Hemp concrete walls: evaluation of the relationship between CO_2 and TVOC

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ABSTRACT

Climate change is driving the construction sector to use of more environmentally friendly and sustainable materials. Hemp concrete has been recently adopted as an innovative solution by the building industry to reduce emissions, as this material stores more CO_2 than the emitted during its production. Part of this storage occurs during its service life leading to a reduction of indoor CO_2 levels. CO_2 has been widely used as a proxy for evaluating indoor air quality (IAQ). However, these assessments do not consider the features of carbon sequestration materials where the use of CO_2 as the sole indicator might lead to a poor IAQ. This paper describes the results of an IAQ monitoring campaign conducted in a CO_2-negative prototype house built with hemp concrete and wood. During the campaign, temperature, relative humidity, total volatile organic compounds (TVOC), and carbon dioxide (CO_2) levels were continuously monitored inside and outside the test house for three months. Due to the low occupancy of the prototype house, the indoor CO_2 levels were generally low. These levels ranged between 400 and 1100 ppm when people was present and decreased down to 30 ppm once the visitors were gone and the house was closed. Such low indoor CO_2 levels suggest that hemp concrete walls could sequestrate a significant amount of CO_2. During the same period, TVOC concentration varied between 0.19 and 3.62 ppm and was negatively correlated to CO_2 levels. The highest TVOC concentrations were recorded in the absence of visitors when the prototype house was closed, indicating that building materials or furniture could potentially emit such compounds. The comparison of CO_2 and TVOC levels showed that, while the CO_2 levels were very low, the levels of TVOC were at their maximum. Consequently, in buildings made of hemp concrete, the use of CO_2 as a single indicator for ventilation might be misleading and could result in the occupants exposure to high pollution levels. Despite the importance of CO_2 monitoring, the findings of this study indicate that in hemp concrete buildings additional measurements may be needed to assess IAQ and identify potential sources of pollution. In some cases, adapting ventilation strategies to CO_2 levels could be sufficient to ensure acceptable IAQ, however, a preliminary assessment of IAQ should be conducted before making any decisions.

KEYWORDS

Hemp concrete, indoor air quality, carbon dioxide, VOC, air infiltration.

1 INTRODUCTION

In the context of climate change, the continuous rise of carbon emissions is a growing concern in the scientific community and the general public. Energy efficiency and the reduction of related greenhouse gas emissions are the major key challenges in all the economic sectors and more specifically, in the construction industry being responsible for about 40% of the global greenhouse gas emissions (Huang et al. 2018). Currently, companies are facing the challenge of rethinking construction design to create environmentally and climate friendly but also socially sustainable buildings. In the last decade, there has been an increasing demand to develop buildings that produce positive impacts in the natural environment, the so-called green buildings (Jami et al. 2019). For instance, positive energy buildings (PEB) which generate more energy than the energy needed for its operation (Hawila et al. 2022; Magrini et al. 2020) or carbon dioxide (CO_2)-negative buildings, able to store more CO_2 than they emit over their lifecycle (Arehart et al. 2020). Hemp concrete has been one of the materials used to construct CO_2-negative buildings. In this material, part of the carbon storage occurs during the plant's growth through photosynthesis (biogenic CO_2 uptake) while the other part happens during its service life (CO_2 uptake by carbonation). It has been estimated that 1 m^3 of hemp concrete wall can sequestrate up to 307 kg of CO_2 (Jami et al. 2016) depending on mixture formulation. Hence, hemp concrete buildings are potential carbon sinks, sequestrating CO_2 from ambient and indoor air through the external façades and internal walls. Outdoors, this process might not be relevant in terms of CO_2 concentration variation, however, the sink effect of hemp concrete walls might notably influence indoor CO_2 levels.

For a long time, indoor CO_2 concentration has been extensively used as a proxy for evaluating indoor air quality (IAQ) (Persily and Polidoro 2019). The basic hypothesis behind assumption was that, as outdoor CO_2 levels are almost stable, the excess of CO_2 indoors is directly correlated with human occupancy. Therefore, the emission of other pollutants related with the occupancy (human bioeffluents) and the level of acceptance of their odors, are expected to be acceptable as long as CO_2 levels do so. This applies in the hypothetical case where human bioeffluents are the only emission source of pollutants. However, in the real world, there are multiple emission sources present (i.e. building materials, furniture, etc.), thus controlling CO_2 levels in certain cases may be an useful tool to manage IAQ but in some others might not be enough to ensure an acceptable IAQ. Assuming that CO_2 is used to control ventilation rates and that hemp concrete could decrease indoor CO_2 levels, the use of this material might lead to lower ventilation rates and to unclear effect on the other indoor air contaminants.

Numerous studies have been conducted to characterize the CO_2 sequestration potential of hemp concrete (Arehart et al. 2020; Jami et al. 2016). Most of these works are focused on the evaluation of its carbon footprint through Life Cycle Assessment (Arrigoni et al. 2017; Pretot et al. 2014) and the ones which investigate its impact on IAQ are primarily centred on its hygrothermal properties (Moujalled et al. 2018; Latif et al. 2015; Maalouf et al. 2014) and its impact on energy consumption (Maalouf et al. 2018). However, the direct influence of hemp concrete on indoor air quality in a real building has not been explored so far. Thus, the aim of this study was to provide evidence on the relationship between CO_2 and other pollutants levels indoors in buildings made of hemp concrete. For that purpose, the IAQ was continuously monitored for a period of three months in a CO_2-negative prototype house built using a combination of hemp concrete and wood. During this period, the effect of hemp walls on CO_2 levels was characterized.

2 METHODOLOGY

2.1 Prototype house

The study was conducted in a prototype house built using a combination of sustainable materials, more specifically, wood and hemp concrete (see Figure 1). The stratigraphy selected for the walls of the house consisted of a timber frame filled with two rows of hemp concrete bricks of 12 and 24 cm thick. The external cladding was made of wood whereas the internal side was covered by a hemp-lime plaster for aesthetic finishing. This prototype was built as an example of CO_2 negative construction and was mainly used to promote sustainable construction in South Tyrol (Italy) and raise awareness of sustainability in the region, therefore some of its features could not be representative of a real house. For example, the house was not equipped with heating or cooling systems.

The prototype was a one-room house of 9.4 x 1.8 x 2.20 m with a total volume of 36.2 m^3. The ceiling and flooring of the house were made of untreated solid wood as well as the furniture inside. The house had a single door and was equipped with two casement windows and a fixed window. As it was built to promote sustainable construction in the region, the prototype was mounted on a mobile platform enabling its transportation among different towns of the region. During this tour, the prototype was open to visitors in the mornings and afternoons, being closed overnight and often at lunchtime.

Figure 1: Prototype house

2.2 Air tightness measurement

Infiltration is the uncontrolled flow of air into a space through adventitious gaps and cracks in the building envelope (Limb 2001) and represents an additional source of ambient air. A measurement of the envelope air tightness is necessary to understand the air infiltration rate at standard conditions and therefore to what extent the ambient CO_2 is entering without control (i.e. when no natural or mechanical ventilation are intentionally used) in the investigated house. In the prototype house, air infiltration was measured according to a standardized fan pressurization method (EN ISO 9972-2015).

2.3 Indoor air quality monitoring

Indoor air quality (IAQ) was monitored inside and outside of the prototype house from July to October 2021. Measurements were collected by using an in-house developed multi-sensor device called "Environmental Quality bOX" (EQ-OX). EQ-OX was conceived to be a portable low-cost device that enable to measure multiple IEQ parameters such as as hygro-thermal parameters, lighting level, and some IAQ parameters. In this study, EQ-OX was used to measure air temperature, relative humidity (RH), total volatile organic compounds (TVOC) and carbon dioxide concentration (CO_2). The sensors integrated in EQ-OX are listed in Table 1.
To monitor both indoor and outdoor air quality, one device was placed inside the house, on a table at a height of 1.20 m approximately whereas the another was located outside the house, close to the main door at a heigh of 1.80 m above the terrace floor. This latter was protected with a hard plastic cover to prevent the sensors from being damaged by the rain or altered by the direct sunlight while leaving some holes for ventilation.

To assure the correctness of the measurements performed, prior to the IAQ monitoring in the prototype house, EQ-OX were tested. Air temperature sensors were tested in a climatic chamber in the range of 10 – 35 °C and compared to a high accuracy RTD Pt100 1/10 DIN sensor, whereas the RH sensors were tested in the range of 20 – 80% and compared to E+E EE060 previously calibrated in an accredited calibration laboratory. In both cases, correlation between the sensor and the reference instrument was high (R^2>0.99). CO_2 sensors were compared with a CO_2 sensor TSI 7525 (TSI Incorporated, USA) during previous on-field measurements. TSI 7525 sensor is based on dual-wavelength non-dispersive infrared spectroscopy and was previously calibrated by an accredited calibration laboratory. The datasets obtained from both sensors during a week were compared and the average Pearson squared correlation coefficient (R^2) was calculated to be 0.86 demonstrating an acceptable performance of the K-30 CO_2 sensors used in this study. The TVOC sensor was factory calibrated with isobutylene prior to the monitoring campaign.

Table 1: Sensors data

Parameter	**Sensor Model**	**Sensor Type**	**Measurement Range**	**Accuracy**
Air Temperature	Littlefuse 11492	Thermistor 10k	-50 - 150 °C	±0.2 °C
Relative Humidity	Sensirion SHT31	CMOS	0 - 100 RH %	±2 %
Carbon Dioxide	CO_2meter K30	NDIR	0 - 10000 ppm	±30 ppm ±3% of reading
Total VOC	Alphasense PID - AH2	Photoionization detector	0 - 50 ppm	±3%

CMOS: Complementary metal-oxide-semiconductor; NDIR: nondispersive infrared sensor

3 RESULTS AND DISCUSSION

3.1 Air infiltration

The air change rate (ACR) per hour in the prototype house determined by the blower door test under a pressure difference of 50 Pa (n50) was found to be 7.22 h^{-1}. This level of air tightness is far from the standard air tightness requirements for new buildings in South Tyrol where the energy efficiency buildings classified as class A and B require n50 $\leq$ 1.5 h^{-1} and Gold class require n50 $\leq$ 0.6 h^{-1}. In renovated buildings, the standard requirement is n50 $\leq$ 3 h^{-1}. As mentioned before, this prototype was built as a proof of concept for CO_2 negative construction and to raise awareness of the importance of sustainability in the construction sector, therefore, some aspects such as the air tightness does not replicate the levels found in new buildings. Nevertheless, the results obtained in this study may provide valuable insights on how carbon sequestration materials affect IAQ. In order to better understand these effects, it is necessary to estimate the air change rate (ACR) at a pressure difference closer to the operational conditions of the building. The simplest method that could be used for this estimation is the CO_2 decay method which is based on the decrease of CO_2 levels once the occupants leave a room. By analysing CO_2 data from different days of the monitoring period, ACR values were estimated to be between 1.16 and 2.44 h^{-1}. Given the CO_2 sequestration capacity of the hemp concrete, it is probable that the CO_2 decay method might slightly overestimate the air exchange rate as the CO_2 decrease observed was not only due to the dilution through infiltration but also to the absorption of CO_2 by the hemp concrete walls. Therefore, a method proposed in the ASHRAE Handbook of Fundamentals (ASHRAE 2017) to determine the ACR at other standard pressure differences from the data obtained at 50 Pa pressure difference was employed. This method consists of two steps. First, to calculate the effective air leakage area using the data obtained from the blower door test using the following equation:

$$A_L = 10\,000\,Q_r \frac{\sqrt{\rho/2\Delta p_r}}{C_D} \tag{1}$$

where A_L is the effective air leakage area (cm^2), Q_r is the predicted airflow rate at Δp_r (m^3/s), ρ is the air density (kg/m^3), Δp_r is the reference pressure difference (Pa) and C_D is the discharge coefficient (assumed as 0.65). Then, the air leakage area at 50 Pa pressure difference can be converted to airflow rate at some other reference pressure difference as follows:

$$Q_{r,2} = \frac{C_{D,1} A_{r,1}}{10\,000} \sqrt{\frac{2}{\rho}} (\Delta p_{r,1})^{0.5-n} (\Delta p_{r,2})^{n} \tag{2}$$

where $Q_{r,2}$ is the airflow rate at reference difference Δp_{r2} (m^3/s), $A_{r,1}$ is the air leakage area at reference pressure difference Δp_{r1} (cm^2), $C_{D,1}$ is the discharge coefficient used to calculate $A_{r,1}$, $C_{D,2}$ is the discharge coefficient used to calculate $A_{r,2}$, $\Delta p_{r,1}$ and $\Delta p_{r,1}$ are the two reference pressure difference (Pa) and n is the pressure exponent. Air flow through the prototype' cracks is assumed to be turbulent, thus the flow exponent n is 0.5. Reference pressure differences of 1 and 4 Pa are commonly used as they are closer to the pressure differences that actually induce air exchange in real buildings, thus, they were the pressure differences chosen. By using these equations, the air exchange rate was estimated to be equal to 1.4 and 0.57 h^{-1} at 4 Pa and 1 Pa, respectively. As expected, the ACR values obtained by the CO_2 decay method were slightly higher than the ones calculated using the analytical method.

3.2 Carbon dioxide

Air quality data during the monitoring period showed, in general, relatively low indoor CO_2 levels corresponding to the usual low occupancy of the house. A repetitive daily pattern was observed over the different weeks of the tour. By way of example, CO_2 levels from 22th July to 13th August measured inside the prototype house are displayed in Figure 2. The orange line represents the outdoor CO_2 concentration which was always close to 400 ppm (background CO_2 level) whereas the blue line is the CO_2 concentration measured inside the prototype. As can be seen in the figure, there is a constant pattern increase-decrease that corresponds to certain time intervals throughout the day. Every morning around 9:30 – 10 am , when the door of the house was opened to the visitors, the indoor CO_2 concentration increased to reach ambient CO_2 levels. These levels were slightly higher (500-750 ppm) when visitors were inside the house. Once the visitors were gone (at around 4:30 – 6:30 pm) and the house was closed, it was expected that the CO_2 concentration returned to the background level (~400 ppm), however, CO_2 levels started to decrease until reaching a steady-state concentration around 50 ppm overnight suggesting a non-negligible CO_2 sequestration capacity of the hemp concrete walls in the prototype house. To estimate the CO_2 absorption rate of hemp concrete, the single-zone mass balance theory was employed. Assuming steady-state conditions, in a ventilated space with a uniform CO_2 concentration, the ventilation rate and CO_2 concentration are related as follows (Persily and Polidoro 2019):

$$C_{ss} = C_{out} + \frac{G}{Q} \tag{3}$$

where C_{ss} is the CO_2 steady-state concentration, C_{out} is the outdoor CO_2 concentration and G is the CO_2 generation or sink rate in the space, Q is the airflow into and out of the space. Indoor CO_2 concentration will only achieve steady-state if conditions (specifically Q and G) are constant for a sufficiently long period of time. One can consider that the steady-state conditions are reached after three time constants (Persily and Polidoro 2019). As the prototype house has an air change of about 0.57 h-1, it will take 5h 15min to achieve the steady-state state, thus confirming that the CO_2 concentration measured overnight can be used as steady-state concentration. Considering an average CO_2 steady-state concentration of 65 ppm, a CO_2 outdoor concentration of 400 ppm, a house volume of 36.2 m^3 and a hemp wall surface of 42.51 m^2, the CO_2 absorption rate of the hemp wall was calculated to be 7.88 $ppm/h \cdot m^2$. Note that this rate may vary based on climatic conditions (T, RH), composition of hemp concrete, type of finishing, surface-to-volume ratio (SA:V, amount of surface area per unit volume) and outdoor air ventilation rate. In fact, the SA:V of the prototype house (1.17 m^2/m^3) was slightly higher compared to the one of the European Reference Room as described in EN 16516 (SA:V = 1.0 m^2/m^3). This difference implies that a larger hemp concrete surface is in contact with air which potentially results in a more significant CO_2 absorption observed in the prototype compared to other rooms with lower SA:V. On the other hand, the prototype house had an air exchange rate at 50 Pa of 7.22 h^{-1} which is relatively high compared with new buildings (n50 = 0.3-1.5 h^{-1}). Thus, CO_2 levels in new or recently refurbished buildings made of hemp concrete may reach even lower values as air renewal occurs at a lower rate.

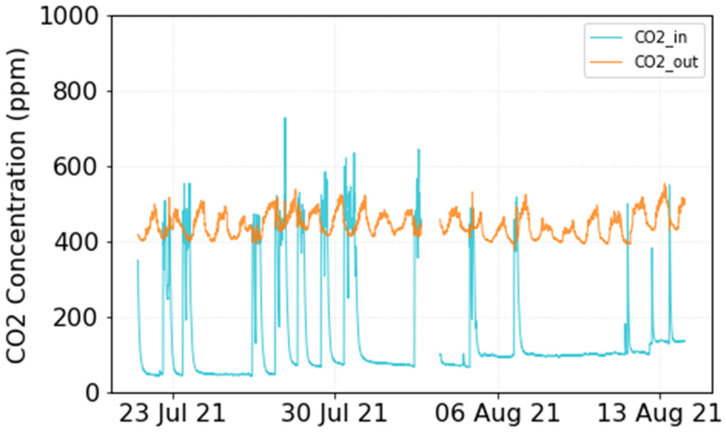

Figure 2: Monthly patterns of indoor and outdoor levels of CO_2

3.3 Total Volatile Organic Compounds

As expected, indoor TVOC levels measured were higher than outdoors during the whole monitoring period. TVOC concentration shown wide fluctuations over time also in a form of repetitive pattern as shown in Figure 3. In this case, TVOC levels started to increase at around 4.30-7.30 pm until reaching the peak maximum at around 9.30-10.30 am, right before the opening of the door to the visitors. Maximum levels were recorded always in the early morning after the prototype house was closed for several hours indicating that the main source of emission was located inside the house. It is well known that wood-based building materials and furnishings are one of the main VOC emission sources (Harb et al. 2018), therefore, these high TVOC levels observed could be potentially emitted by the solid wood furniture, the flooring or the ceiling inside the prototype house.

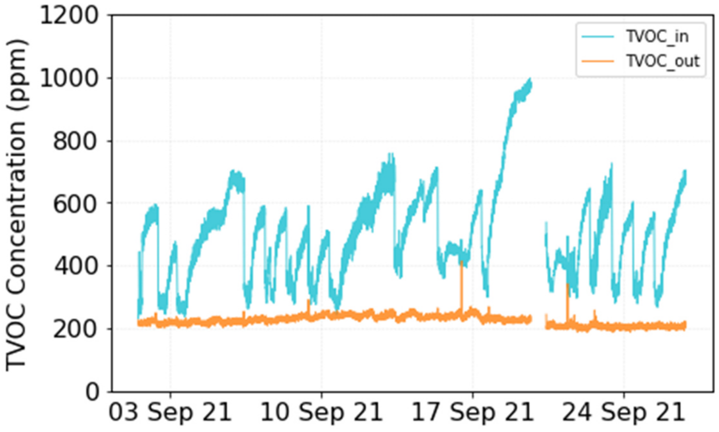

Figure 3: Monthly patterns of indoor and outdoor levels of TVOC

In Table 2, mean, maximum and minimum TVOC concentrations measured over the study are presented. As can be seen, during July and August mean TVOC concentration was 1463 and 1594 ppb, respectively, whereas in cooler months the mean concentration decreased to 499 (September) and 350 ppm (October). In fact, VOC molecules diffuse more easily to the material surface at higher temperatures thus resulting in increased emissions (Wang et al. 2021). Hence, this result reinforces the idea that building materials or furniture inside the prototype were likely to be the main VOC emission source.

Table 2: CO_2 and TVOC levels measured over the monitoring period.

Parameter		July	August	September	October
Indoor CO_2 (ppm)	Mean	169	183	198	323
	Min	43	66	30	131
	Max	729	1056	814	879
Indoor TVOC (ppb)	Mean	1463	1594	499	350
	Min	190	195	230	185
	Max	3622	2923	998	785

Unfortunately, during this study only TVOC measurements using a photoionization detector were conducted thus the different pollutants present could not be identified. TVOC comprises an undefined mix of compounds of varying toxicity and therefore, it cannot be used to estimate the health effects derived from a hypothetical exposure. To conduct this type of study, deeper chemical analysis using lab grade equipment is required. However, TVOC sensors can be used as a screening tool to detect pollution peaks or trends facilitating the identification of the emission sources with a minimum budget.

3.4 Comparison CO_2 vs. TVOC

In many cases, the widespread use of CO_2 as IAQ indicator has led to the belief that keeping levels below a certain threshold will ensure a healthy air quality. CO_2 might be somehow representative of human-related pollutants (bioeffluents), however, it does not account of the pollutants emitted by other sources. The Figure 4 illustrates an overlay of CO_2 and TVOC levels measured during one week of the monitoring campaign. In this figure, the effect of opening the door can be clearly observed: the CO_2 concentration increased until the ambient levels were reached whereas the TVOC levels decreased. The highest TVOC concentrations (500-600 ppb) were recorded overnight and in the early morning when the house was closed for some hours and coinciding when the CO_2 levels were at their lowest (< 100 pm). In this particular case, the use of CO_2 as a single indicator to assure an acceptable IAQ would not be appropriate as CO_2

levels would indicate adequate ventilation whereas in reality, levels of other pollutants were relatively high.

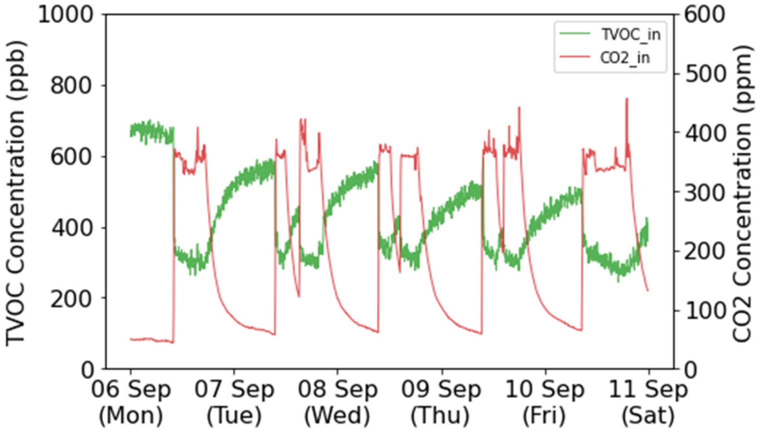

Figure 4: Comparison of weekly patterns of indoor levels of TVOC (green) and CO_2 (red) measured in the prototype house

The results obtained in this study may be extrapolated to a real house made of hemp concrete. The ventilation in the prototype house could be considered similar to the natural ventilation usually conducted in a real house without a mechanical ventilation system where the air renewal is carried out during the day by natural ventilation. If a similar behaviour is followed in a real house, the occupants will probably be exposed to high concentrations of VOC overnight affecting the health and the sleep quality of occupants (Canha et al. 2021).

The results must, however, be considered in context. As a result of low occupancy levels, CO_2 concentration in the prototype house was extremely low. In a non-hemp concrete building with similar occupancy, the average CO_2 levels could likely be relatively low (400-700 ppm). The main difference among these two types of buildings could be potentially observed during periods of occupancy and where no natural ventilation occurs (overnight). In these periods, CO_2 levels in the hemp concrete building would remain low whereas they continuously increase in the non-hemp concrete building. The levels of pollutants emitted by other sources are expected to be the same in both buildings, therefore, using ventilation strategies based solely on the CO_2 concentration could not be sufficient to assure an acceptable indoor air quality in hemp concrete buildings. However, if the influence of hemp concrete on IAQ is characterized, smart ventilation strategies can be adapted to this specific context. For example, the ventilation system could be activated in the evening to prevent the build-up of contaminants overnight and during the day right before the occupancy periods. Alternative indicators could be used for ventilation activation such as humidity, occupants' presence or TVOCs levels but, unfortunately, more research is needed to improve the accuracy and reliability of some of the sensors used to measure these variables (Guyot et al. 2018).

Other key aspects to consider when evaluating the impact of hemp concrete on IAQ are the surface-to-volume ratio and the air tightness of the studied building. The surface-to-volume ratio is a measure of the hemp concrete surface in contact with the air containing CO_2 respect to the total volume of air contained in the room. Larger the surface in contact with air compared to the room volume, faster will be the decrease on the CO_2 levels in the investigated room.
Air infiltration constitute an additional source of CO_2 and thus it will have a significant impact on indoor CO_2 levels. In the prototype house, air infiltration rate (n50) was 7.22 h^{-1}, which approximately represents 0.5-1.4 air exchanges per hour under operational conditions. In hemp concrete buildings with similar infiltration rate, comparable results can be expected. However, in less air tight buildings with higher infiltration rates, the ambient CO_2 can penetrate into the

room more quickly and such low CO_2 concentrations as the ones observed in the prototype house might not be achieved. The effects of hemp concrete on IAQ observed in this study, are therefore, representative of buildings with similar infiltration rates and surface-to-volume ratio.

4 CONCLUSIONS

It is known from the literature that hemp concrete is able to sequester CO_2 during its service life, however, the impact of this material on indoor air quality has not been fully investigated. In this work, IAQ was continuously monitored in a prototype house made of hemp concrete for three months. The air tightness of the prototype house was evaluated by means of a blower door test where the air exchange rate at a pressure of 50 Pa (n50) was determined to be 7.22 h^{-1}. The results of the IAQ monitoring showed substantial decrease of the indoor CO_2 levels overnight reaching values lower than 100 ppm in many cases. This reduction of indoor CO_2 levels indicated a non-negligible CO_2 sequestration capability of hemp concrete. For the type of hemp concrete investigated in this study and under the specific experimental conditions of the monitoring campaign, the CO_2 absorption rate of hemp concrete was calculated to be 7.88 $ppm/h{\cdot}m^2$. Completely opposite trends were observed for TVOC concentration, being the maximum levels recorded overnight. In this case, TVOC levels ranged from 0.19 to 3.62 ppm depending on the time of the day and the month. These results indicate that, in this type of buildings, the widespread use of CO_2 as solely indicator of an acceptable IAQ would not be adequate and could result in the occupants' exposure to high pollution levels.

In the context of climate change, hemp concrete offers path to a greener construction industry and further studies should be conducted to better characterize the CO_2 sequestration properties of hemp concrete and the potential benefits of this passive CO_2 capture material. However, the unusual properties of innovative materials need to be considered when assessing IAQ. The results of this study highlight the importance, besides more traditional CO_2 monitoring, of additional measurements for IAQ evaluation and identification of pollution emission sources. In some cases, ventilation strategies can be adapted based on CO_2 levels but before taking this decision, a preliminary IAQ analysis needs to be performed.

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