μ: Dynamic viscosity of the air (fluid passing through the sample) [Pa.s]. The dynamic viscosity of air at standard room conditions is 1.84E-05 Pa.s.

L: Thickness of the test sample (dimension in the direction of the airflow) [m].
A: Cross-sectional area of the material test sample perpendicular to the direction of the airflow [m^2].
Δp: Pressure difference across the material test sample [Pa].

The equation assumes laminar flow conditions and applies to isotropic porous materials.

3. Description of the effective air permeability measurement setup

The permeameter is composed of two main parts: the extraction fan with airflow measurement (orifice plate) and the sample frame box in which the test sample is mounted (see **Figure 2**). The top of the box is open, meaning there are no constraints on the boundary conditions above the test sample. It is assumed that the test is performed inside a building (laboratory) without a draft above the test sample.

Figure 2: *Overview of the experimental setup for measuring the effective air permeability.*

The operating principle of the permeameter is relatively simple: the air is extracted by a fan (**Figure 3 a**). A pressure difference thus builds up on each side of the test sample (**Figure 3 b**), inducing airflow through the latter. The airflow is measured by an orifice plate (**Figure 3 c**). The pressure gradient through the test sample is measured as the pressure difference between the sample's top and bottom (**Figure 3 d**). An airflow straightener made of plastic straws is placed between the extraction fan and the orifice plate (**Figure 3 e**) to avoid turbulences from the fan, which could disturb the airflow measurement by the orifice plate. Another airflow straightener is placed right after the junction between the duct and the box, in addition to a long duct between the orifice plate and the box to ensure a straightened airflow before the orifice plate.

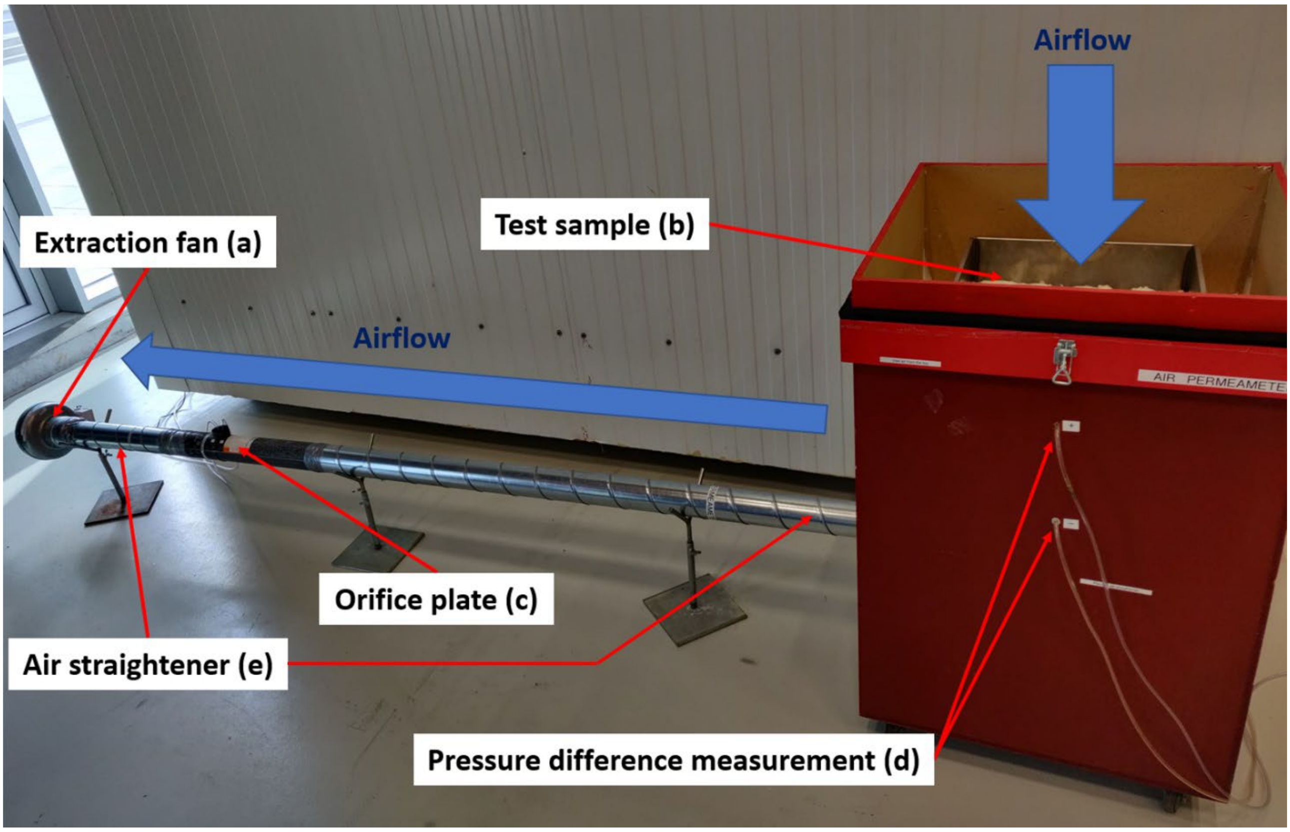

Figure 3: *Elements of the air permeameter.*

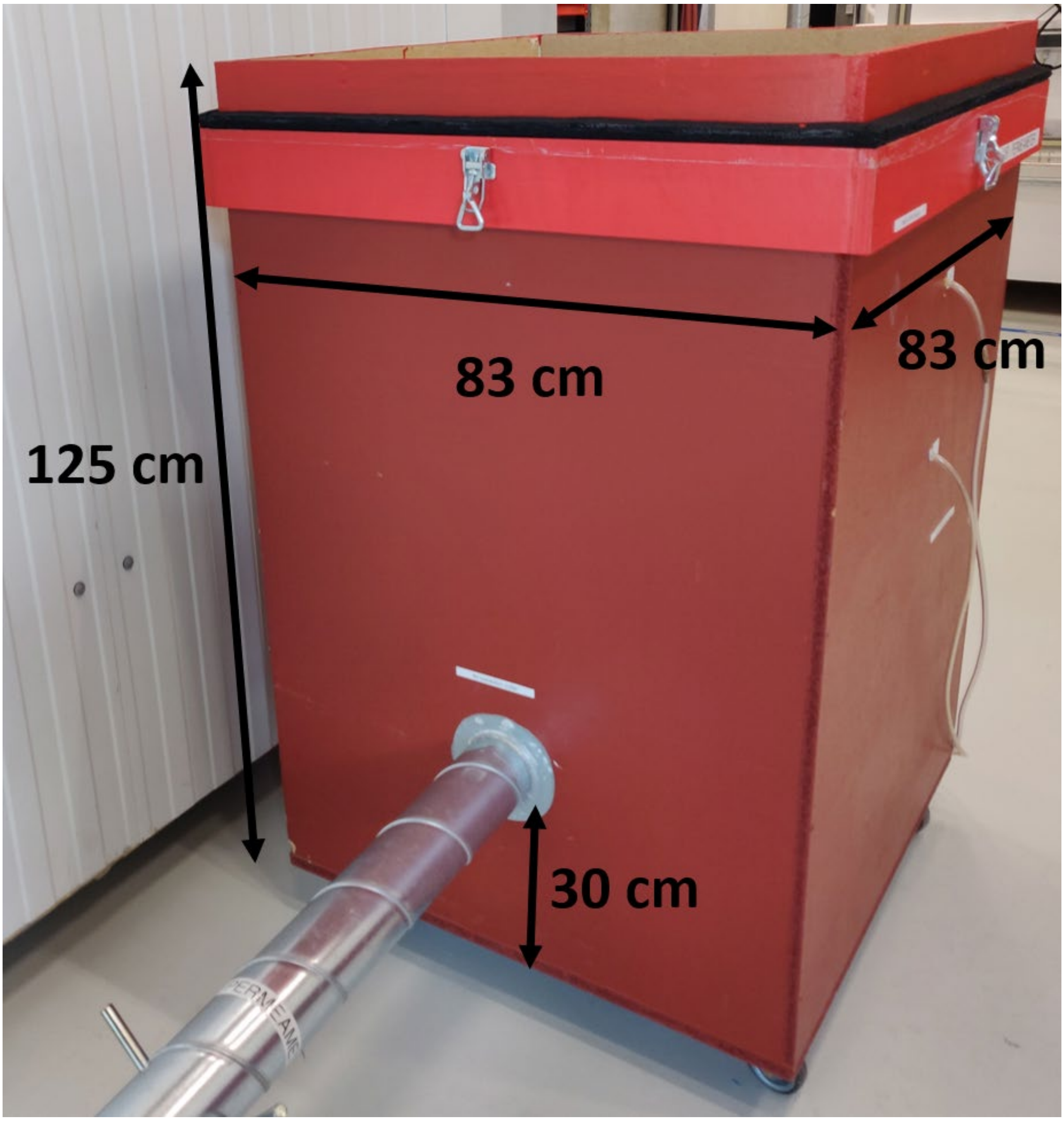

Figure 4: *Dimensions of the air permeameter setup.*

The bottom part of the permeameter's box comprises two plenums (lower plenum and upper plenum) divided by a dense fabric layer of around 2 cm in thickness (see **Figure 5**). This 2-plenum configuration ensures a straightened airflow through the test sample. The test sample is placed inside a cubical sample holder metal frame (50 x 50 cm squared section and 20 cm height) (see **Figure 6** and **Figure 7**). The sample holder metal frame is held in place and tightened to the upper plenum by expanding foam bands compressed by 4 sealing bars. The sealing bars can be tightened by tightening screws (see **Figure 8** and **Figure 9**). The bottom part of the sample holder metal frame is a coarse metal grid to hold the test sample in place. The interface between the upper plenum and the sample holder metal frame is also a coarse metal grid. Those two metal grids do not add any additional air resistivity to the test sample.

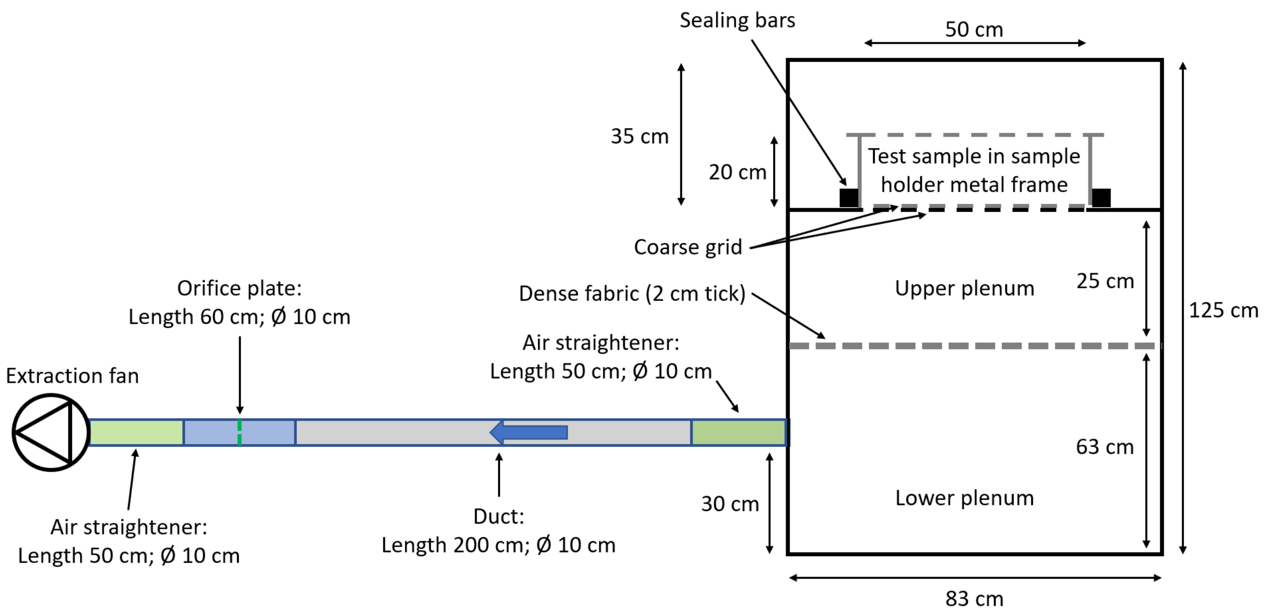

Figure 5: *Dimensions of the air permeameter setup.*

The orifice plate used to measure the airflow through the test sample is a calibrated orifice plate type EHBA-010-1 (Fläkt: AB Svenska Fläktfabriken) with an operating range spanning from 0.015 m^3/s to 0.048 m^3/s and a measurement uncertainty of ± 5% (3σ confidence interval).

The calibration formula to convert the pressure difference measurement on each side of the orifice plate into airflow rate is as follows (assuming the air density to be ρ = 1.2 kg/m^3):

$$\dot{V} = 0.0034731103 \times \sqrt{\Delta p}$$

Where:
$\dot{V}$: Volumetric airflow rate through the orifice plate [m^3/s].
Δp: Pressure difference across the orifice plate [Pa].

Figure 6: *Test sample (glass wool mat) inserted in the sample holder metal frame.*

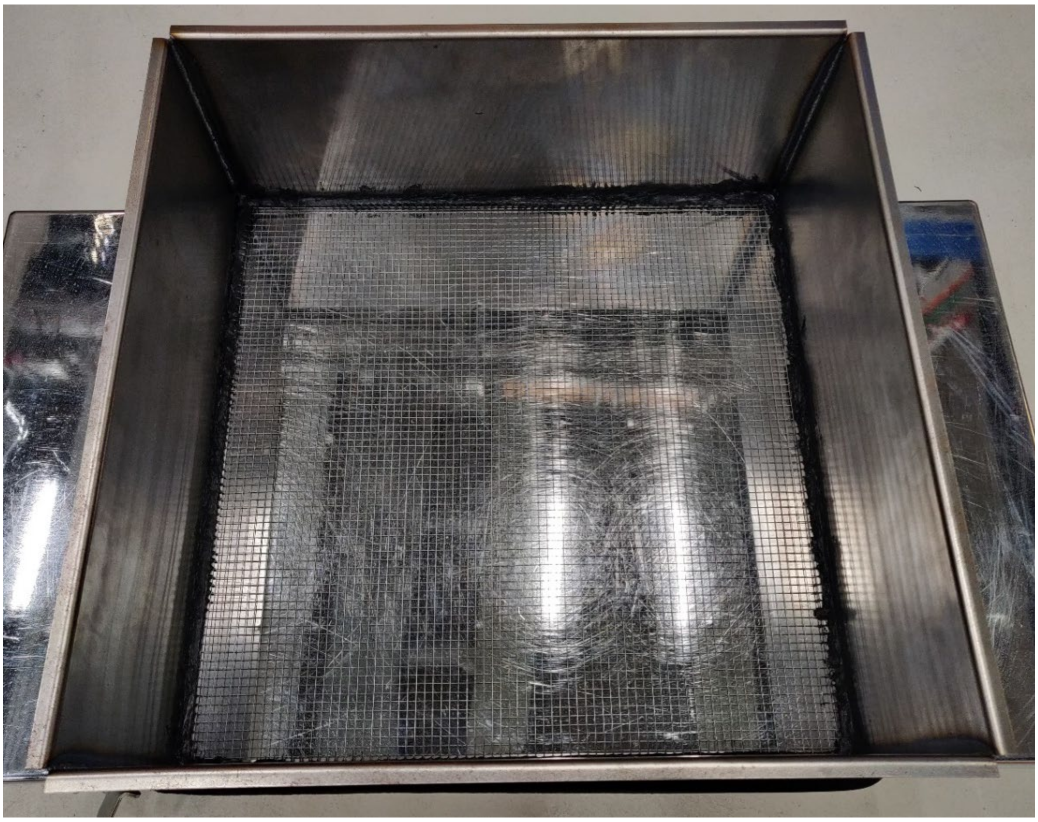

Figure 7: *Sample holder metal frame without any test sample.*

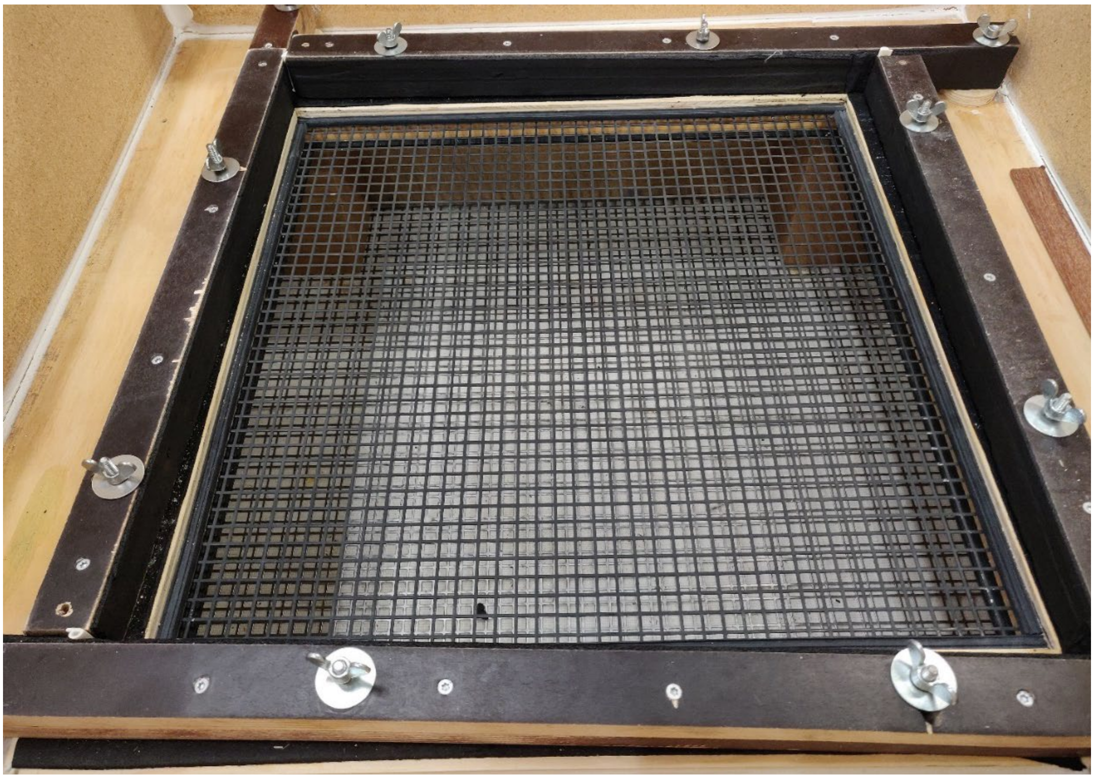

Figure 8: *Connection of the sample holder metal frame to the upper plenum.*

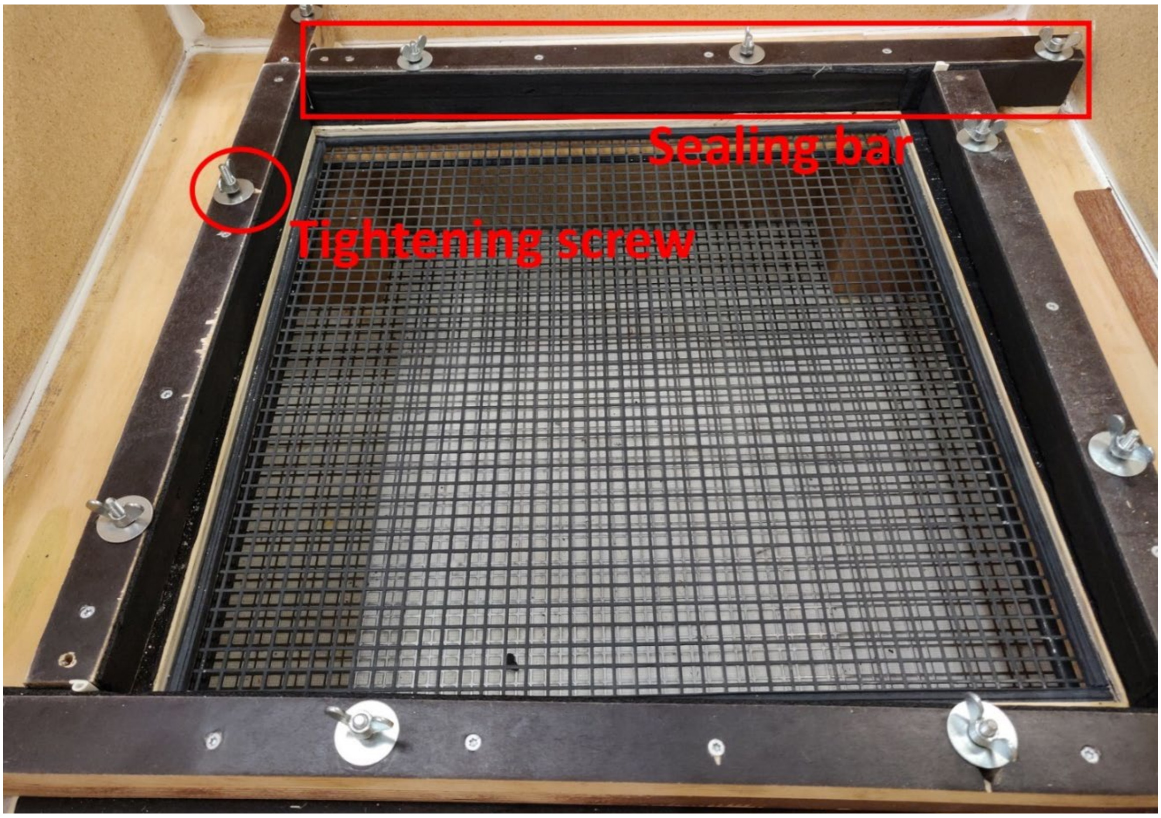

Figure 9: *Sealing bars and tightening screws to maintain the sample holder metal frame onto the upper plenum.*

The measurements of the pressure difference at the orifice plate and the pressure gradient through the test sample are performed with an FCO510 Micromanometer (Furness Controls Limited) (see **Figure 10**). The maximum pressure difference that the micromanometer can measure is 240 Pa. It is recommended to perform all measurements in auto-range mode, differential pressure mode, with measurements in Pa and a running average of 60 seconds. After changing the fan speed, wait for 1 minute then run the measurement with running average and wait for another 1 minute before recording the micromanometer measurement.

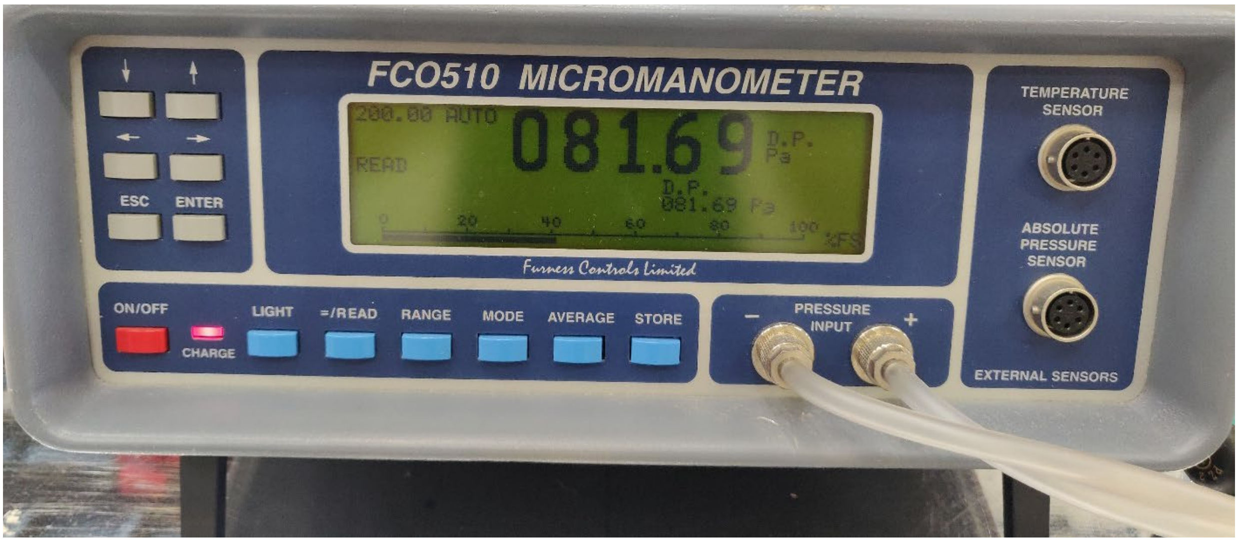

Figure 10: *FCO510 Micromanometer used to measure the pressure difference at the orifice plate and on both sides of the test sample in the air permeameter setup.*

4. Air permeability setup calibration

An air leakage test was performed to assess the sealing effectiveness around the sample holder metal frame. The residual air leakage through the sealing of the sample holder metal frame can thus be subtracted from the airflow measurement of a permeability test to accurately estimate the sample's effective air permeability.

To perform this air leakage test, the sample holder metal frame is attached to the permeameter, tightened, and the top of the sample holder is enterally closed with high-performance sealing tape used for blower door tests in buildings (see **Figure 11**).

Figure 11: *Sealing of the top side of the sample holder metal frame for the air leakage test of the entire air permeameter.*

The residual air leakage is measured for pressure difference through the sample in the sample holder metal frame ranging from 0 to 180 Pa (see **Figure 12**).

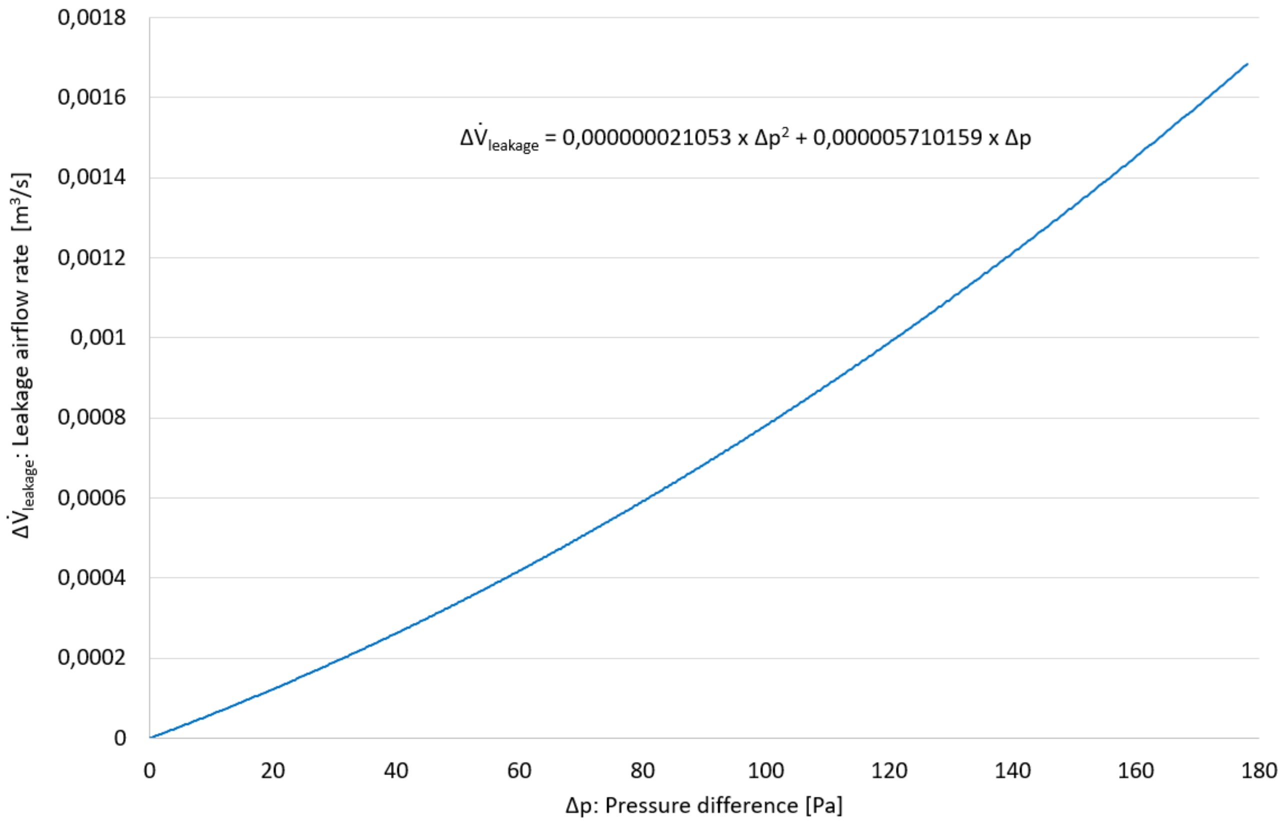

Figure 12: *Air leakage flow rate as a function of pressure difference through the test sample placed in the sample holder metal frame.*

The airflow rate measured during an air permeability test should thus be corrected (subtracting the leakage airflow from the measured airflow for a given pressure difference through the test sample) with the following formula:

$$\Delta\dot{V}_{leakage} = 0.000000021053 \times \Delta p^2 + 0.000005710159 \times \Delta p$$

5. Setup validation

The effective air permeability measurements of this air permeability setup for porous insulation materials have been compared to similar experimental setups from other research institutes. The results of this air permeameter are in very good agreement with that of the other institutes.

6. Performing an air permeability measurement

In order to perform a correct measurement with the air permeameter, follow the steps described hereafter.

Place the test sample in a sample holder metal frame. Ensure that the sample is flat without gaps between the sample and metal frame (see **Figure 13** and **Figure 14**)

Figure 13: *Test sample (glass wool mat) inserted in the sample holder metal frame.*

Figure 14: *Ensuring no air gap between the test sample and the sample holder metal frame.*

Untighten the tightening screws and open the sealing bars (see **Figure 14**).

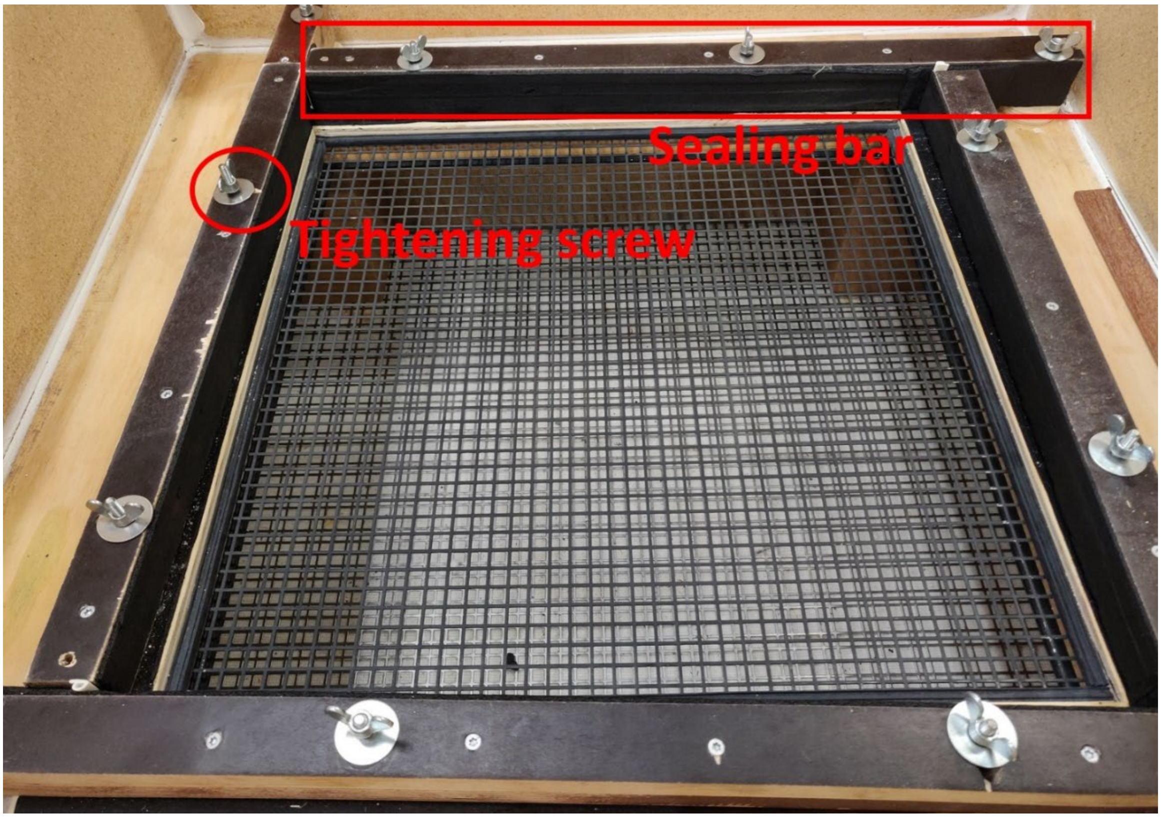

Figure 15: *Sealing bars and tightening screws to maintain the sample holder metal frame onto the upper plenum.*

Place the sample holder metal frame onto the box. Push on the top of the metal frame to make sure it is well in place against the bottom rubber bands.

Ensure that the expanding foam bands of the metal frame are pushed in (downwards) to be squeezed between the metal frame and the inner side of the sealing bars.

Seal the sample holder: push the sealing bars and tighten the sealing screws. Use a piece of wood to press onto the bar while tightening the screws (see **Figure 15**).

Figure 16: *Push on the sealing bars and tighten the tightening screws on each of the 4 sides of the sample holder metal frame.*

Once the sample holder is properly mounted onto the permeameter box, the measurement can commence. The pressure difference measurement at the orifice plate and on both sides of the test sample is performed with the FCO510 Micromanometer. The range of the FCO510 is set as auto-range. The measurement averaging option is activated with an integration (running average) of 60 seconds.

Start the extraction fan at a minimum speed. After a few seconds, use the FCO510 to measure the pressure difference at the orifice plate. Make sure to seal the pipe connected to the sample's negative pressure side when measuring pressure at the orifice plate to avoid air leakage through that hole.

Convert the pressure difference at the orifice plate into an airflow rate [m^3/s]. Record that airflow rate.

Then measure the pressure difference on both sides of the test sample with the FCO510. Record that pressure difference.

Correct the measurement of airflow rate at the orifice plate by subtracting the leakage airflow corresponding to the pressure difference.

Calculate the effective air permeability with the following equation:

$$K = \frac{\dot{V} \cdot \mu \cdot L}{A \cdot \Delta p}$$

Where:
K: Effective air permeability [m^2].
$\dot{V}$: Corrected volumetric airflow rate [m^3/s].
μ: Dynamic viscosity of the air (fluid passing through the sample) [Pa.s]. The dynamic viscosity of air at standard room conditions is 1.84E-05 Pa.s.
L: Thickness of the test sample (dimension in the direction of the airflow) [m].
A: Cross-sectional area of the material test sample perpendicular to the direction of the airflow [m^2].
Δp: Pressure difference across the material test sample [Pa].

Record the calculated effective air permeability.

Repeat the whole process after a slight increase in the extraction fan speed. Record the effective air permeability of the sample on the entire range of extraction fan speed (or until the pressure difference around the test sample reaches 240 Pa or when the airflow rate reaches 0.048 m^3/s).

The final estimate of the effective air permeability can then be calculated as the average of all measurements across the whole fan speed range. The uncertainty of this final estimate can be assessed as 3 times the standard deviation of all measurements across the whole fan speed range. Alternatively, the uncertainty of a single measurement can be evaluated by performing uncertainty propagation (see example in the following section).

7. Calculation of the effective air permeability: examples

Here below is an example of an effective air permeability measurement for a glass wool mat sample (low effective air permeability) (see **Figure 17**). The extraction fan speed is gradually varied from low (minimum)speed to maximum speed to set different air flow rates through the test sample. The reading of the pressure difference across the sample and the orifice plate is taken more than 1 minute after the speed of the fan has been changed in order to ensure that steady-state conditions have been established.

Figure 17: *Glass wool mat test sample in sample holder metal frame of the air permeameter.*

Table 1: *Test sample properties.*

Sample material	**Glass wool mat**
Air dynamic viscosity [Pa.s]	1,84E-05
Sample thickness [m]	0,09
Sample section area [m^2]	0,25
Sample volume [m^3]	0,0225
Sample mass [kg]	0,4549
Sample density [kg/m^3]	20,22

Table 2: *Measurements from the air permeameter.*

Pressure difference orifice plate [Pa]	Airflow rate [m³/s]	Leakage airflow rate [m³/s]	Corrected airflow rate [m³/s]	Pressure drop through sample [Pa]	K: Effective Air Permeability [m²]
0	0	0	0	0	-
16,34	0,0140	0,0006	0,0134	82,87	1,07E-09
40,85	0,0222	0,0011	0,0211	127,57	1,10E-09
56,92	0,0262	0,0014	0,0248	151,95	1,08E-09
66,01	0,0282	0,0015	0,0267	163,5	1,08E-09
71,21	0,0293	0,0016	0,0277	170,23	1,08E-09
75,45	0,0302	0,0016	0,0285	175,15	1,08E-09

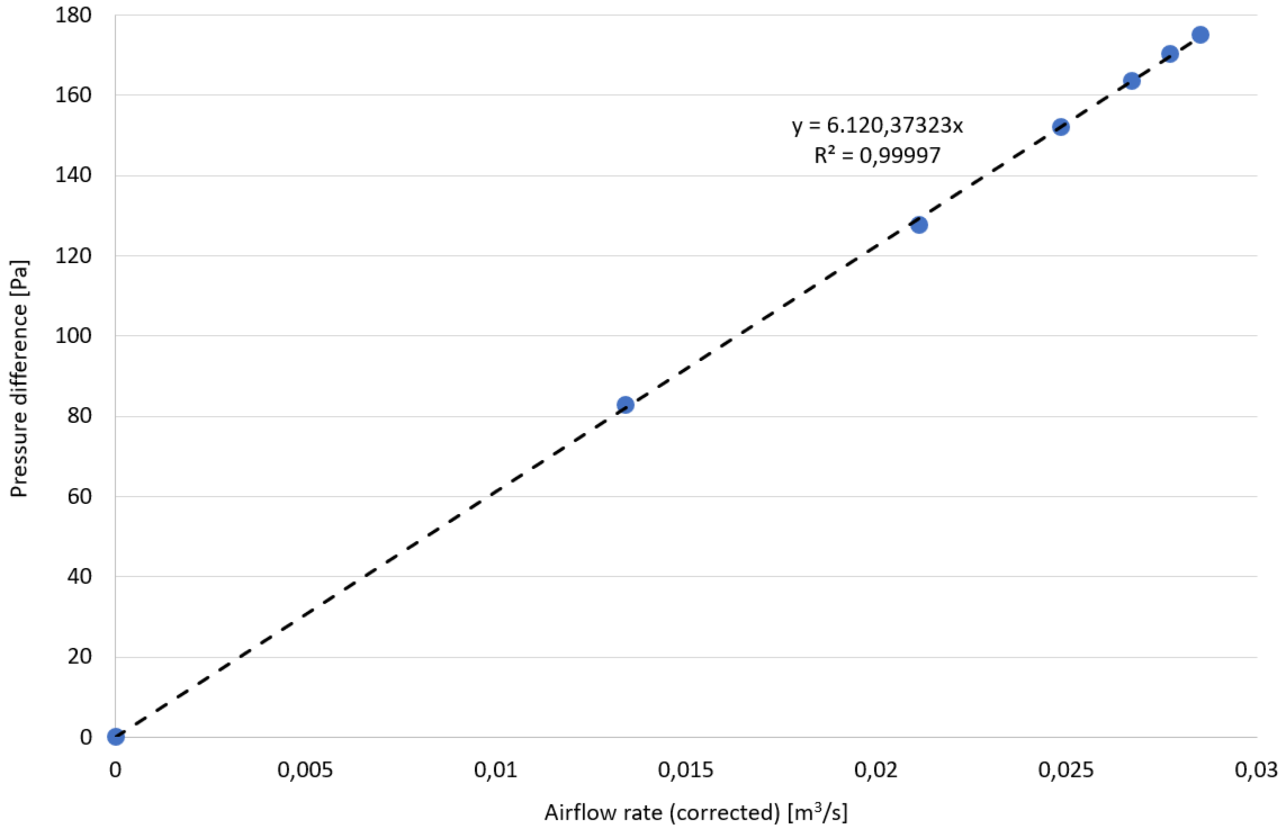

Figure 18: *Measurements from the air permeameter.*

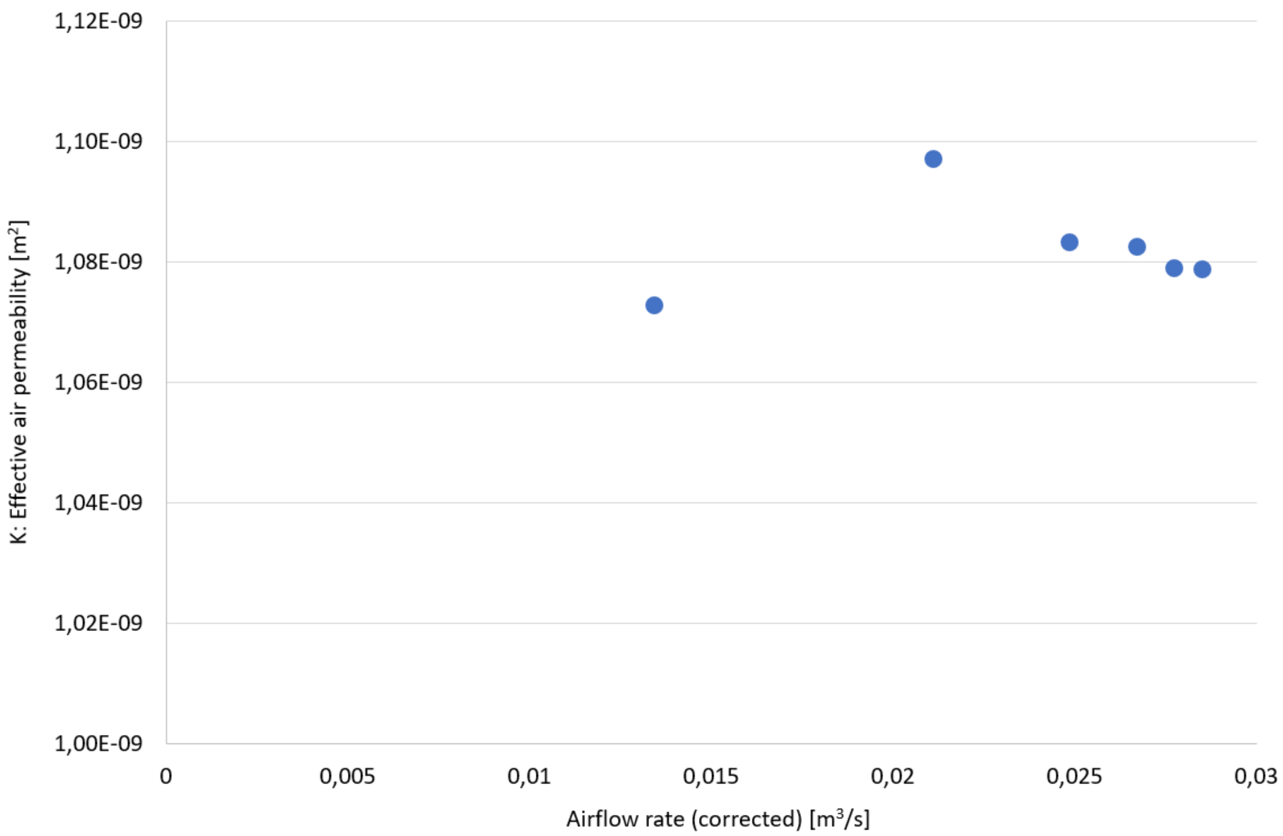

Figure 19: *Results from the effective air permeability measurements.*

Table 3: *Results from the effective air permeability measurements.*

Average measured effective air permeability [m^2]	**1,08E-09**
3 standard deviations [m^2]	**2,23E-11**
3 standard deviations [%]	**2,06%**

The results of this example can be found in the spreadsheet attached to that document.

Here below is an example of effective air permeability measurement for a loose-fill blown glass wool sample (high effective air permeability) (see **Figure 20**).

Figure 20: *Loose-fill blown glass wool test sample in sample holder metal frame of the air permeameter.*

Table 4: *Test sample properties.*

Sample material	**Loose-fill blown glass wool**
Air dynamic viscosity [Pa.s]	1,84E-05
Sample thickness [m]	0,17
Sample section area [m^2]	0,25
Sample volume [m^3]	0,0425
Sample mass [kg]	0,77924
Sample density [kg/m^3]	18,34

__Table 5:__ Measurements from the air permeameter.

Pressure difference orifice plate [Pa]	Airflow rate [m^3/s]	Leakage airflow rate [m^3/s]	Corrected airflow rate [m^3/s]	Pressure drop through sample [Pa]	K: Effective Air Permeability [m^2]
0	0	0	0	0	-
21,03	0,0159	0,0002	0,0158	27,72	7,11E-09
62,25	0,0274	0,0003	0,0271	51,31	6,60E-09
92,71	0,0334	0,0005	0,0330	66,26	6,23E-09
113,92	0,0371	0,0006	0,0365	76,13	6,00E-09
127,43	0,0392	0,0006	0,0386	83,74	5,76E-09
130,67	0,0397	0,0006	0,0391	85,43	5,72E-09

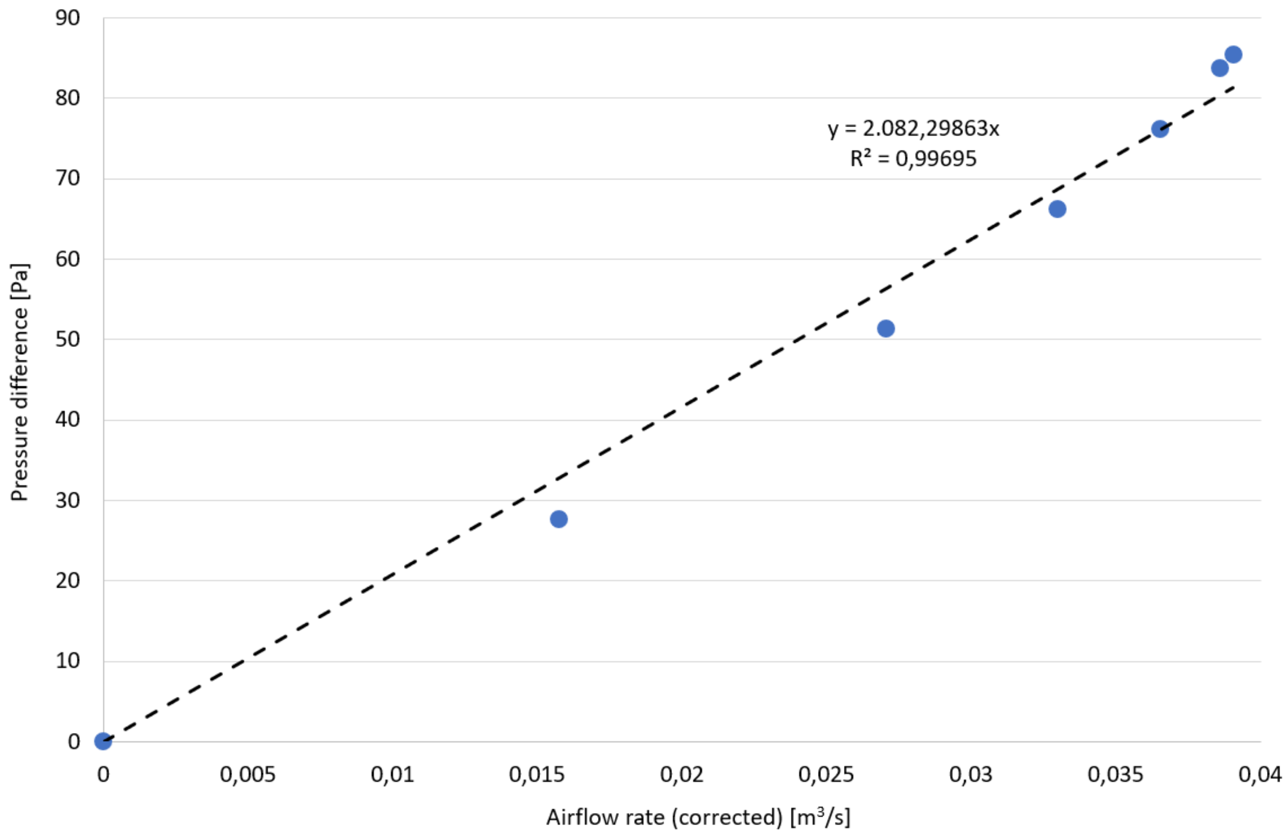

__Figure 21:__ Measurements from the air permeameter.

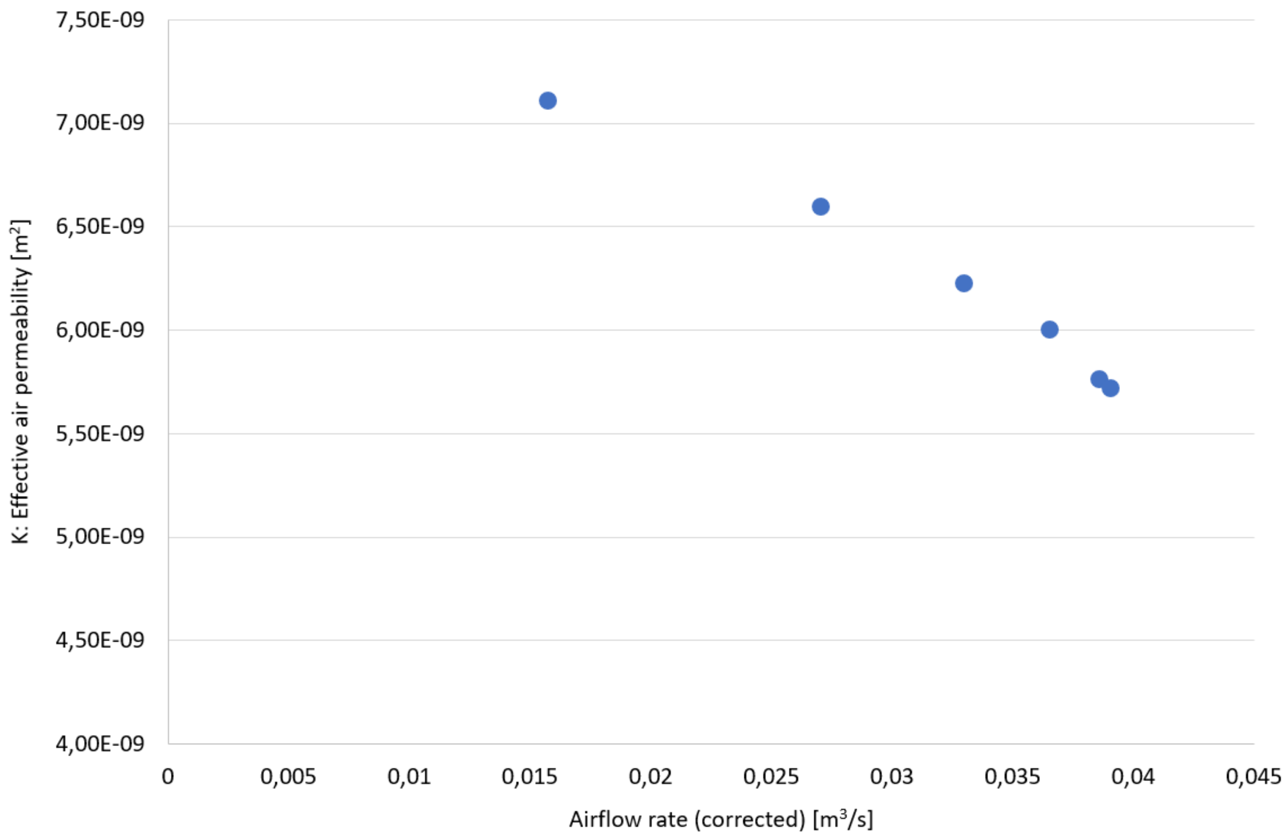

Figure 22: *Results from the effective air permeability measurements.*

Table 6: *Results from the effective air permeability measurements.*

Average measured effective air permeability [m^2]	**6,24E-09**
3 standard deviations [m^2]	**1,47E-09**
3 standard deviations [%]	**23,55%**

The results of this example can be found in the spreadsheet attached to that document.

8. Measurement uncertainty analysis

The uncertainty analysis of a single effective air permeability measurement (here, for the glass wool mat measurement) with the current permeameter setup can be performed with the Kragten method [2] from the uncertainty assessment of each component of the measurand:

- Standard uncertainty (1σ; covering factor k = 1) for the airflow rate: 0.00065 m^3/s
- Standard uncertainty (1σ; covering factor k = 1) for the air dynamic viscosity: 0 Pa.s
- Standard uncertainty (1σ; covering factor k = 1) for the thickness of the sample: 0.00067 m
- Standard uncertainty (1σ; covering factor k = 1) for the section area of the sample: 0.0000013 m^2
- Standard uncertainty (1σ; covering factor k = 1) for the pressure difference across the sample: 1.42 Pa

The combined expanded uncertainty on a single effective air permeability measurement is thus 4.07E-10 m^2 (3σ confidence interval; coverage factor k=3) (see **Figure 23** and **Figure 24**).

The calculation of this example with the Kragten method can be found in the spreadsheet attached to that document.

Quantification of combined uncertainty using the Kragten spreadsheet method

Definition of the measurand:

K: Effective air permeability [m^2]

Mathematical expression of the measurand: $K = \frac{Q \cdot \mu \cdot d}{S \cdot \Delta p}$

Definition of terms (measurant components):

Q: Airflow rate [m^3/s]
μ: Air dynamic viscosity [Pa.s]
d: Thickness of the sample [m]
S: Sample section area [m^2]
Δp: Pressure difference [Pa]

Inputs from the user
Component value
Incremented component variable: component value + standard uncertainty

Component	Component unit [S.I.]	Value of component variable	Standard uncertainty (1σ; k=1) of component variable	Relative standard uncertainty (1σ; k=1) of component	Q+δQ	μ+δμ	d+δd	S+δS	Δp+δΔp
Q	m^3/s	0,03906	0,00065	1,7%	0,03971	0,03906	0,03906	0,03906	0,03906
μ	Pa.s	1,84E-05	0	0%	0	0	0	0	0
d	m	0,17	0,00067	0,4%	0,17	0,17	0,17067	0,17	0,17
S	m^2	0,25	0,0000013	0,001%	0,25	0,25	0,25	0,2500013	0,25
Δp	Pa	85,43	1,42	1,7%	85,43	85,43	85,43	85,43	86,85

Measurand evaluation with the incremented component variables

5,816E-09	5,721E-09	5,743E-09	5,721E-09	5,627E-09

Difference between measurand value and measurand evaluated with the incremented component variables

-9,534E-11	0,000E+00	-2,243E-11	3,051E-14	9,378E-11

$(\text{Difference})^2$

9,09E-21	0,00E+00	5,03E-22	9,31E-28	8,80E-21

Measurand	Measurand unit [S.I.]	Value of the measurand	Combined standard uncertainty (1σ; k=1) of measurand	Relative standard uncertainty (1σ; k=1) of measurand	Squared combined standard uncertainty of the measurand (u_c^2) = Sum(Difference^2)
K	m^2	5,721E-09	1,36E-10	2,4%	1,84E-20

Contribution of the different components to the squared combined standard uncertainty (u_c^2) of the measurand

Q	μ	*d*	*S*	Δp	Sum
49,4%	0%	2,7%	0,00001%	47,8%	100%

Measurand	Measurand unit [S.I.]	Value of the measurand	Coverage factor: k	Combined expanded uncertainty (3σ; k=3) of measurand	Relative expanded uncertainty (3σ; k=3) of measurand
K	m^2	5,721E-09	3	4,07E-10	7,1%

The effective air permeability K is 5,7206911941919E-09 m2 ± 4,06817702633344E-10 m2 (3σ confidence interval; coverage factor k=3)

Figure 23: *Uncertainty analysis with Kragten method.*

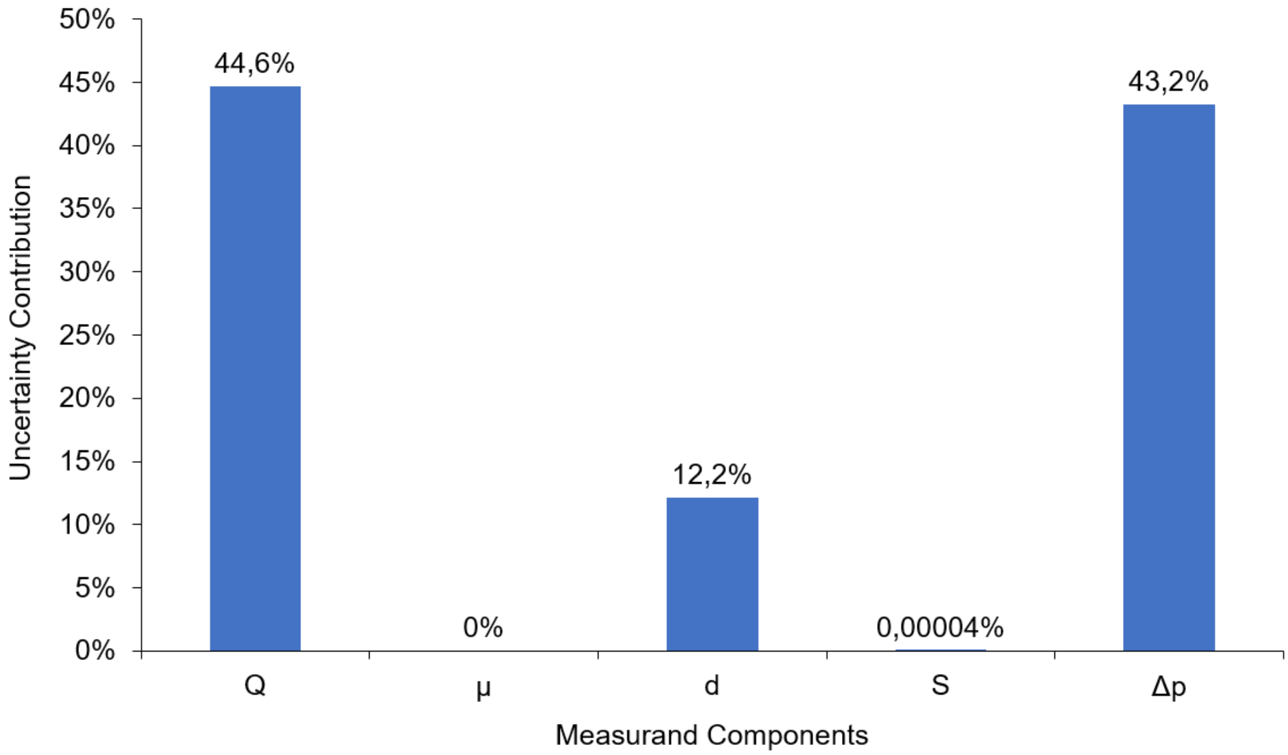

Figure 24: *Uncertainty contributions of the different measurand components.*

9. Suggestions for future work and setup improvement

Although adequate for state-of-the-art effective air permeability measurements, the current air permeameter setup could be enhanced in many ways, or be tested for certain details in order to improve the reliability and accuracy of the results:

- Round Robin tests with other laboratories performing similar measurements with equivalent equipment or, on the contrary, comparing the current setup results against effective air permeability measurements performed with different methods.
- Measurement of the leakage or tightness between the orifice plate and the sample holder junction.
- Measurement of the plenum fabric air straightener pressure loss.
- Measurement of the whole setup pressure loss without test sample.
- Test the effect of adding an air straightener hood above the test sample.
- Add an air temperature and relative humidity measurement on the setup with automated air density calculation to correct the orifice plate measurement of airflow rate (currently assuming a constant air density of 1.2 kg/m^3).
- Accurate re-calibration of the orifice plate.
- Improve the sealing around the permeameter junctions and the sample holder.
- Estimate air leakage around the test sample at the internal junction between the test sample and the metal frame (necessary for test samples with low air permeability): test different joint or sealant system to mitigate the sample-metal frame air free path which might increase the apparent air permeability of low-permeability materials.
- Test different configurations of sample holder/metal frame.
- Improve fan speed control.
- Automate the entire test.
- Test the suitability of adding 2 different orifice plates to have a broader range of airflow measurements.
- Improve the accuracy and stability of the pressure measurement around the sample and the orifice plate.

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[1] Hicham Johra (2021). Thermal Properties of Building Materials - Review and Database. DCE Technical Reports No. 289. Aalborg University, Department of the Built Environment. https://doi.org/10.54337/aau456230861

[2] J. Kragten (1994). Calculating Standard Deviations and Confidence Intervals with a Universally Applicable Spreadsheet Technique. Analyst 119(10), 2161-2165. https://doi.org/10.1039/an9941902161

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