Carbon dioxide permeability of building materials and their impact on bedroom ventilation need

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Abstract

This research determined the carbon dioxide permeabilities of different materials and cellulose-insulated wall structures without a vapour barrier as well as the CO_2 balance of bedroom air. Material tests have indicated that the CO_2 permeabilities of building materials correlate closely with their water vapour permeabilities. Thus, the more permeable the external wall structures are, the bigger their impact on the CO_2 content of indoor air. Yet, higher permeability allows more water vapour to pass through the structures, which make them more at-risk for condensation and mould growth. Some

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calculations on the CO_2 balance of bedroom air were also made which indicated that the need of ventilation is not reduced by the use of gas permeable structures.

Keywords

Building materials, carbon dioxide, material properties, material testing, permeability

1   Introduction

People spend, on average, 80–90 per cent of their time indoors.[1-3] The construction of airtight buildings, prompted by the energy crisis of the 1970's, has sometimes led to deficient ventilation or mould-related problems, and consequently lower indoor air quality. The increased time spent indoors together with occasionally poor air quality has caused health problems for some people.[4,5]

Carbon dioxide (CO_2) is one of the many impurities in indoor air. It is a normal constituent of exhaled air and quantitatively the most significant impurity produced by the human body.[6] Various aspects of indoor air pollution have been discussed in a number of studies, some of which concentrated on carbon dioxide and ventilation[7-14].

According to a literature review concerning mainly office buildings, ventilation rates below 10 dm^3/(s,person) were commonly associated with worsened health or perceived air quality. About half of the reviewed studies suggested that the risk for health problems decreased significantly when the carbon dioxide concentrations were below 800 ppm. The carbon dioxide concentration is not considered very accurate substitute for the actual air flow rate, because of the spatial and temporal variations, measurement errors and differences in production per user.[7] However, the CO_2 concentration is in many cases used as an indicator of the indoor air quality directly[7,10,15].

Various indoor air classifications and guidelines can be formed based on measured content, as presented in Table 1.[15-19]

Table 1 Carbon dioxide limit values.

CO_2 content (ppm)	Description
250–600	Normal carbon dioxide content of outdoor air.[15]
750	Finnish Class S1, excellent indoor air. Indoor air quality meets the requirements of special groups (elderly, allergic persons, respiratory disease sufferers).[19]
900	Finnish Class S2, good indoor air.[19]
950–1300	ASHRAE recommends adjustment of the building's ventilation system.[18]
1200	Finnish Class S3, satisfactory indoor air. Indoor air quality meets the minimum requirements set by the Finnish Indoor Air Organisation.[19]
5000	Max. permissible exposure limit for carbon dioxide over any eight-hour shift of a 40-hour work week.[17]
30,000	Max. exposure limit for a 10-minute period based on acute inhalation data.[16,17]

In a Danish study of homes of 500 small children, 57% of the homes had a ventilation rate (calculated from carbon dioxide measurements) lower than 0.5 1/h, which is the required value for Danish new buildings. Of the measured bedrooms, 68% had an average carbon dioxide concentration above 1000 ppm during the nights of the 2.5-day measurement period. It is also mentioned, that the error in the defined air change rates depend also e.g. on the occupancy and ventilation rates between the adjacent rooms.[11]

In a study conducted in Korea, the outdoor air temperature conditions affected the behaviour of the people, causing them to keep windows and doors open or closed depending on the outdoor air temperature. This was concluded to have an impact on the carbon dioxide levels inside the measured bedrooms.[12] A similar phenomenon is visible

from a Greek study, which focused on school buildings: The mean CO_2 concentration during teaching periods dropped inversely proportional to the air flow rate per person. At the same time the average air flow rate increased with increasing indoor air temperature due to window opening.[13]

In a Monte Carlo simulation study, the use of four different demand-based control strategies were compared to a continuously operating mechanical exhaust ventilation. Based on the results, the window trickle vent solution that allowed the mechanical exhaust ventilation to stay continuously on, had the second lowest median CO_2 concentration in the indoor air, right after the continuously operated exhaust ventilation.[14]

Based on these literature sources, it would be desirable to keep the indoor air carbon dioxide concentration in a sufficiently low level. Ventilation and diffusion through building envelope would contribute also to maintaining low concentrations of other pollutants. However, although many studies have been conducted on indoor air quality, the impact of the diffusion of indoor air pollutants through building envelope has been investigated to a lesser extent.

Different measurement methods have been presented or used in the literature to determine the gas permeability of different materials. These include for example a time-variable pressure difference method originally for concrete [20], permeability cell for edible films[21], a constant pressure device for membrane-like materials, especially paper[22] and a dual chamber method for contact lenses[23]. Also, a number of standard methods exist for different situations, e.g. for determining the oxygen transmission rate

through plastic film and sheeting[24], gas permeability of dense refractory products[25], carbon dioxide permeability of masonry and concrete coatings[26], gas permeability of clay geosynthetic barriers using a constant pressure difference[27] and the cup method to determine the water vapour permeability of building materials and products[28]. However, it was felt that none of these sources were directly applicable to determining the carbon dioxide permeability of different construction materials, which had varying thicknesses and carbon dioxide permeabilities.

Due to these reasons, the Building Physics research group at Tampere University of Technology decided to find a reliable method for determining the carbon dioxide permeability of permeable building materials. Carbon dioxide was selected to be used in the studies, because it is desired to keep the carbon dioxide concentration itself on a low level, it can be used as one indicator of the indoor air quality, there are many reliable devices for measuring carbon dioxide concentration, it is well suited for examining the gas permeability of wall structures in laboratory tests and because it is easily available for use.

The aim of the study was to determine the transmission rate of the carbon dioxide in indoor air through different materials and wall structures by diffusion, i.e. their carbon dioxide permeability. The values were then compared to literature values of water vapour permeability of the same materials. Calculations were also made to determine whether more permeable structures would reduce the need for ventilation.

This article is based on a research report[29], with the following modifications: The derivation of equation (24) and Figures 3 and 4 were added. The minimum and

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maximum estimates for carbon dioxide resistance values were added to Tables 2, 3 and 5. Also a Monte Carlo sensitivity study was added and the text was largely rewritten to improve the readability.

2 Materials and research methods

2.1 General

We studied diffusion based on concentration difference. Gases can migrate in structures also by convection, thermodiffusion and effusion, but these methods were not included in our study.

The diffusion of gases has been studied extensively. Several calculation models have been developed for theoretically determining the rate of diffusion through air. The correlation based on experimentation suggested by Fuller depicts the actual situation well and gives accurate results.[30,31]

$$D_{AB} = 0.001 \cdot \frac{T^{1,75} \cdot \left(\frac{1}{M_A} + \frac{1}{M_B}\right)^{\frac{1}{2}}}{p \cdot \left[(\sum v_A)^{\frac{1}{3}} + (\sum v_B)^{\frac{1}{3}}\right]^2} \tag{1}$$

where

D_{AB} is the diffusion coefficient of gas A through material B, cm^2/s

T is temperature, K

p is total pressure, (1 atm)

M_A and M_B are the molecular masses of the examined gases, which is 44 g/mol for carbon dioxide and 29 gmol for air, and

Σv_A and Σv_B are so-called diffusion volumes, which are 26.9 for carbon dioxide and

20.1 for air.

The movement of gas molecules is proportional to the temperature so that the molecular movement and the rate of diffusion decelerate as temperature decreases. The diffusion coefficient for carbon dioxide through air is $15.3\cdot10^{-6}$ m^2/s, $13.6\cdot10^{-6}$ m^2/s and $11.9\cdot10^{-6}$ m^2/s at 20°C, 0°C and -20°C, respectively. These values were calculated using equation (1).[31]

Diffusion of a gas through a structure occurs when the content of the gas is different on the opposite side of a structure. Thus, the gas flow caused by diffusion is a movement of molecules through a structure from an area of higher concentration to an area of lower concentration until a state of equilibrium is reached.

The density of the diffusion flow rate is based on Fick's law, equation (2)

$$j_A = -D_{AB} \cdot \frac{\partial c_A}{\partial x} \tag{2}$$

where

j_A is the density of one-dimensional diffusion flow rate of component A, kg/(m^2·s)

c_A is the concentration of component A, kg/m^3, and

x is the spatial coordinate parallel to flow, m.

Analysing the transmission of water vapour through structures is an essential part of building physics. Equation (2) is the typical starting point for calculating the diffusion of water vapour, but it can be used for carbon dioxide (CO_2) also. By using difference approximation and changing the notation, equation (2) can be written as equation (3).

$$j_{CO2,diff} = -A \cdot \delta_{CO2} \cdot \frac{dc}{dx} = A \cdot \delta_{CO2} \cdot \frac{c_1 - c_2}{x_2 - x_1} \qquad (3)$$

where

$j_{CO2,diff}$ is the diffusion flow rate, kg/s

A is the area of which through the diffusion occurs, m^2

δ_{CO2} is the CO_2 permeability of the material, m^2/s

c_1, c_2 are the CO_2 concentrations at points 1 and 2, kg/m^3

x_1, x_2 are the coordinates of points 1 and 2, m

The diffusion flow rate through multiple homogeneous material layers can be calculated from equation (4).

$$j_{CO2,diff} = A \cdot \frac{c_1 - c_2}{Z_{CO2}} \qquad (4)$$

where

Z_{CO2} is the total CO_2 diffusion resistance between two points, s/m.

The total CO_2 diffusion resistance of a structure consisting of multiple homogeneous layers can be calculated with equation (5).

$$Z_{CO2} = \sum_{i=1}^{n_{layers}} Z_i = \sum_{i=1}^{n_{layers}} \frac{d_i}{\delta_{CO2,i}} \qquad (5)$$

where

i is the index for each layer, -

n_{layers} is the total number of layers in a structure, -

Z_i is the diffusion resistance of an individual layer, s/m

d_i is the thickness of layer i, m, and

$\delta_{CO2,i}$ is the CO_2 permeability of layer i, m^2/s.

The diffusion of carbon dioxide through a material is theoretically a simpler phenomenon than the diffusion of water vapour. The application of Fick's law (equation (2)) to carbon dioxide diffusion eliminates at least two problems arising when evaluating the diffusion of water vapour. Firstly, air does not have a temperature-dependent maximum capacity for carbon dioxide (at normal temperatures), as it has for water vapour. Secondly, regular building materials (excluding concrete) do not absorb carbon dioxide molecules – at least not to the extent to which organic materials absorb water vapour.

The familiar CO_2 levels given in literature are in volume fractions (ppm). Also the carbon dioxide concentrations received from the test equipment are in volume fractions in percent (%). To use mass concentrations (kg/m^3 of air volume) similarly to water vapour diffusion calculations, the CO_2 volume fractions were converted to mass fractions by multiplying them with air density (kg/m^3) and the quotient of CO_2 and air molar masses (44 g/mol / 29 g/mol = 1.52) where necessary.

2.2 Measurements

2.2.1 *Test equipment*

The tests were conducted using equipment built at the laboratory of Tampere University of Technology. The test equipment was designed for permeable building materials and structures, which reduces the accuracy of measurements on materials with low carbon dioxide permeability.

The test chamber was made of 2 mm stainless steel sheeting with external dimensions of approximately 600 x 400 x 500 mm^3. The chamber had six sides with one vertical side open. The specimens were measured 590 mm x 390 mm ($\pm$ 5 mm) with varying thicknesses. A specimen was inserted through the open side and sealed against the flanges for some distance inside the chamber. The flanges were positioned so that the volume of the space on the primary side of the specimen, fully enclosed by the chamber walls and the specimen, was 0.0579 m^3. The other side of the specimen, facing the one open wall of the chamber, was designated the secondary side. The clear opening between the flanges was measured 0.196 m^2. The test piece was vertical during testing. The test equipment is pictured in Figure 1.
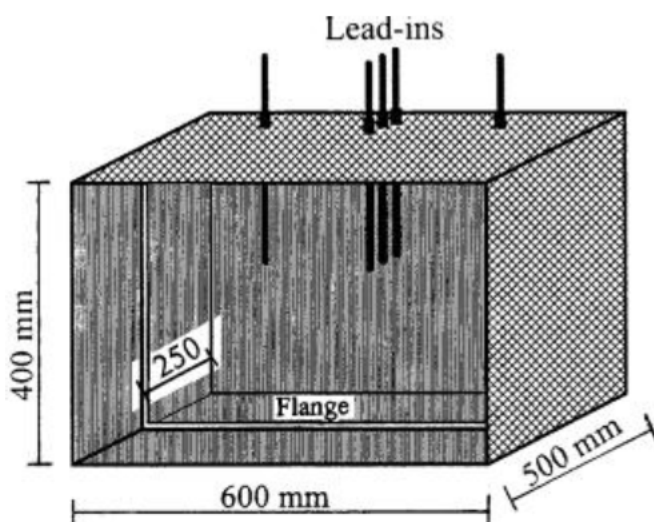

Figure 1 An illustration of the test chamber.

The carbon dioxide concentration of the primary side was measured with the SERVOMEX 1400B4 gas analyser. It was located outside the chamber, and the air on the primary side was circulated through the analyser by a separate pump. On the secondary side, CO_2 measurement was conducted with the HORIBA APBA-250E

analyser, which was positioned on the secondary side of the test piece so that the distance between the devices' air intake and the test piece was 10 cm. Both analysers were calibrated once a week throughout the test series, using two calibration gases (pure nitrogen and 4% CO_2) with controlled contents according to the values provided by the SERVOMEX analyser.

The temperature and relative humidity from the primary and secondary sides were measured with National Semiconductor LM 335 temperature sensors and Vaisala HMI 31 moisture meters respectively.

Two vents of 2 mm and 10 mm of diameter were also added to the test chamber, which connected the primary side to the secondary side room air. The larger vent was added to make sure that the pressure difference between the chamber and room air stayed at zero during the feeding and stabilization of carbon dioxide to the chamber. The smaller vent was kept open and the larger vent was closed during the actual tests to keep the same pressure difference at zero during the measurement periods (while the carbon dioxide was diffusing through the test materials).

Air pressure was measured on both the primary and secondary sides with a relative pressure gauge, but this became unnecessary after the installation of the 2 mm continuously open vent pipe.

2.2.2 Calibration

The test equipment was calibrated using a steel sheet as a specimen. Two requirements were set for the equipment: firstly, no pressure difference was allowed between the sides, and secondly, the carbon dioxide concentration on the primary side

had to remain constant during the calibration. Initially, the calibration was conducted with the primary side completely isolated from the secondary side. Thereby, the CO_2 content of the primary side stayed constant, but a pressure difference occurred between the primary and secondary sides in all measurements due to the temperature fluctuations. Consequently, the pressure of the primary side was regulated in tests by an additional pipe 2 mm in diameter. After the installation of the vent pipe, no pressure difference between the sides could be detected.

The effect of the 2 mm vent pipe on the carbon dioxide concentration had to be taken into account by calculating a correction factor. This factor was determined experimentally by measuring the amount of CO_2 that passed through the vent pipe during a time interval, with different carbon dioxide concentrations in the test chamber. Due to the small diameter of the vent pipe, the correction of the primary-side gas content was approximately 300 ppm for the calibration measurement. On the other hand, in tests on materials which CO_2 permeated the fastest, the impact of the correction factor was insignificant.

2.2.3 Tests

The tests began by sealing of the specimen against the flanges and walls of the test chamber with silicone. After the silicone had dried, a plastic sheet was taped onto the secondary side of the specimen. Then, 100% carbon dioxide was conveyed into the primary side of the test chamber from a gas container, so that CO_2 concentration exceeded 1.0%, and the gas mixture was allowed to stabilise for at least an hour.

After the stabilisation period, the moisture content of the air was measured, the

pressure equalisation hole (10 mm) was sealed, the measurement program was launched, and the plastic sheet was removed from the secondary side of the specimen. The measurement program monitored the carbon dioxide content on the primary side and started recording data when content fell just below 1.0%. CO_2 content, temperatures and changes in air pressure were measured at one minute intervals.

The tests were continued until the carbon dioxide content on the primary side dropped below 0.15% or 24 hours had passed, whichever occurred first. If after 24 hours the carbon dioxide content on the primary side was still over 0.90%, the material's carbon dioxide resistance and permeability was not determined.

The experiments were repeated by feeding a new dose of carbon dioxide into the primary side at the end of the first test. No significant difference was observed between the results of the first and second measurements with regard to any specimen.

The test equipment was also used to test two wood-based specimens to determine the impact of moisture on their carbon dioxide permeability. In these tests, the relative humidity of the air on the primary side was increased with moisture evaporation from free water surface while normal room humidity prevailed on the secondary side. The moisture tests followed the regular test procedures described above.

2.3   Calculations

2.3.1   General

The carbon dioxide resistances of specimens consisting of various materials and the coated test pieces, were determined by the following calculation method. The

conservation of mass for carbon dioxide within a specific volume of air can be written as equation (6)

$$V\frac{dc_{in}}{dt} = -j_{CO2,diff} - j_{CO2,ventilation} + S_{CO2} \tag{6}$$

where

V is the air volume with a time varying CO_2 concentration, m^3

c_{in} is the CO_2 concentration of the air volume under consideration, kg/m^3

t is the time, s

$j_{CO2,diff}$ is the CO_2 flow rate by diffusion, kg/s

$j_{CO2,ventilation}$ is the CO_2 flow rate by ventilation, kg/s, and

S_{CO2} is the source term for CO_2 production inside the air volume, kg/s.

The carbon dioxide flow rate by ventilation can be written as equation (7):

$$j_{CO2,ventilation} = nV(c_{in} - c_{out}) \tag{7}$$

where

n is the air change rate between inside and outside of the studied air volume, 1/s.

The equations (4) and (7) were substituted back into the conservation equation (6), and then it was simplified into the form of equation (8):

$$\frac{dc_{in}}{dt} + \left(\frac{\frac{A}{z_{CO2}}+nV}{V}\right) \cdot c_{in} = \left(\frac{\frac{A}{z_{CO2}}+nV}{V} \cdot c_{out} + \frac{S_{CO2}}{V}\right) \tag{8}$$

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Then the definitions for the auxiliary variables a and b, presented in equations (9) and (10), were substituted into equation (8)

$$a = \frac{\frac{A}{z_{CO2}}+nV}{V} \tag{9}$$

$$b = \frac{\frac{A}{z_{CO2}}+nV}{V} \cdot c_{out} + \frac{S_{CO2}}{V}, \tag{10}$$

Thereby, the conservation of mass for carbon dioxide was finally written as equation (11)

$$\frac{dc_{in}}{dt} + a \cdot c_{in} = b \tag{11}$$

The equation (11) is a first-order, linear and non-homogeneous ordinary differential equation. It was solved by finding the homogeneous ($c_{in,h}$) and particular ($c_{in,p}$) solutions and summing them together (the method of undetermined coefficients[32]). The homogeneous solution was found by setting the right-hand side of the equation (11) to zero

$$\frac{dc_{in}}{dt} + a \cdot c_{in} = 0 \tag{12}$$

By separation, integration and solving the resulting logarithmic function, equation (13) was obtained for the homogeneous solution. It contains the integration constant C_1

$$c_{in,h} = C_1 \cdot e^{-at} \tag{13}$$

The particular solution was obtained by first selecting a guess function, based on the form of the right-hand side of equation (11). Because it has a constant value, a constant value B_0 was selected as the guess function (equation (14)).

$$c_{in,p} = B_0 \tag{14}$$

The value was substituted back into equation (11) in order to get equation (15):

$$\frac{dB_0}{dt} + aB_0 = b \tag{15}$$

B_0 is a constant, so its derivative is zero. Thus with this information B_0 could be solved:

$$B_0 = \frac{b}{a} \tag{16}$$

The complete solution to equation (11) is the sum of the two solutions, equations (13) and (16):

$$c_{in} = c_{in,h} + c_{in,p} = C_1 e^{-at} + \frac{b}{a} \tag{17}$$

Finally, the integration parameter C_1 was calculated by using an initial value condition:

$$c_{in}(t=0) = c_{in,0} \ \rightarrow C_1 = c_{in,0} - \frac{b}{a} \tag{18}$$

The value $c_{in,0}$ is the carbon dioxide concentration at the beginning of the evaluation period. By substituting the value of C_1 back into the equation (17) and simplifying it, a function is obtained to calculate the CO_2 concentration inside the test chamber (or other similar volume) as a function of time (equation 19).

$$c_{in} = \left(c_{in,0} - \frac{b}{a}\right) e^{-at} + \frac{b}{a} \tag{19}$$

2.3.2 Carbon dioxide resistance of the specimen

In the test chamber application, the air change rate by ventilation was assumed zero, as was the source coefficient, meaning $n = 0$ and $S_{CO2} = 0$. With these conditions we can calculate the following quotient in order to shorten the calculations

$$\frac{b}{a} = c_{out} \tag{20}$$

Taking into account that $n = 0$, equations (9) and (20) were substituted back into equation (19):

$$c_{in} = \left(c_{in,0} - c_{out}\right) e^{-\frac{A}{ZV} \cdot t} + c_{out} \tag{21}$$

Two new auxiliary variables were used to simplify the notation (equations (22) and (23)):

$$\Delta c = c_{in} - c_{out} \tag{22}$$

$$\Delta c_0 = c_{in,0} - c_{out} \tag{23}$$

where

Δc is the carbon dioxide concentration difference between the inside and outside of the test chamber, kg/m^3, and

Δc_0 is the carbon dioxide concentration difference between the inside and outside of the test chamber at the beginning of the measurement period, kg/m^3.

Using equations (22) and (23), equation (21) was written in the following form to give the CO_2 diffusion resistance of the test sample:

$$Z_{CO2} = \frac{A}{V} \cdot t \cdot \frac{1}{\ln\left(\frac{\Delta c_0}{\Delta c}\right)} \tag{24}$$

The equation (24) gives the CO_2 diffusion resistance as a function of time, of which an example is given in Figure 3. The results are presented as arithmetic means of the time-varying values, where the number of data points depends on the duration of the measurement period (time step was always five minutes). If there were clear outliers in the carbon dioxide resistance data (e.g. at the beginning), they were removed manually before further analysis.

2.3.3   *Second calculation method for carbon dioxide diffusion resistance*

To have comparison values regarding the calculation method also another method was used to calculate the CO_2 diffusion resistance of different test samples. The idea was to assume each five minute time interval of the measurement as a steady-state situation. The average CO_2 concentration difference over the test sample and the CO_2 flux through were calculated for each time step separately. The final diffusion resistance was eventually taken as the arithmetic mean of the individual time step values. Equation (4) was written as equation (25):

$$Z_{CO2} = \frac{1}{n_t}\sum_{i=1}^{n_t} Z_{CO2,i} = \frac{1}{n_t}\sum_{i=1}^{n_t}\frac{\Delta c_i}{j_{CO2,diff,i}} \tag{25}$$

where

i is the index running through the time steps in the measurement data, -

n_t is the number of time steps in the specific test run, -

Δc is the average difference in the CO_2 concentration over the test sample (equation 26), kg/m^3

$j_{CO2,diff,i}$ is the average CO_2 flow through the test sample for each time step (equation 27), kg/(m^{2}s).

The average CO_2 concentration over the test sample for each time step (equation 26) and the average density of the CO_2 flow rate (equation 27) were:

$$\Delta c_i = \frac{c_{in,i-1}+c_{in,i}}{2} - \frac{c_{out,i-1}+c_{out,i}}{2} \tag{26}$$

$$j_{CO2,diff,i} = \frac{(c_{in,i}-c_{in,i-1})V}{(t_i-t_{i-1})A} \tag{27}$$

2.3.4 Determination of carbon dioxide permeability

The carbon dioxide permeability of a homogeneous test piece was determined by dividing the material's thickness by the calculated resistance value according to equation (28):

$$\delta_{CO2} = \frac{d}{z_{CO_2}} \tag{28}$$

2.3.5 The carbon dioxide content of a room

In addition to the material tests, equation (19) was used to calculate the carbon dioxide content of a room. It is first noticed that if $Z = Inf$, then $a = n$. The characteristic time gives the time duration in which $1/e \approx 63\%$ of the change has occurred after a step-like change in the prevailing conditions. By setting the exponent $(-at)$ equal to -1, the characteristic time could be solved to be $t_c = 1/a = 1/n$. For an air change rate of n = 0.5 1/h this means a characteristic time of two hours, and for an air change rate of 2 1/h the characteristic time is half an hour.

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On the other hand, the smaller the value of Z, the larger the parameter a becomes. This way, the smaller the carbon dioxide resistance of the building envelope is, the shorter the characteristic time becomes. The volume of the air space has a similar effect on the characteristic time, so that as the air volume varies between $V = 0 \ldots \infty$, the characteristic time varies between $t_c = 0 \ldots 1/n$. These values mean that the carbon dioxide content level inside typical room spaces should generally reach steady state conditions during the night.

The analytical equation (19) would allow first solving the steady-state solution and then by calculating the partial derivatives from that, estimate the sensitivity of the room carbon dioxide content to changes in different variables. However, there would still be multiple choices for the numerical values of the variables in the partial derivatives, which would decrease the usefulness of the analytical solution in this case. Because of this, Monte Carlo -simulations were done by calculating the time-dependent solution of equation (19) in a Python script and taking the input values for each run from a uniform distribution. When the calculations were done, Spearman correlation coefficients were calculated to describe the correlation between the resulting carbon dioxide concentration in a room after eight hours and different influencing factors. The details of the calculations are given in the results section.

The time-dependent equation (19) was used in the calculations, but the results were also compared to the steady-state results. By letting $t \rightarrow \infty$ and by substituting for a and b, we got equation (29) for the carbon dioxide content of a room in a steady-state conditions:

$$c_{in,steady-state} = c_{out} + \frac{S_{CO2}}{\frac{A}{z_{CO2}} + nV} \qquad (29)$$

Equation (29) is analogous to calculating the water vapour excess inside a building in steady-state conditions.

3 Results and discussion

3.1 Decrement diagram of CO2 content on the primary side

Some decrement curves are presented in Figure 2. The time required for the CO_2 content to reach 0.15% varied greatly between the specimens. Therefore, only the measurement results of the first 300 minutes are shown in Figure 2.
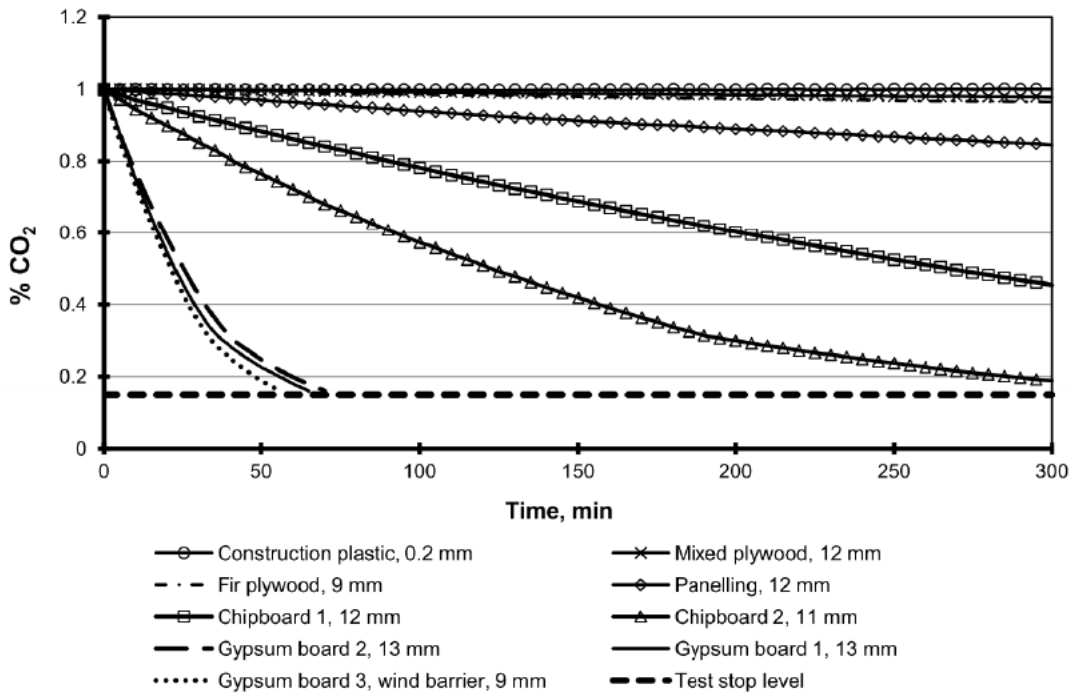

Figure 2 Carbon dioxide content of various materials on the primary side.

The CO_2 concentration on the outside of the test chamber was fairly constant 400 ± 30 ppm. On some occasions the concentration was higher than this, but based on the repeated runs, this didn't have significant effect on the results.

3.2 Carbon dioxide resistance of the test pieces

The diffusion resistance for CO_2 calculated with equation (24) is presented in Figure

3 for permeable insulation materials and air barriers.
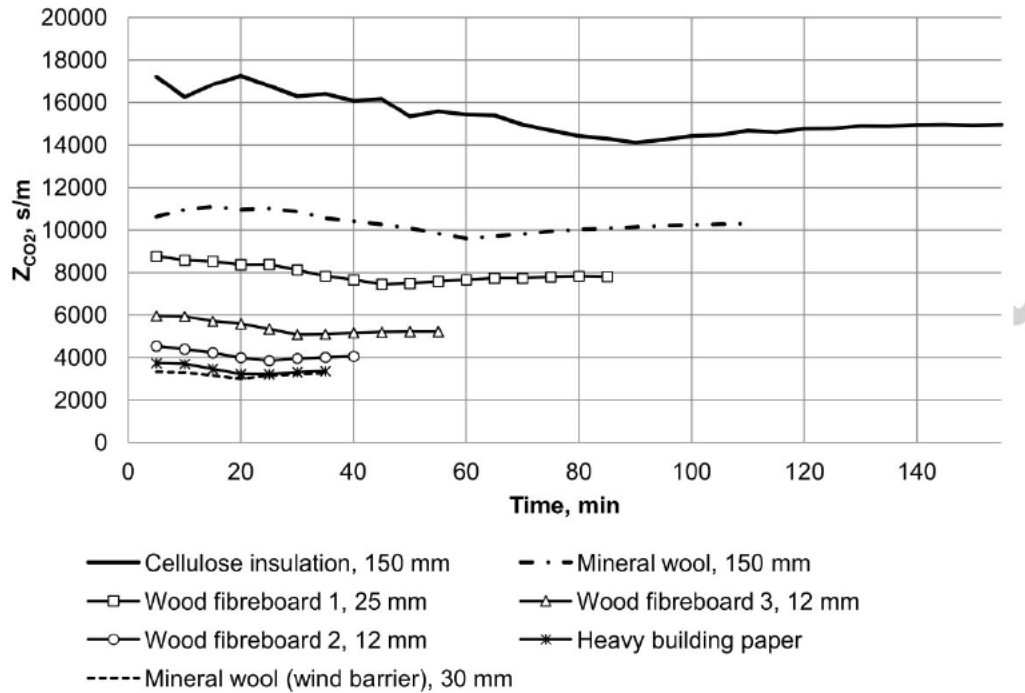

Figure 3 Carbon dioxide diffusion resistance of tested permeable insulation materials and wind barriers, calculated with equation (24).

Figure 3 shows a local minimum in all tested permeable materials, which is

occurring the earlier the start of the test, the smaller the diffusion resistance of the

material layer is. A small bend is in the CO_2 content can also be seen in Figure 2.

All tested materials, finishes and structures are given in Tables 2–4. The resulting

CO_2 resistances (average values in Figure 3) calculated with equation (25) had 5 %

accuracy compared to the first method for different materials, but on average the results

were very close to each other. However, the analytical solution (equation 24) is

preferred, because it gives the exact solution for the mathematical problem and the CO_2

resistance values calculated with it had much less noise than the values calculated with equation (25).

A material's carbon dioxide resistance and permeability were not determined if its carbon dioxide concentration remained over 0.90% after 24 hours of test, as explained earlier. Results of the material tests are presented in Table 2. Maximum temperature fluctuation between tests was 2°C meaning that temperature had no practical impact. Please note that gypsum boards 1 and 2 were by different manufacturers and porous fibreboards 2 and 3 were different trademarks. In three of the tests, the temperature and air humidity were not measured.

Table 2 Average carbon dioxide resistances of materials derived from the tests. The minimum, mean and maximum values correspond to the values similar to those in Figure 3.

Material (number of data points)	Thickness (mm)	RH (%)	T (°C)	Carbon dioxide resistance, Z_{CO2} (x 10^3 s/m)		
				Min	Mean	Max
Building paper (7)	-	20	20	3.2	3.4	3.7
Cellulose insulation (45 kg/m^3) (31)	150	25	20	14	15	17
Chipboard 1 (197)	12	40	20	63	72	79
Chipboard 2 (89)	11	41	21	31	33	37
Construction plastic (-)	0.2	-	-	-	-	-
Fir plywood (55)	9	37	20	1390	1550	1910
Gypsum board 1 (13)	13	-	-	5.8	6.3	7.4
Gypsum board 2 (14)	13	37	21	6.4	6.9	7.5
Gypsum board (windshield) (11)	9	40	21	5.3	5.7	6.4
Interior panelling, STV 12x95 (uncoated) (57)	12	23	20	320	350	430
Mineral wool (17 kg/m^3) (22)	150	41	22	9.6	10	11
Mineral wool (windshield, 80 kg/m^3) (7)	30	44	21	3	3.2	3.3
Mixed plywood (53)	12	-	-	2060	2440	3090
Wood fibreboard 1 (17)	25	47	21	7.4	8	8.8
Wood fibreboard 2 (8)	12	34	21	3.9	4.1	4.5
Wood fibreboard 3 (11)	12	37	21	5.1	5.4	6
Timber slab (uncoated) (57)	13	45	21	280	310	340

Table 3 shows the carbon dioxide resistances of the wall finishes. They were determined by subtracting the carbon dioxide resistance of the backing (Gypsum board 2) from the total carbon dioxide resistance of the finished board. The normal latex paint in the table was water-based, semi-gloss (4/RT class) interior acrylate latex paint, and the matt latex was water-based matt (6/RT class) PVA latex paint suitable for interior use.

Table 3 Average carbon dioxide resistances of the wall finishes. The minimum, mean and maximum values correspond to time-series data similar to Figure 3.

Material (number of data points)	RH (%)	Temperature (°C)	Carbon dioxide resistance, Z_{CO_2} (x 10^3 s/m)		
			Min	Mean	Max
Matt latex paint (23)	30	21	3.6	4.1	4.5
Normal latex paint (47)	38	22	3800	4500	6800
Vinyl wallcovering (21)	30	21	3.0	3.1	3.5
Wallpaper (18)	28	20	1.4	1.5	1.7

The carbon dioxide resistance values of the tested structures are presented in Table 4. The total CO_2 resistances were determined by the calculations as well as by adding together the resistance values of the material layers of layered structures. The average air humidity during the measurement period for Structure 1 was 28% RH and temperature 20°C; for Structure 2 these values were 23% RH and 21°C, respectively.

Table 4 Comparison of the carbon dioxide resistance values derived by different methods and structural tests.

	Carbon dioxide resistance, Z_{CO2}, derived from structural tests (x 10^3 s/m)	Sum of carbon dioxide resistances, ΣZ_{CO2}, derived from material tests (x 10^3 s/m)
Structure 1	24	27.5
Wallpaper		1.5
Gypsum board 2, 13 mm		6.9
Cellulose insulation, 150 mm		15
Porous fibreboard 2, 12 mm		4.1
Structure 2	18	18.4
Building paper		3.4
Cellulose insulation, 150 mm		15

A comparison of the values in Table 4 indicates that summing up the resistance values of various layers gives a total resistance value of almost the same magnitude as the test value.

3.3 The results of the humidity tests

The results of the humidity tests presented in Table 5 indicate that as humidity increases, the diffusion of carbon dioxide inside the interior panelling decelerated noticeably. In the case of Structure 2, no noticeable difference in carbon dioxide permeability was detected in relation to humidity.

Table 5 Specimens and, average conditions and results from the humidity tests.

Material	RH (%)		T (°C)	Carbon dioxide resistance, Z_{CO2} (x 10^3 s/m)					
	Primary side	Secondary side		Dry			Wet		
				Min	Mean	Max	Min	Mean	Max
Interior panelling, STV 12x95	93	21	21	320	330	360	530	560	920
Structure 2	89	20	21	18	19	20	17	18	19

The results in Table 2 are from single tests and the second tests were used only for error checking. The results in Table 5 are average values from both two tests. This was done to show the impact of choosing between these two methods, which in this case was that averaging decreased the average and maximum values.

3.4 Comparison of carbon dioxide and water vapour permeability

Water vapour permeability is generally studied by a standardised research method, the so-called cup method (standards EN ISO 12572:2001[28] and ASTM E96 / E96M-14[33]). Moisture transfer through building materials is a complex transport-storage-mechanism, but when the pore structure remains the same for gas diffusion, there should be some similarities between carbon dioxide and water vapour diffusion.

The carbon dioxide permeability values are presented in Table 6, derived from equations (24) and (28). It also contains water vapour permeability values from literature.

Table 6 Comparison of CO_2 permeability values defined in this study to water vapour permeability values (at 20 °C) from literature.

Material	Water vapour permeability δ_v, (x 10^{-6} m^2/s)	Carbon dioxide permeability, δ_{CO2} (x 10^{-6} m^2/s)
Air	24.6[34]	15.3
Cellulose insulation	17-21[35]	9–11
Chipboard	0.4-1[35]	0.15–0.35
Gypsum board	2.6-3.9[35]	1.4–2.3
Mineral wool	22.3-25.7[35]	9–16
Porous fibreboard	1.7-5.7[35]	2.0–3.4
Wood	0.33[35]	0.03–0.05

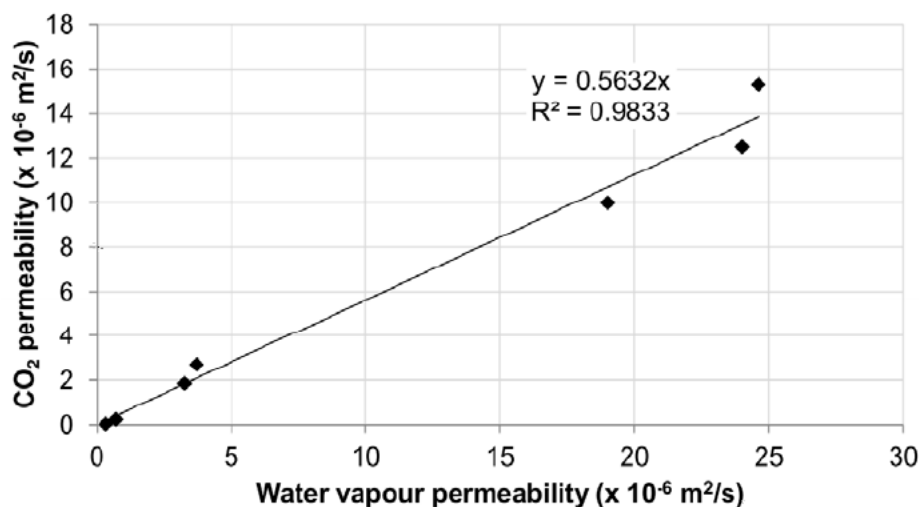Figure 4 shows the average values of Table 6 plotted against each other.

Figure 4 Comparison of carbon dioxide permeability values to water vapour permeability values for materials presented in Table 6. If a range was given in Table 6, average value was used.

A linear fit with an intersection at zero was added to Figure 4. For simple engineering applications with common permeable building materials, CO_2 permeability seems to be close to half of the water vapour permeability. However, further studies are still recommended due to lack of standardized measurement method for CO_2 permeability of structures, variation in the material properties between different manufacturers and product batches and the impact of surrounding conditions on the CO_2 diffusion, e.g. impact of temperature and material moisture content.

3.5 The carbon dioxide balance of a bedroom

3.5.1 Baseline results

An attempt was made to model the impact carbon dioxide permeable wall structures on the indoor air carbon dioxide content. The impact of permeable wall structures on total carbon dioxide balance is, all in all, a complicated mass transfer event. The simple calculation method used in this study provides only a rough estimate.

The conditions determining the quality of the indoor air of detached and semi-detached houses often occur in bedrooms at night, when the occupants sleep and the communicating door is closed.[12] Calculations were done using equation (19) to take into account the carbon dioxide production from occupants and the transfer with ventilation and diffusion through structures.

The corner room of a one-storey detached or semi-detached house, with two external walls and two partitions, was selected for the calculation. The chosen structures are presented in Table 7.

Table 7 Structures used in calculation and their carbon dioxide resistance values (mean values).

Structure	Material	Carbon dioxide resistance, Z_{CO2} (x 10^3 s/m)
External wall	Wallpaper	1.5
	Gypsum board 2, 13 mm	6.9
	Building paper	3.4
	Cellulose insulation, 150 mm	15
	Porous fibreboard 2, 12 mm	4.1
	Total	**30.9**
Partition	Wallpaper	1.5
	Gypsum board 2, 13 mm	6.9
	Cellulose insulation, 100 mm	10
	Gypsum board 2, 13 mm	6.9
	Wallpaper	1.5
	Total	**26.8**
Ceiling	Matt latex paint	4.1
	Gypsum board 2, 13 mm	6.9
	Building paper	3.4
	Cellulose insulation, 300 mm	30
	Total	**44.4**

The following initial values were used: the dimensions of the bedroom were 3 m x 4 m x 2.7 m, the external wall had one window (2.0 m^2) and the partition had a door

(1.6 m^2) and both were closed. Furthermore, it was assumed that the two people

sleeping in the room would produce 215 ml/min/person of carbon dioxide (an adult's

resting production).[12,36] This amount corresponds to 6.5x10^{-6} kg/(s·person). The impact

of temperature and relative humidity on the carbon dioxide permeability of materials

was not taken into account. The calculation period was 8 hours.

The room's air change rate was varied in order to produce different values for the

final carbon dioxide content. The air change rates 0.5 h^{-1} and 0.9 h^{-1} (0.139·10^{-3} 1/s and

0.25·10^{-3} 1/s in equation (7)) are the minimum air change rates of the Finnish building

code. The value 0.5 h^{-1} is a general value for rooms of regular height if no more

accurate information is available. The value 0.9 h^{-1} is based on the number of occupants:

The minimum air change rate for two persons in the studied bedroom is: (2 people x 4

dm^3/(person·s)/(3 m x 4 m x 2.7 m) = 0.89 h^{-1}), where 4 dm^3/(person·s) is the minimum

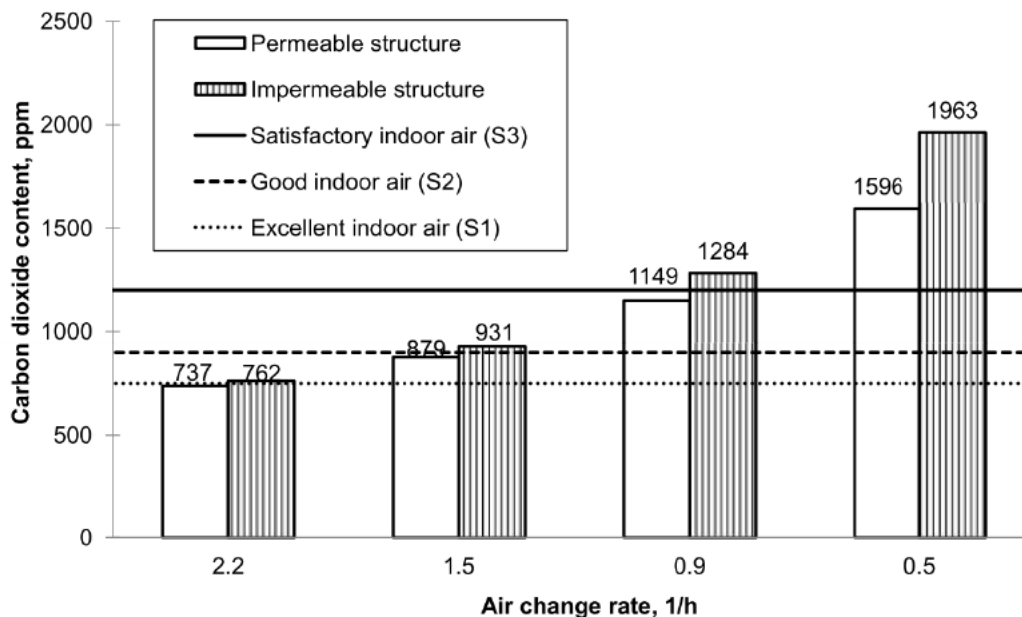supply air flow per person[37,38]. The calculation results are given in Figure 5.

Figure 5 The stabilized carbon dioxide contents in a detached house corner bedroom at different air change rates. The CO2 levels are from the Finnish classification of building climate.[17]

The air change rate 0.5 h^{-1} was not effective enough to fulfil the minimum requirement for indoor air set by the Finnish classification of building climate. With an air change rate 0.9 h^{-1} the minimum requirement (Class S3) was met with permeable structures. In the case of permeable structures, air change rate 1.5 h^{-1} gave a level of carbon dioxide that met the demands of Class S2. For permeable structures to fulfil the demands of Class S1, the air change rate needs to be 2.2 h^{-1}. The classes are described in Table 1.

In a real-life situation many other factors besides diffusion affect the carbon dioxide balance of indoor air – such as variations in CO_2 production air flow routes inside the buildings. Also, the calculation method used here does not consider the amount of carbon dioxide that the pore air of structures may contain. If the CO_2 content of pore air is low at the start of the loading period, the carbon dioxide flow is resisted only by the

wall board and finish, meaning that the calculation underestimates the reduction in carbon dioxide indoors, at least at the beginning of the observation period. Due to its heavier molecular weight compared to air, carbon dioxide tends to concentrate more in the lower sections of a building's air space, which is why calculations overestimate the reduction in carbon dioxide through the ceiling to some extent. Changes in outdoor and indoor temperatures or moisture contents of materials were not taken into account either.

3.5.2 Sensitivity study

The input values used for 2000 Monte Carlo -calculations were otherwise the same than in the previous chapter 3.5.1, but with the changes presented in Table 8. The Spearman correlation coefficients calculated from the results are also shown in the same table.

Table 8 Description of the parameters used in the Monte Carlo calculations and the Spearman correlation coefficients calculated for the variable mentioned and the carbon dioxide concentration of the room at the end of the calculation period (eight hours).

Variable	Value or range used	Spearman correlation coefficient, p-value
Air change rate, 1/s	Uniform(0.35, 2.2)/3600	-0.79, <0.001
Size of the room, m	B = Uniform(2.0, 6.0)	Floor area:
	L = Uniform(3.5, 6.0)	-0.55, <0.001;
	H = Uniform(2.4, 2.7)	Room height:
		-0.059, 0.008
Size of windows (CO_2 impermeable area), %	Uniform(10% of floor area, 50 % of envelope area)	0.18, <0.001
CO_2 production per person, ml/(min*person)	Uniform(175, 255)	0.17, <0.001
CO_2 permeability of the envelope, x 10^3 s/m	Uniform(20, 2000)	0.030, 0.18

The minimum room size and the window area are based on the Finnish building regulations. The variation in the carbon dioxide production per person is based on selecting roughly a 20% change into both directions.

Based on the results of the Monte Carlo calculations, 98% of the runs had the final carbon dioxide concentration of the room at least 97% of the steady-state carbon dioxide concentration. The lowest amount was 95% of the steady-state value, which occurred at the case of the highest absolute carbon dioxide concentration. The grand mean of carbon dioxide concentration of the whole night was 92% of the corresponding steady-state values. These results mean, that the carbon dioxide concentration inside the studied bedroom environment reached the steady-state values well, as was indicated in chapter 2.3.5.

Based on the Spearman rank-correlation coefficients, the two most important parameters for the carbon dioxide concentration of a room at the end of the night were the air change rate and the floor area. The variation in carbon dioxide production per person and the amount of CO_2 impermeable area had the second biggest impact. Room height and carbon dioxide resistance of the envelope structures had the smallest impact. These correlation coefficients represent the whole data sets, whereas the results in Figure 5 show a few specific combinations. When the results from Figure 5 and Table 8 are compared, there are certain situations where the impact of carbon dioxide permeable envelope structures can have a bigger benefit (e.g. 100% x (1963 ppm – 1596 ppm)/1963 ppm = 19 %, but in general the benefit is much smaller.

The Spearman rank-correlation coefficient was used instead of the Pearson correlation coefficient, because some of the variables were not linearly correlated to the carbon dioxide content at the end of the eight hours' calculation period. Those variables in Table 8, that had negative correlation coefficients, had an inversely proportional change to the carbon dioxide concentration. However, the Pearson correlation coefficients were also calculated as a reference values and the results behaved similarly to the Spearman correlation coefficients. The impact of using the reciprocals of air change rate, floor area and room height increased the Pearson correlation coefficient values, but it didn't change the order of magnitude compared to the values in Table 8. The inverse proportionality means that the changes in the air change rate and room volume have the biggest impact when the absolute values are small, but the impact decreases as the absolute values become larger. For air change rate this can be also seen in Figure 5.

4 Conclusions

The study examined the transmission of carbon dioxide through structures that allow the diffusion of gases. The results of the tests and calculations were as expected. Moisture seems to lower the carbon dioxide permeability of wood, but the test results did not demonstrate how moisture affects the carbon dioxide flow through a structure composed of other materials. Theoretically, lower temperature slows down the diffusion of carbon dioxide, but development of methods that take this into account would probably provide insignificant benefits for real-life situations.

Based on the measured carbon dioxide permeability values of building materials and the conducted bedroom air carbon dioxide concentration calculations, using more

carbon dioxide permeable building envelope structures does decrease the carbon dioxide concentration in the room spaces during night-time, but its impact isn't big enough to compensate for the lack of ventilation. It is also important to notice, that carbon dioxide is only one gaseous substance and the final ventilation rates in room spaces depend on the total amount of impurities in those areas.

A linear correlation was found between carbon dioxide and water vapour permeability ($\delta_{CO2} = 0.56\delta_v, R^2 = 0.98$), which means that the more permeable the materials are for carbon dioxide the more permeable they are also for water vapour diffusion. In Nordic countries with almost continuous indoor air moisture excess compared to outdoor air, this leads to increased moisture loads to envelope structures from indoor air and this way also increased risk of excessive condensation in autumn and winter, and thus, mould growth.[39]

The calculations made on the carbon dioxide content of a room were simple and must be viewed critically since they involve many assumptions. According to sensitivity studies, steady-state values were reached or almost reached in most of the cases. The air change rate (in 1/h) and floor area had the biggest impact on the carbon dioxide concentration of the bedroom air. The size of CO_2 impermeable window area and production rate had the second biggest impact on the resulting values, while the room height and the CO_2 resistance of the room envelope had only a small impact on the results. Further studies could improve the accuracy of the results by taking the impacts of actual temperature and moisture conditions and air leakages into account. From the

sensitivity study point of view, it would also be beneficial to be able to narrow the range of input data variation.

As a summary, carbon dioxide permeable building envelope structures can alleviate the harmful effects of temporarily elevated carbon dioxide content, but the more effective and adjustable way is to have a properly functioning ventilation in the room spaces. If carbon dioxide permeable building envelope structures are to be used, it is important to also properly design and implement the moisture durability of envelope structures and sufficient room ventilation.

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