

## A NEW APPROACH CHANGING EXPECTATIONS FROM SOLID PARTS OF BUILDING ENVELOPES: TESTING THE CARBON DIOXIDE DIFFUSION AND RETAINING PERFORMANCES OF BUILDING MATERIALS (1)

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### INTRODUCTION

Contemporary building technology focuses on fully airtight building envelopes supported with mechanical or hybrid ventilation systems for energy-efficient buildings and healthier indoors. In fact, during COVID-19 pandemic and associated lock-downs, people realized how valuable fresh air is in built environments. Experts and governments promoted natural ventilation to meet higher air change rates. If mechanical ventilation is the only option, it is recommended to stop recirculation and feed the indoor air with 100% outdoor air (ASHREA, 2020; REHVA, 2021). These recommendations are quite challenging for a sustainable construction sector aiming at energy efficiency. This challenge presents an opportunity to think out of the box. In other words, this situation awakens curiosity to other undiscovered horizons beyond the common approach which encourages fully airtight built environments and advanced mechanical ventilation solutions. Here, this study asks a striking question: "What if the key to healthier indoor air is the breathable building envelopes?" This question may be considered as a paradigm shift for the building science community obsessed with airtightness. In fact, the concept of breathable walls is not new, but this hitherto underestimated approach is worth reconsidering.

The disadvantages of the fully-airtight built environments cannot be ignored. That is why the airtight building envelopes consisting of impermeable exterior walls by using moisture-proof and vapor-proof layers in their multi-layered compositions is no longer the only approach anymore. The experiences in construction practices over time have revealed that any failure in one of these impervious layers results in entrapped moisture within the wall section (Massari and Massari, 1993; Richardson, 2001).

In contrast to airtight building envelopes, the "breathable skin" concept has gained importance in today's construction practices in the last few decades.

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Here, the term “breathable skin” refers to a multi-layered wall composed of highly water vapor permeable layers that allows water vapor to diffuse back and forth through the wall section. The historical and traditional material technologies achieved in the past have proved that the breathing features of a wall contribute to its long-term durability by preventing condensation and entrapped moisture problems (Kömürçüoğlu, 1962; Houben and Guillaud, 1989; Akkuzugil, 1997; Caner, 2003; Esen et al., 2004; Keefe, 2005; Örs, 2006; Morton, 2008; Šadauskiene et al., 2009; Tavukçuoğlu et al., 2013; Mlakar and Štrancar, 2013). In addition, that kind of breathable building envelopes provide a sort of self-ventilation through the porous body and are expected to contribute to cleaning the indoor air at a certain level (Yüncü et al., 2014; Yüncü 2016; Niemela et al., 2017; Benavente and Pla, 2018). However, there is a lack of knowledge in the literature on the quantitative assessment of the air exchange potential of porous building materials, specifically forming the solid part of the building envelope. Building envelopes composed of building materials with a certain CO<sub>2</sub> reduction (CO<sub>2</sub> transmission and retaining) performance can also be useful for regulating the concentrations of occupant-related indoor air pollutants. That approach of testing materials for CO<sub>2</sub> reduction behavior in order to identify the appropriate building materials to create breathable and CO<sub>2</sub>-reducing wall systems, rather than airtight ones, is a novel and challenging research topic in the field.

A comprehensive discussion of the relevant literature is summarized under the following heading. The outputs of the discussion revealed the necessity of testing the CO<sub>2</sub> reduction performance of building materials in terms of measurable parameters and assessing the impact of that performance on indoor air quality. In this regard, the study proposes “CO<sub>2</sub> diffusion coefficient” and “CO<sub>2</sub> retaining ratio” as indicators to measure CO<sub>2</sub> reduction performance of building materials and introduces a practical testing method to assess the materials’ contribution to indoor air quality.

## DISCUSSION ON BACKGROUND INFORMATION

Depending on the daily activities of today’s modern lifestyle, people spend most of their time in buildings (Walden, 2018). It is well-known that healthy indoor air is a right for every human being (WHO, 2000). However, the recent COVID-19 pandemic shows that poorly-ventilated indoor environments can easily become a source of airborne contagious diseases. Accordingly, providing good indoor air quality is essential for the built environment. In this regard, there are so many studies on finding out solutions for maintaining healthy indoor air in airtight buildings. On the other hand, a new approach that changes expectations from solid parts of building envelopes is emerging. At that point, it is worth investigating the potentials of building materials in cleaning indoor air. Accordingly, there is a scarcity of knowledge related to the impact of the solid parts of the building envelope on indoor air quality. This signals the necessity of measurable parameters and experimental methods to assess such an impact on a quantitative basis.

Achieving high airtightness seems to be desirable from the energy efficiency point of view since the presence of air leakage is expected to weaken the energy efficiency of the building envelope (Feist et al., 2005; Sassi, 2013; PHI, 2013; Cotterell and Dadeby, 2013; Pukhal et al., 2015). On the other side, the fully-airtight indoors engender the risk of poor IAQ (indoor air quality), therefore necessitating the integration of continuous

and automated mechanical ventilation and air conditioning (VAC) systems in buildings to achieve healthy indoor air. According to the COVID-19 pandemic measures, mechanical ventilation systems has to be fed by 100% fresh air (ASHREA, 2020; REHVA, 2020; Elsaid and Ahmed, 2021; ECDC, 2021). Like a vicious circle, the operation of these systems with fresh air feed increases the consumption of electrical energy and decreases the energy efficiency of the building (Van de Wal et al., 1991; Sakaguchi and Akabayashi, 2003; Williams, 2012; Derbez et al., 2014). Moreover, in the case that the mechanical VAC systems are not properly functional or maintained, the concentration of indoor air pollutants reaches unhealthy levels that may cause sick building syndrome and the spread of air-borne contagious diseases. Considering all, smart approaches with focuses on breathable envelopes and pollutant-removal finishing materials are the recent interests of the scientific research studies (IOM, 2011; Heidari et al., 2017; EPA, 2019).

An approach based on human skin analogy is guiding a better understanding of the indoor air cleaning performances of building envelopes (Gruber and Gosztanyi, 2010; Pohl and Nachtigall, 2015; Öztoprak, 2018). Despite the fact that the contribution of human skin to the total oxygen supply mechanism of the whole body is proportionally very small, this contribution has vital importance for the whole body system (Stücker et al., 2002; Pucci et al., 2012). Apart from O<sub>2</sub> and CO<sub>2</sub> exchange, human skin also plays a role in the exclusion of toxic materials such as numerous volatile organic compounds (VOCs) (Mochalski et al., 2013; Mochalski et al., 2014; Mochalski et al., 2018). Similar to the respiratory function of human skin, the self-ventilation ability of building envelope is predicted to have important effects on providing a healthy building skin and healthy indoor environment. Here, the term “self-ventilation” refers to the natural ventilation capability of a building material itself through its porous body. Departing from the widely used architectural analogy between the human skin and the building envelope, such an indoor air cleaning function performed by the building skin contributes to reducing the concentration of indoor air pollutants (Clements-Croome, 2004; British Gypsum, N.D.). Therefore, there is a necessity to measure indoor air pollutant reduction performances of building materials forming the building envelope and to develop relevant testing methods for assessment of such performances.

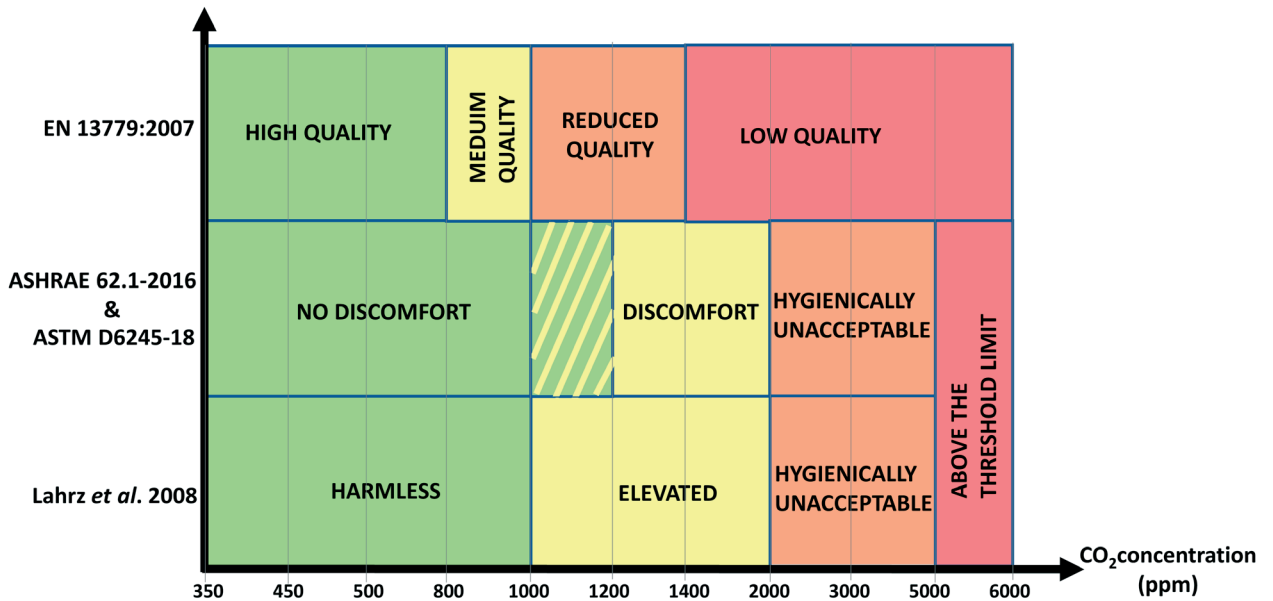
### **Indoor Air Quality (IAQ) and CO<sub>2</sub> as an IAQ Indicator**

Achieving physical indoor comfort conditions, including healthy indoor air, is within the responsibilities of designers and engineers. Being part of the architectural design, the building envelope is expected to eliminate building-related inefficiencies such as inadequate ventilation, heating and cooling conditions, poor lighting and acoustical features, and the use of VOC-emitting materials. Several studies show that occupants experience physical symptoms of sick building syndrome and they feel discomfort due to inadequate indoor air (Fisk and Rosenfeld, 1997; Samet and Spengler, 2003). To avoid that inconvenience and to provide healthier indoor air, it is simply suggested to supply fresh air and increase air exchange rate (ESFA, 2018). Worldwide indoor CO<sub>2</sub> monitoring studies show that serious indoor air quality issues have been present even in developed countries. One of the challenging issues is the design of building skins which contribute to indoor air pollutant reduction. However, the unknowns related to air pollutant reduction performance of building materials are

so many. Unfortunately, many international and national institutes such as GREENGUARD Environmental Institute (GEI), American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), California Department of Public Health (CDPH), American Society for Testing and Materials (ASTM) do not consider air pollutant reduction performance of building materials in the widely-used IAQ assessment and estimation methods (GEI, 2010; ANSI/ASHRAE 62.1-2016, 2016; CDPH, 2017; ASTM E741-11:2017, 2017; ASTM D6245-18:2018, 2018). Therefore, the relevant existing standards and applications are to be investigated and discussed accordingly.

The pollutants – which adversely affect the indoor air quality – are classified mainly in two groups namely; outdoor-related and indoor-related pollutants. This study deals with the pollution of indoor air with a focus on occupant-related pollutants. The sources of occupant-related indoor air pollutants originate from human breath and skin metabolism (Fanger, 1998; Phillips et al., 1999). These pollutants are mostly composed of CO<sub>2</sub> and human VOCs. Among those pollutants, CO<sub>2</sub> is the well-known one that is emitted by the human body. As a gas, CO<sub>2</sub> is one of the widely-used indicators for assessing indoor air quality as well as the human presence in interior spaces (Yang et al., 2014; Candanedo and Feldheim, 2015; Huang and Mao, 2016) Therefore, the activity-dependent correlation between occupant presence and indoor carbon dioxide concentration encourages the CO<sub>2</sub> monitoring studies for the IAQ assessment.

Literature presents some international standards and guidelines to define indoor air quality in terms of CO<sub>2</sub> concentration levels. For instance, according to ASHRAE 62.1-2016 standard, an indoor CO<sub>2</sub> concentration ( $C_{IN}$  ppm) above 5000 ppm is considered an unacceptable level that can pose a health risk for occupants (ANSI/ASHRAE 62.1-2016, 2016). In addition, if the indoor CO<sub>2</sub> concentration is 700 ppm above the outdoor level, occupants are expected to experience discomfort. The indoor CO<sub>2</sub> concentration level above the level of outdoor CO<sub>2</sub> concentration ( $C_{OUT}$  ppm) also signals the presence of odorous bio-effluents which are the other contaminants, sourced from occupants (ANSI/ASHRAE 62.1-2016, 2016; ASTM D6245-18:2018, 2018). Therefore, the difference between the indoor and outdoor CO<sub>2</sub> concentration levels in ppm ( $\Delta C$ , ppm) is used as an indicator of bio-effluents; in other words, an indicator of occupant discomfort. According to the EN 13779:2007 standard, indoor air quality is assessed by taking into consideration both the  $C_{OUT}$  level and  $\Delta C$  levels (EN 13779:2007, 2007). The range of  $C_{OUT}$  level is given as 300-500 ppm in ASHRAE 62.1-2016 standard while the  $C_{OUT}$  level is defined as 350 ppm for rural areas, 375 ppm for suburban areas or small towns and 400 ppm for polluted city center in European Standards (EN 13779:2007, 2007; ANSI/ASHRAE 62.1-2016, 2016; ASTM D6245-18:2018, 2018). Considering the reference  $\Delta C$  and  $C_{OUT}$  levels given in EN 13779:2007 standard, the indoor CO<sub>2</sub> concentration levels can be categorized into certain ranges: the  $C_{IN}$  level below 800 ppm corresponding to high quality; between 800-1000 ppm corresponding to medium quality; between 1000-1400 ppm corresponding to reduced quality and; above 1400 ppm corresponding to low quality (as in Figure 1). According to the reference  $\Delta C$  and  $C_{OUT}$  levels given in ASHRAE 62.1-2016 standard and ASTM D6245-18 standard guide, the  $C_{IN}$  levels above 1000-1200 ppm may lead occupants to experience discomfort and that range is consistent with the reduced quality range as categorized in EN13779:2007 standard (Figure 1). In addition, the  $C_{IN}$  level above 2000 ppm is considered to be hygienically unacceptable (Lahrz et al., 2008;



**Figure 1.** The indoor CO<sub>2</sub> concentration levels (C<sub>IN</sub>, ppm) categorized by taking into consideration the reference CO<sub>2</sub> concentration difference (ΔC, ppm) and outdoor CO<sub>2</sub> concentration levels (C<sub>OUT</sub>, ppm) levels given in international standards and the literature. This figure is prepared by the authors.

Twardella et al., 2012) and the C<sub>IN</sub> level above 5000 ppm is accepted as the threshold limit value where the CO<sub>2</sub> concentration may cause health risks (ANSI/ASHRAE 62.1-2016, 2016; ASTM D6245-18:2018, 2018).

Currently, EN 13779:2007 standard has been withdrawn and replaced by EN16798-3:2017 standard (EN 16798-3:2017, 2017). The new standard declared in 2017 does not contain the main classification defining the high, medium, reduced and low ranges for indoor air quality in terms of CO<sub>2</sub> concentrations. Instead, it introduces a classification based on supply air quality. Since measuring the concentration of indoor air pollutants is a reliable method for confirming whether the IAQ is on the safe side or not, the inclusion of carbon dioxide concentration classification is recommended (Mazzarella and Hogeling, 2018).

Most recent studies investigate the relationship between indoor CO<sub>2</sub> concentration levels and occupants' health, comfort and cognitive performances. For instance, if the CO<sub>2</sub> concentration is increased from 600 ppm to 1000 ppm in controlled room conditions, a moderate reduction in six of nine scales of decision-making performance is observed while a significant reduction in seven of nine scales of decision-making performance is observed when CO<sub>2</sub> concentration is increased from 1000 ppm to 2500 ppm (Satish et al., 2012). In spite of the significant reduction in cognitive performances of the occupants, a slight increase is observed in the focused activity scale. Another study revealed that when the indoor air CO<sub>2</sub> concentration increases up to 3000 ppm from 600 ppm, the air quality becomes significantly less comfortable for occupants in terms of subjective comfort parameters (Kajtar and Herczeg, 2012). Data on several physiological and psycho-physiological measures prove that when people spend 2 to 3 hours in indoor air with a CO<sub>2</sub> concentration of 3000 ppm or above, greater efforts are needed for performing mental tasks; therefore, the occupants feel much more exhausted (Kajtar and Herczeg, 2012). In short, people feel worse and their focusing capacity gradually decline with the increase in C<sub>IN</sub> levels. Besides, the reference C<sub>IN</sub> levels categorized in international standards as "uncomfortable range (C<sub>IN</sub> > 1000 ppm)", "reduced air quality range (1000 ppm < C<sub>IN</sub> < 1400 ppm)", "low air quality

ranges ( $1400 \text{ ppm} < C_{\text{IN}} < 2000 \text{ ppm}$ )” and “hygienically unacceptable range ( $C_{\text{IN}} \text{ level} > 2000 \text{ ppm}$ )” (Figure 1), are the contaminated circumstances for occupants that may cause decline in their cognitive performances and require fresh air intake by ventilation.

The studies which measured the actual  $\text{CO}_2$  concentration levels in various spaces such as classrooms, meeting rooms, offices and bedrooms reveal that the daily average  $\text{CO}_2$  concentration levels ( $C_{\text{AVG}}$  levels) are mostly above 1000 ppm which indicate uncomfortable circumstances (**Table 1**) (Corsi et al., 2002; Whitmore et al., 2003; Fromme et al., 2007; Fisk et al., 2010; Kim et al., 2011; Bulut, 2012; Batog and Badura; 2013; Gaihre et al., 2014; Muscatiello et al., 2015; Canha et al., 2016; Petersen et al., 2016; Vilčeková et al., 2017; Shin et al., 2018). Among those measurements, the  $C_{\text{AVG}}$  levels exceeding 1400 ppm and 2000 ppm exhibit low air quality and hygienically unacceptable air quality, respectively. Especially in cold seasons, the maximum  $\text{CO}_2$  concentration levels are observed to reach above 3000 ppm that signal noticeably-polluted indoor air (Corsi et al., 2002; Fromme et al., 2007; Kim et al., 2011; Batog and Badura; 2013). Another study exhibits that the maximum  $\text{CO}_2$  concentration levels ( $C_{\text{MAX}}$ ) in a meeting room with around a volume of  $500 \text{ m}^3$  can reach up to 2000 ppm or more within the periods of 30 to 90 minutes (Fisk et al., 2010). Considering all these studies, indoor air may become unhealthy for occupants within a short period of time in case that fresh air intake is not allowed or not enough. One way or another, fresh air intake is necessary to avoid such polluted interiors and to reduce  $\text{CO}_2$  concentration. Besides, building envelopes composed of building materials with a certain  $\text{CO}_2$  reduction performance can also be useful for regulating the concentrations of indoor air pollutants. This approach is a novel and challenging research topic in the field.

### **$\text{CO}_2$ Diffusion Coefficient as an Indicator of $\text{CO}_2$ Reduction Performance**

The breathing features of a building material is commonly determined by measuring the amount of water vapor diffused through its porous matrix in a certain period of time when a certain difference in water vapor pressures of two neighboring media is provided (TS EN ISO 7783:2015, 2015). However, the major indicator that presents the concentration of occupant-related indoor pollutants in a space is the  $\text{CO}_2$  gas. The molecular volume and molar mass of  $\text{CO}_2$  is larger than those of water vapor ( $\text{H}_2\text{O}$ ) and the  $\text{CO}_2$  diffusion coefficient in the air ( $\text{cm}^2\text{s}^{-1}$ ) is smaller than the  $\text{H}_2\text{O}$  diffusion coefficient in the air (**Table 2**) (Cussler, 1997; Welty, 2019). The water vapor diffusion rate ( $\text{g}/\text{hm}^2$ ) is a well-accepted parameter to define breathability characteristics of building materials (TS EN ISO 7783:2015, 2015; Strother and William, 1990; Richardson, 2001; ASTM E96/E96M-16:2016, 2016; DIN EN ISO 12572:2017). On the other hand, water vapor diffusion rate is not enough to define the pollutant reduction capability of building materials concerning indoor air quality (Yüncü 2016; Niemela et al., 2017). Considering that diffusion of  $\text{CO}_2$  is slower than that of  $\text{H}_2\text{O}$  in porous media, the effective  $\text{CO}_2$  diffusion coefficient in materials is comparatively a more decisive parameter of occupant-related pollutant reduction performance. In addition, any possible interaction between the  $\text{CO}_2$  and the building material may cause  $\text{CO}_2$  to be retained by the material. In this regard, this study introduces “effective  $\text{CO}_2$  diffusion coefficient ( $D_{\text{EFF}} \text{ cm}^2\text{s}^{-1}$ )” and “ $\text{CO}_2$  retaining ratio ( $M_{\text{RET}}/M_{\text{P}}$  % by weight)” as material-specific parameters to assess pollutant reduction features of building materials.

Room function	$C_{AVG}$ (ppm)	$C_{MAX}$ (ppm)	$C_{OUT}$ (ppm)	Country	Reference
Classroom	1180	1828	340-410	USA	Corisi et al. 2002
	1653	2570			
	2857	3337			
	NA	4172 (in winter)	381-490	Germany	Fromme et al., 2007
	NA	1875 (in summer)	338-509		
	2417	4113	382-530	Korea	Kim et. al, 2011
	998	2324	313-475	Turkey	Bulut, 2012
	1086	2167	NA	UK	Gaihre et al., 2014
	812	1591	NA	USA	Muscatiello et al., 2015
	1610±500	2740	NA	Denmark	Petersen et al., 2016
	1290	2220	NA	France	Canha et al. 2016
	1315 (winter) 1094 (summer)	1651 (winter) 1241 (summer)	400	Slovakia	Vilčekováa et al., 2017
	1064 (portable) 1074 (traditional)	above 2000 above 2000	426.5	USA	Whitmore et al., 2003
1695-987	above 3000	363-566	Italy	Schibuola and Tambani 2020	
Office	885	1685	313–475	Turkey	Bulut, 2012
Meeting room	NA	1910±263	510	USA	Fisk et al.,2010
Bedroom	1508 (object 1)	3277±554	NA	Poland	Batog and Badura, 2013
	2755 (object 2)	3874±628			
	1935 (object 3)	2730±104			
	719 (object 4)	1583±200			
	535 (object 5)	1894±44			
	NA	2216	NA	Korea	Shin et al., 2018
1210-712	above1250	NA	Portugal	Belmonte et al., 2019	
Living room	971-653	above1250	NA		

**Table 1.** Time-weighted average of CO<sub>2</sub> concentration levels ( $C_{AVG}$ ) and maximum CO<sub>2</sub> concentration levels ( $C_{MAX}$ ) measured during working hours (in classrooms, offices and meeting rooms) or sleeping hours (in bedrooms). This table is prepared by the authors.

### PROPOSED TESTING METHOD

The new testing method proposed in the study is based on measuring the CO<sub>2</sub> concentration changes in neighboring spaces in a certain period of time when partial pressure difference of CO<sub>2</sub> is provided between those two adjacent spaces separated by a building material. The common approach in the literature is testing the airtightness of building envelope by means of monitoring the indoor CO<sub>2</sub> concentration when a certain amount of CO<sub>2</sub> intake to the enclosed space is provided. For that purpose, three testing methods, namely; “concentration decay test method”, “constant injection test method” or “constant concentration test method” are recommended to measure air leakages through the air gaps of building envelope with the use of CO<sub>2</sub> as the tracer gas (ASTM E741-11:2017, 2017). However, the main target of the testing method proposed in the study is to measure the CO<sub>2</sub> reduction performance of a building material forming the solid parts of building envelope rather than to measure the airtightness performance of a building envelope. The other target of the proposed testing method is to

**Table 2.** The comparison of CO<sub>2</sub> and H<sub>2</sub>O in the gas form under 1 atm. pressure in terms of diffusion coefficient (cm<sup>2</sup>s<sup>-1</sup>) in air, molecular volume and molar mass (Cussler, 1997; Welty, 2019). This table is prepared by the authors.

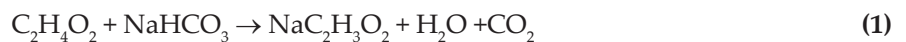
Gas	Diffusion coefficient in air (cm <sup>2</sup> s <sup>-1</sup> )	Temperature (°C)	Molecular Volume (cm <sup>3</sup> .mol <sup>-1</sup> )	Molar Mass (g)
H <sub>2</sub> O	0.282	16	18.9	18
	0.26	25		
CO <sub>2</sub>	0.148	9	34.0	44
	0.16	25		

develop a practical and repeatable experimental setup that does not require sophisticated instruments used for controlled managing and measuring CO<sub>2</sub> intake and outtake.

Here, the test method proposed in the study is composed of two experimental setups, namely; “single-chamber” and “double-chamber”. The single-chamber setup is a system that permits CO<sub>2</sub> transmission through a building material from inside to outside and the CO<sub>2</sub> concentration reduction in the chamber is monitored during the transmission of CO<sub>2</sub> through the porous material. The double-chamber setup is a closed system that does not permit CO<sub>2</sub> escape and CO<sub>2</sub> transmission through the building material is monitored by taking CO<sub>2</sub> concentration measurements in neighboring chambers. The joint interpretation of the data achieved by those setups are used to determine the CO<sub>2</sub> reduction performance of building material in terms of measurable parameters, namely; “CO<sub>2</sub> diffusion rate (E, mg. s<sup>-1</sup>)”, “effective CO<sub>2</sub> diffusion coefficient (D<sub>EFF</sub> cm<sup>2</sup>.s<sup>-1</sup>)” and “CO<sub>2</sub> retaining ratio (M<sub>RET</sub>/M<sub>T</sub>, % by weight).

“The CO<sub>2</sub> supply” and “the duration of one test session” are two main issues considered to make the testing method as practical as possible. A simple CO<sub>2</sub> source providing a high level of initial CO<sub>2</sub> concentration in a chamber is used. The high CO<sub>2</sub> concentration as an initial level enables monitoring CO<sub>2</sub> diffusion through a building material in more detectable ranges and shortening the test period to 24 hours. In daily life, occupant related indoor CO<sub>2</sub> emission occurs during working hours in an office room, whereas it occurs during sleeping hours in a bedroom on a daily basis. For that reason, examining the CO<sub>2</sub> reduction capability of building materials within a one-day cycle is more crucial to better understand their contribution to enhance indoor air quality.

For the single and double chamber diffusion tests, the source of CO<sub>2</sub> is provided by mixing acetic acid (C<sub>2</sub>H<sub>4</sub>O<sub>2</sub>) and sodium bicarbonate (NaHCO<sub>3</sub>) in a beaker put in the chamber (Equation 1). The mixture of 50 ml acetic acid and 2 g sodium bicarbonate generates approximately 500 mg CO<sub>2</sub> which approximately corresponds to the CO<sub>2</sub> concentration of 17500 ppm. The relative humidity (RH, %) in the sealed chamber is observed to increase by 2.5% at most within 10 hours after the reaction begins. Such a slight impact of the CO<sub>2</sub> source on the moisture content in the chamber shows that this source is appropriate for testing CO<sub>2</sub> diffusion. Together with the existing CO<sub>2</sub> amount in the fresh air, the highest level of CO<sub>2</sub> concentration provided is around 18000 ppm in a fully-airtight acrylic glass chamber with a volume of 0.016 m<sup>3</sup>. The tightness of the sealed acrylic glass chambers used in the experimental setups has been verified by preliminary tests that monitor CO<sub>2</sub> concentration in the chamber for 24 hours (ASTM E741-11:2017, 2017).



The CO<sub>2</sub> concentration measurements inside and outside the chambers are taken in specific time intervals with a CO<sub>2</sub> measuring device and CO<sub>2</sub> monitoring probes. The accuracy of the instruments should be similar for the CO<sub>2</sub> concentration ranges of below and above 5000 ppm. For reliable data acquisition, the calibration of the CO<sub>2</sub> monitoring probes, which will be positioned inside and outside the chambers, needs to be done.

The conversion of CO<sub>2</sub> concentration data collected by the CO<sub>2</sub> measuring device and the CO<sub>2</sub> monitoring probes from ppm to mg.m<sup>-3</sup> units is done



by using Equation 2 and by considering a pressure of 1 atmosphere and a temperature of 25 degrees Celsius in the equation (Mihelcic et al., 2021). These conditions are typical assumption for the conversions of chemicals in the air (Boguski, 2020).

$$C(\text{in mg. m}^{-3}) = C(\text{in ppm}) \times MW \times \frac{P}{RT} \quad (2)$$

where,

C (in mg.m<sup>-3</sup>): CO<sub>2</sub> concentration in mg.m<sup>-3</sup>

C (in ppm): CO<sub>2</sub> concentration in parts per million

MW: molecular weight (44.01 g/mole for CO<sub>2</sub>)

P: Pressure in atm (1 atm)

R: Gas constant (0.08205 L·atm·mol<sup>-1</sup>·K<sup>-1</sup>)

T: Temperature in K (25°C=298.15 K)

The single-chamber and double-chamber experimental setups, data acquisition and evaluation in terms of measurable parameters are explained under the related subheadings. Exemplary graphs are used to explain the data acquisition and evaluation stages of the test procedures. The experimental data presented in those graphs belong to the adobe samples which will be described further in Section 3.

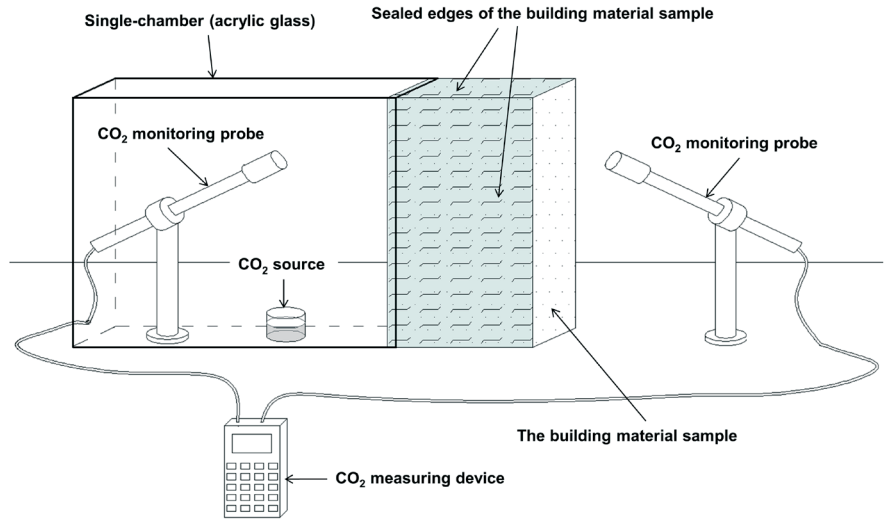
### Single-Chamber Experimental Setup

The single-chamber is composed of an acrylic glass rectangular prism with one of its sides enclosed with building material sample allowing CO<sub>2</sub> diffusion and the other side sealed to air passage (Figure 2). In addition, the edges where the material sample and test chamber meet, and the peripheral surfaces of the material sample are fully sealed against air leakages. Acrylic sealant and at least three layers of stretch film is used for that purpose. In short, the CO<sub>2</sub> transmission is only permitted through the building material in one direction. Criteria that ought to be considered while deciding the dimensions of the chamber include; the sizes of the building material sample under examination and achievement of enough space to host the CO<sub>2</sub> measuring probes. Here, the building material samples are prepared in the form of rectangular prisms with the dimensions of 180 mm × 125 mm × 305 mm (thickness × width × length). The thickness of the sample is the distance where CO<sub>2</sub> transmission occurs. The fully-airtight acrylic glass chamber is produced with a volume of 0.016 m<sup>3</sup> (with dimensions of 390 mm × 130 mm × 310 mm). In addition, the building material sample is kept in the test environment for a week to be in equilibrium with the microclimatic conditions of the testing environment. A constant CO<sub>2</sub> concentration level outside the chamber, i.e., around 500 ppm corresponding to the outdoor concentration should be provided.

The CO<sub>2</sub> concentration decay in the chamber is due to the material's CO<sub>2</sub> diffusion characteristics and the partial pressure difference between its inside and outside. The decrease in CO<sub>2</sub> concentration in the chamber is a building material's performance defined as "CO<sub>2</sub> concentration decay rate (RD<sub>SINGLE</sub> mg.m<sup>-3</sup>.s<sup>-1</sup>)". The test procedure for the same sample should be repeated several times. Achieving similar results also verify the targeted airtightness of the setup.

### Double-Chamber Experimental Setup

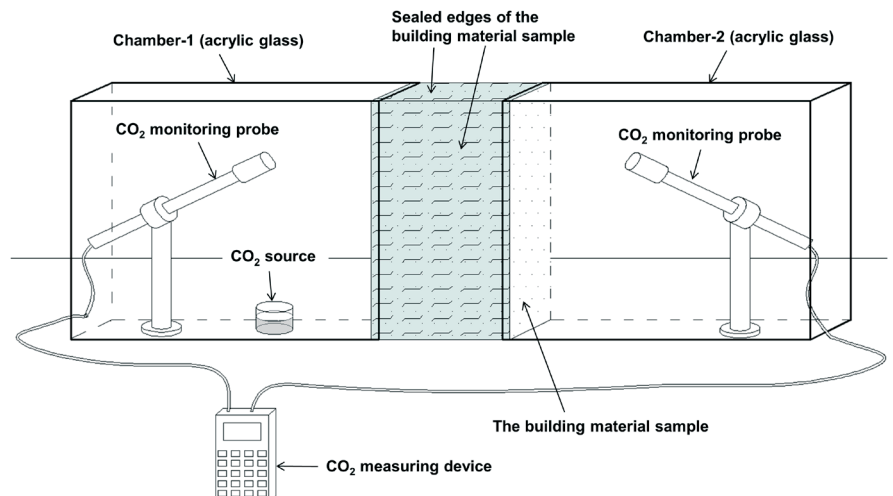
The double-chamber setup is composed of fully-sealed two acrylic glass rectangular prisms and the building material sample positioned in between



**Figure 2.** The descriptive sketch of the single-chamber experimental setup. This figure is prepared by the authors.

the two chambers (Figure 3). The edges where the material sample and test chambers meet, and the peripheral surfaces of the material sample are fully sealed against air leakages; by using acrylic sealant and at least three layers of stretch film. The chambers used in the double-chamber experimental setup are the same in size with dimensions of 390 mm × 130 mm × 310 mm. The building material samples are prepared in the form of rectangular prisms with dimensions of 180 mm × 125 mm × 305 mm (thickness × width × length) and kept in the test environment for a week to be in equilibrium with the microclimatic conditions of the testing environment. A high CO<sub>2</sub> concentration level is provided by placing the CO<sub>2</sub> source in Chamber-1. An initial CO<sub>2</sub> concentration level in Chamber-2, around 500 ppm corresponding to the outdoor concentration, is provided.

The data obtained from the single-chamber setup reveals the CO<sub>2</sub> reduction performance of the material. That performance is due to CO<sub>2</sub> diffusion and CO<sub>2</sub> retaining characteristics which are related to the pore structure and mineralogical composition of the material. The double-chamber experimental setup is a closed system and enables measuring the CO<sub>2</sub>



**Figure 3.** The descriptive sketch of the double-chamber experimental setup. This figure is prepared by the authors.

retaining performance of the material. Any difference between the overall amount of CO<sub>2</sub> in the closed system (M<sub>T</sub>, mg) and the total amount of CO<sub>2</sub> measured in the chambers (M<sub>Ch1-F</sub>+M<sub>Ch2-F</sub>) reveals that the building material keeps a certain amount of CO<sub>2</sub> in its body due to its CO<sub>2</sub> absorption/adsorption characteristics. This knowledge is valuable to interpret the CO<sub>2</sub> concentration decay rate (RD<sub>SINGLE</sub>, mg.m<sup>-3</sup>.s<sup>-1</sup>) data obtained from the single-chamber experiment. In short, the joint evaluation of the data obtained from the single-chamber and double-chamber experiment is necessary to discuss CO<sub>2</sub> reduction performance in terms of CO<sub>2</sub> diffusion and retaining behaviors. The CO<sub>2</sub> retaining behavior of building material samples can be investigated by means of chemical and mineralogical property analyses.

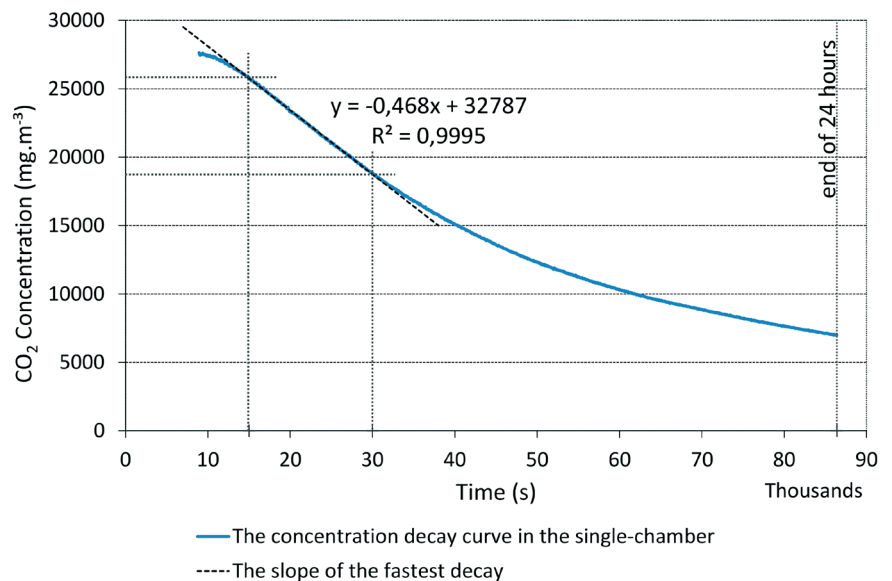
The test procedure for the same sample should be repeated several times. The total amount of CO<sub>2</sub> (M<sub>T</sub>, mg) in this closed system is the key control parameter to verify the targeted airtightness of the setup.

**Data Acquisition and Evaluation in terms of Measurable Parameters**

The CO<sub>2</sub> concentration decay rate (RD<sub>SINGLE</sub>, mg.m<sup>-3</sup>.s<sup>-1</sup>) is obtained by producing the graph which shows the CO<sub>2</sub> concentration data measured in the single-chamber as a function of time. The slope of the linear regression belonging to the fastest CO<sub>2</sub> reduction is used to determine the RD<sub>SINGLE</sub> value (Figure 4). The experimental data presented in Figure 4 is obtained by testing the adobe samples.

The RD<sub>SINGLE</sub> data extracted from that graph is used to calculate the CO<sub>2</sub> diffusion rate (E, mg. s<sup>-1</sup>) and the effective CO<sub>2</sub> diffusion coefficient (D<sub>EFF</sub>, cm<sup>2</sup>.s<sup>-1</sup>) of the building material based on Equation 3 and 4, respectively. A brief definition of the parameters related to the single-chamber diffusion test are given below:

- **Concentration decay rate in single-chamber (RD<sub>SINGLE</sub>, mg.m<sup>-3</sup>.s<sup>-1</sup>):** It is the initial rate presenting the fastest reduction in CO<sub>2</sub> concentration until the fastest concentration decay starts to slow down due to the significant decrease in the partial pressure difference between the inside and outside of the chamber (Figure 4). That initial period of



**Figure 4.** The CO<sub>2</sub> concentration decay curve versus time obtained from the 24hrs experiment period of the single-chamber diffusion test and showing the slope of the fastest CO<sub>2</sub> concentration decay in the chamber (The experimental data belongs to the adobe samples). This figure is prepared by the authors.

concentration decay is considered during the regression analysis.  $RD_{\text{SINGLE}}$  is the slope of the best-fit linear regression of this initial period.

- **CO<sub>2</sub> diffusion rate** ( $E$ , mg.s<sup>-1</sup>): It is the amount of CO<sub>2</sub> that diffuses through a porous material in time (Jacobs, 1967; Wilson et al., 2009). It is calculated by using  $RD_{\text{SINGLE}}$  values obtained from the single-chamber tests using Equation 3.

$$E = RD_{\text{SINGLE}} \times V \quad (3)$$

where,

$E$ : CO<sub>2</sub> diffusion rate, mg.s<sup>-1</sup>

$RD_{\text{SINGLE}}$ : CO<sub>2</sub> concentration decay rate measured by the single-chamber test, mg.m<sup>-3</sup>.s<sup>-1</sup>

$V$ : Volume of the chamber, m<sup>3</sup>

- **Effective CO<sub>2</sub> diffusion coefficient** ( $D_{\text{EFF}}$ , cm<sup>2</sup>.s<sup>-1</sup>): It is the amount of CO<sub>2</sub> which crosses through the unit section area of a porous material perpendicular to the diffusion direction in unit time and at the unit concentration gradient. It is calculated using Equation 4 which is based on Fick's law (Jacobs, 1967; Wilson et al., 2009).

$$D_{\text{EFF}} = \frac{E \times L}{A(C_{\text{SOURCE}} - C_0)} \quad (4)$$

where,

$D_{\text{EFF}}$ : Effective CO<sub>2</sub> diffusion coefficient, cm<sup>2</sup>.s<sup>-1</sup>

$E$ : CO<sub>2</sub> diffusion rate, mg.s<sup>-1</sup>

$L$ : Thickness of the building material sample, cm

$A$ : Area of the plane perpendicular to the diffusion direction, cm<sup>2</sup>

$C_{\text{SOURCE}}$ : The initial CO<sub>2</sub> concentration in the single-chamber, mg.cm<sup>-3</sup>

$C_0$ : The CO<sub>2</sub> concentration outside the chamber, mg.cm<sup>-3</sup>

The data obtained from the double-chamber diffusion test is crucial to clarify whether the CO<sub>2</sub> concentration decay ( $RD_{\text{SINGLE}}$ ) is induced by the CO<sub>2</sub> retaining behavior of the material or not. The double-chamber experimental setup is a closed system and the total amount of CO<sub>2</sub> ( $M_T$ , mg) in this closed system should be the same before and after the diffusion test. The data evaluation for determining the amount of CO<sub>2</sub> retained by the building material is explained below:

- The total amount of CO<sub>2</sub> in the closed system ( $M_T$ , mg), as shown in Equation 5, is the sum of the CO<sub>2</sub> amount in the chambers before the test was initiated and the CO<sub>2</sub> amount generated by the source.

$$M_T = M_{\text{Ch1-I}} + M_{\text{Ch1-S}} + M_{\text{Ch2-I}} = M_{\text{Ch1-F}} + M_{\text{Ch2-F}} + M_{\text{RET}} \quad (5)$$

where,

$M_T$ : The total amount of CO<sub>2</sub> in the closed system, mg

$M_{\text{Ch1-I}}$ : Initial amount of CO<sub>2</sub> in Chamber-1, mg

- $M_{CH1-S}$ : Amount of  $CO_2$  generated by the source in Chamber-1, mg
- $M_{CH2-I}$ : Initial amount of  $CO_2$  in Chamber-2, mg
- $M_{CH1-F}$ : Final amount of  $CO_2$  in Chamber-1 by the end of 24h test duration, mg
- $M_{CH2-F}$ : Final amount of  $CO_2$  in Chamber-2 by the end of 24h test duration, mg
- $M_{RET}$ : Amount of  $CO_2$  retained by the material sample by the end of 24h test duration, mg

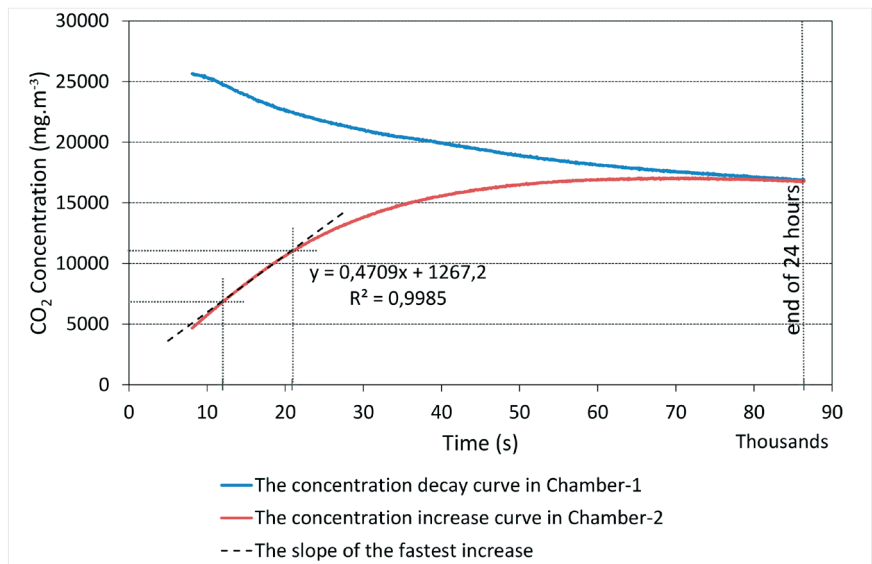
- After the 24 hours test duration, the difference between the total  $CO_2$  amount in the closed system ( $M_T$  mg) and the measured  $CO_2$  amount in the chambers ( $M_{CH1-F} + M_{CH2-F}$  mg) is the amount of  $CO_2$  retained by the material ( $M_{RET}$  mg) (Equation 6).

$$M_{RET} = M_T - (M_{CH1-F} + M_{CH2-F}) \quad (6)$$

- **$CO_2$  retaining ratio** ( $M_{RET}/M_T$  % by weight): It is the ratio of  $M_{RET}$  to the total  $CO_2$  amount in the closed system and an indicator in percentage to define the  $CO_2$  retaining behavior of the material on quantitative basis.

The amount of  $CO_2$  retained by the material after 24 hours can be confirmed by the curves of  $CO_2$  concentration decay in Chamber-1 and the increase in Chamber-2. The data achieved during the double chamber diffusion test is summarized in the graph showing the plot of  $CO_2$  concentration in the chambers versus time (Figure 5). Concentration increase rate in Chamber-2 ( $RI_{DOUBLE}$   $mg.m^{-3}.s^{-1}$ ) is extracted from that graph.

- **Concentration increase rate in Chamber-2** ( $RI_{DOUBLE}$   $mg.m^{-3}.s^{-1}$ ): It is the initial rate presenting the fastest increase in  $CO_2$  concentration in Chamber-2 until the fastest concentration increase starts to slow down (due to the significant decrease in the partial pressure difference between Chamber-1 and Chamber-2). That initial period of concentration increase is considered during the regression analysis.  $RI_{DOUBLE}$  is the slope of the best-fit linear regression of this initial period.



**Figure 5.** The  $CO_2$  concentration decay curve in Chamber-1 (in blue) and the  $CO_2$  concentration increase curve in Chamber-2 (in red), obtained by plotting the  $CO_2$  concentration data versus time during the 24-hour experimental period of double-chamber diffusion test. (The experimental data belongs to the adobe samples.) This figure is prepared by the authors.

- The  $RI_{\text{DOUBLE}}$  value, if noticeably lower than the  $RD_{\text{SINGLE}}$  value, signals that building material retains  $\text{CO}_2$  in its body. On the other hand, the  $RI_{\text{DOUBLE}}$  value, if close to the  $RD_{\text{SINGLE}}$  value, signals that the  $\text{CO}_2$  reduction capability of the building material to a certain extent, is provided by means of  $\text{CO}_2$  transmission through the material's body.

### A SAMPLE USE OF THE PROPOSED TEST METHOD

The proposed test method is used for measuring the  $\text{CO}_2$  reduction performance of two types of porous building materials; adobe as a traditional building material and the autoclaved aerated concrete (AAC) as a contemporary building material. The adobe sample refers to the molded and sun dried mud-based masonry unit without any mortar and/or plaster layers. It represents adobe material which has kaolin and illite group clay minerals (Yüncü, 2016). The AAC samples are two types of samples: load bearing unit (AAC/G4) and infill masonry unit (AAC/G2). No mortar or plaster layer is used. Although both types of materials are well-known by their high water vapor permeability characteristics (Kömürcüoğlu, 1962; Örs, 2006; Meriç et al., 2013; Meriç et al., 2014), their  $\text{CO}_2$  reduction performances have not been tested and identified yet in published literature. The basic physical and physicochemical properties of the examined material samples in terms of bulk density ( $\rho$ ), effective porosity ( $\phi$ ), ultrasonic pulse velocity (UPV), modulus of elasticity (MoE), water vapor diffusion resistance factor ( $\mu$ ) and equivalent air thickness of water vapor resistance (SD) are summarized in **Table 3** (Yüncü 2016).

The single and double chamber diffusion tests are conducted on adobe and autoclaved aerated concrete (AAC) samples prepared in the dimensions of 180 mm × 125 mm × 305 mm (thickness × width × length). The thickness of 180 mm is the distance where  $\text{CO}_2$  transmission occurs. These samples are kept at  $25^\circ\text{C} \pm 1^\circ\text{C}$  and  $35\% \pm 1\%$  relative humidity in laboratory conditions for a week so as to be in equilibrium with the microclimatic conditions of the testing environment. The fully-airtight acrylic glass chambers are produced with a volume of  $0.016 \text{ m}^3$  (with dimensions of 390 mm × 130 mm × 310 mm). The material samples are individual adobe and AAC masonry units which are not plastered and do not involve any bedding or jointing mortar. The peripheral surfaces of the samples are wrapped with three layers of stretch film. The width and length of the chambers are 5 mm greater than those of samples to allow complete fitting of each wrapped material sample into the acrylic glass chamber. The edges where the material sample and the chamber meet are fully sealed with acrylic sealant. The pressure and the temperature of the laboratory environment

Table 3. The basic physical and physicochemical properties of the adobe and autoclaved aerated concrete samples. This table is prepared by the authors.

Building material	Bulk density	Effective porosity	Ultrasonic pulse velocity	Modulus of elasticity	Water vapor diffusion resistance factor	Equivalent air thickness of water vapor resistance (for 18cm-thick sample)
	$\rho$ ( $\text{g.cm}^{-3}$ )	$\phi$ (%)	UPV ( $\text{m.s}^{-1}$ )	MoE (GPa)	$\mu$ (unitless)	SD (m)
Adobe Load bearing unit	1.60±0.03	42.4± 0.3	1321±65	2.57± 0.24	3.59 ±0.29	0.65 ±0.05
Autoclaved aerated concrete (AAC/G2) Infill unit	0.42±0.00	74.1±1.2	1703±20	1.11±0.02	2.13±0.45	0.38 ±0.08
Autoclaved aerated concrete (AAC/G4) Load bearing unit	0.62±0.02	67.7±2.5	1955±30	2.17±0.12	3.34±1.04	0.64 ±0.17

and the chambers of each setup were also constantly measured during the test duration to confirm isobaric and isothermal conditions. The pressure difference between the chambers and the laboratory environment was not over 0.0002 atm.

The data obtained from the single and double chamber diffusion tests are summarized in **Table 4**. Using Equation 3 and Equation 4, the  $RD_{SINGLE}$  data obtained from the single-chamber diffusion test is used to calculate the  $CO_2$  diffusion rate ( $E, mg \cdot s^{-1}$ ) and the effective  $CO_2$  diffusion coefficient ( $D_{EFF} cm^2 \cdot s^{-1}$ ) of the building material, respectively. The results of the single-chamber diffusion tests show that adobe and AAC samples have certain  $CO_2$  reduction performances. The  $RD_{SINGLE}$  values of adobe, AAC/G2 and AAC/G4 samples were  $0.47 mg \cdot m^{-3} \cdot s^{-1}$ ,  $0.41 mg \cdot m^{-3} \cdot s^{-1}$  and  $0.35 mg \cdot m^{-3} \cdot s^{-1}$  respectively (**Table 4**). According to these data, the highest  $CO_2$  decay rate belongs to the adobe sample followed by the AAC/G2 and AAC/G4 samples respectively. The effective  $CO_2$  diffusion coefficient ( $D_{EFF}$ ) values of adobe and autoclaved aerated concrete samples fall into the range of  $0.012 cm^2 \cdot s^{-1}$  and  $0.0138 cm^2 \cdot s^{-1}$  (**Table 4**).

There are a few recent studies in which  $D_{EFF}$  values of some porous building materials have been measured. For instance, in these studies; Namouniara et al., 2016 and Niemelä et al., 2017), the  $D_{EFF}$  values of gypsum board, porous fiberboard and highly-porous limestone are given as  $0.014-0.023 cm^2 \cdot s^{-1}$ ,  $0.02-0.034 cm^2 \cdot s^{-1}$  and  $0.0153 cm^2 \cdot s^{-1}$  respectively. The  $D_{EFF}$  values of adobe and AAC measured in this study corresponds to the range of  $D_{EFF}$  values given for those porous building materials in the literature.

Considering their  $D_{EFF}$  values, the examined adobe and autoclaved aerated concrete materials are porous materials that may have the potential to reduce indoor  $CO_2$  concentration. The results of the double-chamber diffusion test reveal that the  $CO_2$  reduction performance of adobe is mostly due to the  $CO_2$  transmission through the material while the performance of AAC is due to its high  $CO_2$  retaining characteristics. AAC/G2 and AAC/G4 blocks retain a considerable amount of  $CO_2$  in their body with the  $M_{RET}/M_T$  values of 53% and 88% respectively, and permits less amount of  $CO_2$  transmission from Chamber-1 to Chamber-2 by the end of the 24 hour-experiments (**Table 4**). The  $RI_{DOUBLE}$  values of AAC samples are lower than their  $RD_{SINGLE}$  values (**Table 4**) and these data confirm the  $CO_2$  retaining performance of AAC samples. The  $CO_2$  retaining behavior is an expected characteristic for the autoclaved aerated concrete samples. This behavior is attributed to the calcium carbonate formation resulting from the reaction of calcium hydroxide ( $Ca(OH)_2$ ) existing in AAC with  $CO_2$  in the chambers, at atmospheric humidity conditions (Kus and T. Carlsson, 2003; Matsushita et al., 2000; Matsushita et al., 2004).

The adobe sample has similar  $CO_2$  reduction performance with AAC samples due to  $D_{EFF}$  values being close to each other (**Table 4**). On the other hand, the  $RI_{DOUBLE}$  value of adobe is close to its  $RD_{SINGLE}$  value and the  $CO_2$  retaining ratio is at most 1% by weight which is negligible (**Table 4**). The

**Table 4.** The  $CO_2$  diffusion and retaining properties of the adobe and autoclave aerated concrete samples. This table is prepared by the authors.

Sample	$RD_{SINGLE}$ ( $mg \cdot m^{-3} \cdot s^{-1}$ )	$E$ ( $mg \cdot s^{-1}$ )	$D_{EFF}$ ( $cm^2 \cdot s^{-1}$ )	$RI_{DOUBLE}$ ( $mg \cdot m^{-3} \cdot s^{-1}$ )	$M_{RET}/M_T$ (% by weight)
Adobe	-0.4680	0.0075	0.0131	0.4709	0.74
AAC/G2	-0.4173	0.0067	0.0138	0.3569	53.23
AAC/G4	-0.3457	0.0055	0.0120	0.0144	88.35

joint interpretation of those data shows that the adobe sample is a highly CO<sub>2</sub> permeable material and has a potential of self-ventilation.

## CONCLUSION

The enhancement of indoor air quality is one of the main concerns in airtight buildings. The impact of breathable envelopes, specifically the solid parts of the building walls, on enhancing indoor air quality is a challenging research topic that yet to be comprehensively investigated. This research tries to draw the attention of the building science community and sustainable construction sector to the pollutant reduction potentials of building materials in indoor environments. This study presents a new approach, new measurable parameters and a new practical test method. In contrast to the common approach of airtight buildings, the breathable building skin approach changes the performance expectations from solid parts of a building envelope. From this perspective, investigating the carbon dioxide reduction performance of building materials is a pioneer study.

A practical testing method including single-chamber and double-chamber experimental setups is proposed in the study for the assessment of the CO<sub>2</sub> reduction performance of building materials in terms of measurable parameters. To demonstrate an example of the test procedure, the proposed testing method was conducted on adobe and autoclaved concrete samples, which are well-known for their highly-porous and water vapor permeability properties;. The main parameters which are used to evaluate the data achieved by the single-chamber and double-chamber diffusion tests are as follows:

- CO<sub>2</sub> decay rate ( $RD_{\text{SINGLE}}$ , mg.m<sup>-3</sup>.s<sup>-1</sup>)
- CO<sub>2</sub> diffusion rate ( $E$ , mg. s<sup>-1</sup>)
- Effective CO<sub>2</sub> diffusion coefficient ( $D_{\text{EFF}}$ , cm<sup>2</sup>.s<sup>-1</sup>)
- CO<sub>2</sub> increase rate ( $RI_{\text{DOUBLE}}$ , mg.m<sup>-3</sup>.s<sup>-1</sup>)
- CO<sub>2</sub> retaining ratio ( $M_{\text{RET}}/M_{\text{T}}$ , % by weight)

The results show that the proposed method is promising. The combined interpretation of the data obtained in terms of these measurable parameters is useful to define the CO<sub>2</sub> reduction performance with focus on their CO<sub>2</sub> diffusion and CO<sub>2</sub> retaining performances. The CO<sub>2</sub> diffusion through a building material is measured in terms of  $RD_{\text{SINGLE}}$  and that data is used to determine the  $D_{\text{EFF}}$  value. On the other hand, the CO<sub>2</sub> retaining behavior of the material is determined in terms of  $M_{\text{RET}}/M_{\text{T}}$ . The  $D_{\text{EFF}}$  value has to be evaluated together with the  $M_{\text{RET}}/M_{\text{T}}$  value in order to better interpret the CO<sub>2</sub> diffusion characteristics of building materials and to discuss their potential of self-ventilation in reducing occupant related indoor air contamination. In short, the reference data on CO<sub>2</sub> reduction performances of building materials can be established by using this practical and repeatable test method.

Further studies are needed to comprehensively investigate the contribution of self-ventilation behavior of building materials to healthier indoor air. The proposed method can be adapted and further developed for indoor air pollutants besides CO<sub>2</sub> such as, volatile organic compounds. Reference data on CO<sub>2</sub> reduction performances of various building materials and multi-layered wall components can be established by using this practical testing method. This is a promising interdisciplinary research area that will also advance indoor air quality modeling and simulation analyses. In



conclusion, this study is the pioneer of a sustainable future where indoor air cleaning and self-ventilating in a passive manner is a standard feature of building envelopes.

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## ABBREVIATIONS

A: Area of the plane perpendicular to the direction of diffusion, cm<sup>2</sup>

AAC: Autoclaved aerated concrete

AAC/G2: Autoclaved aerated concrete infill unit

AAC/G4: Autoclaved aerated concrete load bearing unit

C: CO<sub>2</sub> concentration, ppm, mg.m<sup>-3</sup>

C<sub>IN</sub>: The indoor CO<sub>2</sub> concentration level, ppm

C<sub>OUT</sub>: The outdoor CO<sub>2</sub> concentration level, ppm

C<sub>SOURCE</sub>: CO<sub>2</sub> concentration at the source, mg.m<sup>-3</sup>

C<sub>0</sub>: Concentration at the destination, mg.m<sup>-3</sup>

ΔC: Difference between C<sub>IN</sub> and C<sub>OUT</sub> ppm)

D<sub>EFF</sub>: Effective diffusion coefficient of CO<sub>2</sub> in the building material, cm<sup>2</sup>.s<sup>-1</sup>

E: CO<sub>2</sub> diffusion rate, mg.s<sup>-1</sup>

IAQ: Indoor air quality.

L: Thickness of the building material which diffusion occurs through, cm

M<sub>CH1-I</sub>: Initial amount of CO<sub>2</sub> in Chamber-1, mg

M<sub>CH1-S</sub>: Amount of CO<sub>2</sub> generated by the CO<sub>2</sub> source in Chamber-1, mg

M<sub>CH2-I</sub>: Initial amount of CO<sub>2</sub> in Chamber-2, mg

M<sub>CH1-F</sub>: Final amount of CO<sub>2</sub> in Chamber-1 by the end of 24h test duration, mg

M<sub>CH2-F</sub>: Final amount of CO<sub>2</sub> in Chamber-2 by the end of 24h test duration, mg

M<sub>RET</sub>: Amount of CO<sub>2</sub> retained by the material sample by the end of 24h test duration, mg

M<sub>RET</sub>/M<sub>T</sub>: CO<sub>2</sub> retaining ratio, % by weight

M<sub>T</sub>: Total amount of CO<sub>2</sub> in the closed system, mg

MW: Molecular weight, g/mole

NA: Not applicable

RD<sub>SINGLE</sub>: CO<sub>2</sub> concentration decay rate in the single-chamber, mg.m<sup>-3</sup>.s<sup>-1</sup>

RI<sub>DOUBLE</sub>: CO<sub>2</sub> concentration increase rate in Chamber-2 in the double-chamber test setup

SBS: Sick building syndrome



V: Volume of a chamber, m<sup>3</sup>

VAC: Ventilation and air conditioning

VOC: Volatile organic compound

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**Anahtar Sözcükler:** Karbondioksit difüzyon deneyi; yapı malzemeleri; CO<sub>2</sub> azaltma performansı; iç hava kalitesi; etkin CO<sub>2</sub> difüzyon katsayısı; CO<sub>2</sub> tutma davranışı.

## **BİNA ÇEPERİNİN DOLU KISIMLARINDAN BEKLENENLERİ DEĞİŞTİREN YENİ BİR YAKLAŞIM: YAPI MALZEMELERİNİN KARBONDİOKSİT DİFÜZYON VE TUTMA PERFORMANSLARININ TEST EDİLMESİ**

COVID-19 salgını, tüm dünyaya iç mekan hava kalitesinin ne kadar hayati olduğu göstermiştir. Dolayısıyla, sağlıklı ve sürdürülebilir iç ortamlar için "nefes alabilen bina kabuğu" yaklaşımı, yapı bilimi camiasının dikkatini hak eden önemli bir husustur. Hava sızdırmayan bina kabuğu tasarımlarının aksine, "nefes alabilen kabuk" yaklaşımı, bir bina çeperinin dolu kısımlarından beklenenleri değiştirir. Bu araştırma ile yeni bir bakış açısı, yeni ölçülebilir parametreler ve yeni bir pratik test yöntemi sunulmaktadır. Burada, iç hava kalitesini artırmak amacıyla, yapı malzemelerinin kirletici azaltma ve kendi kendini havalandırma potansiyellerinden faydalanılması hususuna odaklanan bir bakış açısı sunulmaktadır. Bu kapsamda, bina çeperinin dolu kısımlarında kullanılan yapı malzemelerinin kirletici azaltma (difüzyon ve tutma) performansını ölçmek için test yöntemleri geliştirmek gerekir. Binalarda, kullanıcı kaynaklı iç hava kirleticileri arasında CO<sub>2</sub>, iyi bilinen ve iç hava kalitesini değerlendirmek için yaygın olarak kullanılan göstergelerden biridir. Bu çalışmada, yapı malzemelerinin iç ortamdaki CO<sub>2</sub> miktarını azaltma performansını ölçebilen standart bir test yöntemi önerilmiş; bu yöntemle elde edilen verilerin analizi için "CO<sub>2</sub> konsantrasyon düşüş hızı", "etkin CO<sub>2</sub> difüzyon katsayısı" ve "CO<sub>2</sub> tutma oranı" olmak üzere üç ölçülebilir parametre tanımlanmıştır. Önerilen test yönteminin deney düzeneği ve veri analizi ile ilgili prosedürleri açıklamak amacıyla, kerpiç ve gazbeton olmak üzere seçilen iki nefes alan ve çok gözenekli kağır yapı malzemesi üzerinde yapılan örnek ölçümler ve analizleri ayrıntılarıyla sunulmuştur. Bu test yöntemi ve düzeneği, tek odacıklı ve çift odacıklı difüzyon deneylerinin birlikte kullanımını içermektedir. Tek odacıklı düzenek, gözenekli bir malzemedan CO<sub>2</sub> geçişine izin veren ve CO<sub>2</sub> konsantrasyon düşüş hızını ölçen bir sistemdir. Çift odacıklı deney düzeneği ise, CO<sub>2</sub> kaçışını önleyen kapalı bir sistemdir ve CO<sub>2</sub> tutma davranışının CO<sub>2</sub> konsantrasyon düşüş hızı üzerindeki etkisini ölçer. Bu verilerin birlikte yorumlanması, malzemelerin iç mekan CO<sub>2</sub> konsantrasyonlarını azaltma performanslarının tartışılmasına olanak verir. Bu pratik deney yöntemi yaygın kullanıldıkça, yapı malzemelerinin CO<sub>2</sub> azaltma performansları hakkında ölçülebilir parametreler üzerinden referans verilerin üretilebilmesi mümkün olacak ve nefes alabilen bina kabuğu tasarımları için bilimsel değerlendirmeler ilerleyebilecektir.

## A NEW APPROACH CHANGING EXPECTATIONS FROM SOLID PARTS OF BUILDING ENVELOPES: TESTING THE CARBON DIOXIDE DIFFUSION AND RETAINING PERFORMANCES OF BUILDING MATERIALS (1)

The COVID-19 pandemic has made the world realize how vital indoor air quality is. For healthy and sustainable indoor environments, the "breathable building skin" approach deserves the attention of the building science community. In contrast to the common approach of airtight buildings, the "breathable skin" approach changes what is expected from the solid parts of a building envelope. Here, a new approach, new measurable parameters, and a new practical testing method are presented. Benefitting from the pollutant reduction and self-ventilation potentials of building materials is a new approach introduced here for enhancing indoor air quality. The effectiveness assessment of that approach requires developing testing methods for measuring the pollutant reduction (diffusion and retaining) performance of building materials. Among the occupant-related indoor air pollutants, CO<sub>2</sub> is well-known and one of the widely-used indicators for assessing indoor air quality. The testing method proposed in this study assesses CO<sub>2</sub> reduction performance of building materials in terms of "CO<sub>2</sub> concentration decay rate," "effective CO<sub>2</sub> diffusion coefficient," and "CO<sub>2</sub> retaining ratio" as the related measurable parameters. Sample use of the testing method conducted on adobe and autoclaved aerated concrete was presented to explain the proposed testing procedure. This procedure involved the combined use of single-chamber and double-chamber diffusion tests. The single-chamber setup is a system that permits CO<sub>2</sub> transmission through a porous material and measures the CO<sub>2</sub> concentration decay rate. The double-chamber setup is a closed system that prevents CO<sub>2</sub> from escaping thereupon measures the impact of CO<sub>2</sub> retaining behavior on CO<sub>2</sub> concentration decay rate. Joint interpretation of the data allows discussing the potentials and limitations of materials in reducing indoor CO<sub>2</sub> concentrations. For further evaluations, this practical testing method is useful in producing reference data on CO<sub>2</sub> reduction performances of building materials.

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