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EXPERIMENTAL AND NUMERICAL STUDIES OF MOISTURE AND TOLUENE BUFFERING CAPACITY OF HEMP CONCRETE

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Abstract

Hemp lime concrete (HLC) is an environment-friendly material increasingly used in building construction. Many studies have focused on the moisture buffer capacity of HLC, but its pollutant buffering capacity remains unknown. To address this research gap, the potential for moisture and toluene buffering capacity of hemp concrete is presented in this article. The sorption capacity toward toluene (TOL), a typical indoor volatile organic compound (VOC), of HLC has been measured and investigated with a 50 L environmental chamber at 23°C and a relative humidity of 50%. Moisture buffering capacity of HLC has been determined according to the *Nordtest* protocol. The experimental data have been used to evaluate the model parameters of the **CHAMPS-bio** model (Coupled Heat, Air, Moisture and Pollutant Simulation transport model dedicated to **Bio**-based building materials) that assesses VOC transfers and hygrothermal behavior of building materials under dynamic conditions. The results are innovative and new for hemp concrete, and evidence that this bio-based material can mitigate the indoor toluene concentration and regulate indoor relative humidity thanks to its buffering capacity.

Keywords: Hemp lime concrete, toluene buffering capacity, moisture buffering capacity, Indoor air quality

Biography

Anh Dung Tran-Le is an associate professor and **Fathia Dahir Igue** is a Ph.D student in the Laboratoire des Technologies Innovantes, EA 3899 – Université de Picardie Jules Verne, Amiens, France.

Bing Beverly Guo is a Research Associate, **Jianshun Jensen Zhang** is a Professor and **Zhenlei Liu** is a Ph.D student in the Department of Mechanical and Aerospace Engineering, Syracuse University, Syracuse, NY, USA.

Marie Verrièle is an Associate professor, **Jérôme Lasne** is a researcher and **Frédéric Thevenet** is a Professor in IMT Nord Europe, Institut Mines-Télécom, Univ. Lille, Centre for Energy and Environment, Lille, France

INTRODUCTION

To keep indoor relative humidity (RH) and pollutant concentration below a threshold level is necessary and essential to improve building performance in terms of indoor air quality (IAQ), energy performance and durability of building materials. In order to assess IAQ and thermal comfort, indoor VOC concentrations, indoor temperature and relative humidity in buildings are the most important factors. A review of the literature shows that one passive way to keep the variation of RH in an optimal range relies on the moisture buffering capacity of materials (including the building's envelope, and interior objects) [1-9]. Similarly, mitigation of indoor VOC concentrations through sorptive processes is an important research target due to its potential to improve the quality of life for individuals in exposed spaces [10-12]. The diversity of typical indoor surfaces provides contrasted sorptive capacities as evidenced by Thevenet et al. using terpene as model indoor VOC [13]. [14] carried out a study of formaldehyde sorption/ desorption processes on gypsum boards and showed that this material has a significant storage capacity, and impacts significantly the formaldehyde concentration in air. The contributions from several consumer goods and building materials (gypsum board, ceiling tiles, furniture and carpet) to the overall formaldehyde (typical indoor VOC) concentration were investigated by climate-controlled chamber experiments by [15]. The results showed that the formaldehyde concentration in indoor air is always influenced by multiple parameters, and cannot be simply calculated from the area-specific emission rate of a building material under consideration of loading rate and air exchange rate, as is usually done. At the scale of a room, experimental data [13] and semi-empirical models [16] showed that

sorption processes on typical residential surfaces can influence gas-phase concentrations to the same extent as ventilation. It appears that, beyond sorption, interaction of VOCs with a typical indoor surface may even be reactive [17].

Regarding building materials, the use of natural particles (such as hemp shives, flax shives, straw bales, etc.) as aggregates is an interesting solution, as they are eco-friendly materials and have low embodied energy. Among these natural particles, hemp shives have been extensively studied [18-20]. Hemp shives can be used in the composition of as particle boards, biodegradable plastics, thermal and acoustic insulation products [21]. Experimental results show that emissions of bacteria and VOCs by hemp concrete are negligible [22;23]. Therefore, hemp concrete was chosen for this study because it is increasingly recommended by eco-builders with regard to its low environmental impact. The literature survey showed that hemp concrete offers high moisture buffering capacity and an interesting compromise between insulation and inertial materials. At present, most studies focus on the hygrothermal behavior and mechanical performance of bio-based materials. However, the study of pollutant behavior (VOCs) at the interface of bio-based materials is very important, because building materials represent an important part of indoor environments and impact directly crucial parameters, such as hygrothermal comfort and IAQ. Recently, using model simulations, [24] showed that the VOC buffering capacity of hemp concrete can be used to improve IAQ by reducing the peak concentration of indoor pollutants. In the literature, similar results have been reported by experimental studies carried out with other porous building materials [9;25;26]. Note that diffusion and sorption of VOCs and / or water vapor in building materials are related to the physical and chemical properties of materials. [10] show that the characteristics of the adsorption and desorption processes are related to material microstructure and VOC polarity. Therefore, the difference in VOC physical properties (size, molar mass, polarity, etc.) could play a role in their behavior similar to water vapor, which needs to be further investigated. The studies of [26;27] showed that this similarity can be used to estimate VOC diffusion coefficients, provided that water vapor diffusivity in the same material is known based on the conventional dry cup method. Based on the previous experimental study of [27], the similarities between VOC and moisture buffering capacity of calcium silicate, a porous indoor building material, has been extensively studied in [28]. The results obtained help emphasizing the importance of moisture and formaldehyde buffering capacities as a new key parameter when selecting clean and hygroscopic

materials in building design, because they can contribute to mitigate indoor RH as well as indoor formaldehyde variations. In addition, [28] showed that the impact of RH variations is significant and needs to be accounted for in simulations to correctly predict the concentration of indoor VOC.

To date, a survey of the literature shows a lack of knowledge on combined hygric and pollutant behavior of bio-based materials. It is very important to note that the study of [24] is a numerical study, solely based on the assumption that water and VOC diffusion through hemp concrete proceed similarly. An experimental study is necessary to confirm these results. Therefore, to bridge this gap, experimental and numerical studies focusing on the moisture and VOC buffering capacities of hemp concrete are presented in this paper. The purpose is to show the potential application of VOC and moisture buffering concept to improve IAQ and thermal comfort in buildings, as hemp concrete can adsorb VOC and moisture from the ambient air when indoor VOC concentration/humidity increases, and release VOC and moisture to the ambient air when VOC concentration/humidity decreases. Toluene (TOL) was selected as reference in the present study because it is a typical indoor VOC.

MATERIALS AND METHOD

Hemp lime concrete named “hemcrete” used in this study has been produced by the Hempitecture USA Company who is the USA leader in hemp construction. The moisture, toluene transport and storage coefficients of hemcrete are determined by the experiments, jointly carried out in USA and France, using a small test chamber (in BEESL laboratory, Syracuse University) for toluene behavior and a climate chamber (in LTI laboratory, University of Picardie Jules Verne, France) for moisture behavior.

Experimental study of toluene behavior towards hemcrete

The experiment has been carried using the small-scale chamber sorption test system, consisting of a clean air supply system, a Dynacalibrator as VOC injection unit, chamber assemblies, a thermal environment control system (temperature and relative humidity control), and a data acquisition system. A hemp concrete sample with a thickness of 5 cm was cut into a 15 cm by 45 cm test specimen and the five edges of the specimen were sealed by VOC-free tape (to prevent toluene diffusion through the edges) which resulted in a real exposed area of 12.7 cm by 42.67 cm. Such preparation of the test specimen has been done to ensure that the sorption of toluene occurs only through the top surface of

hemp concrete and only unidirectional flux which allows for exact boundary conditions to be known for the simulation. The hemp concrete specimen was kept in a well-ventilated laboratory room for over 3 months before the tests. The test has been done at 23°C and 50% RH. This study used a stainless steel chamber with a volume of 50 liters ($0.5\text{m} \times 0.4\text{m} \times 0.25\text{m}$) as specified in [29]. Teflon gaskets were used to airtight-seal the edges of the chamber and the chamber itself has a negligible sorption effect.

The test chamber was cleaned before each experiment. The test material specimen was then placed in the test chamber, supplied with clean humidified air at an air change rate of one air change per hour (1 ACH), for two days. This would ensure that the background toluene concentration with the test specimen would be negligible; the experimental result showed that toluene concentration is very low and negligible. The adsorption phase started after the injection of toluene to the chamber inlet. Toluene was generated by Dynacalibrator with a permeation tube to ensure a consistent injection rate. Air samples were collected at the chamber exhaust and inlet. Toluene was detected using a PTR-MS (Ionicon Analytik Ges.m.b.H., Austria) with sampling flow set at 75 ml/min to minimize the sampling effect on the flow field in the test chamber.

The air from the inlet was sampled thrice per day to ensure that the small-scale chamber test system was working properly and the data will be used for modelling. The air velocity in the test chamber is 0.05 m/s as previously measured by [29].

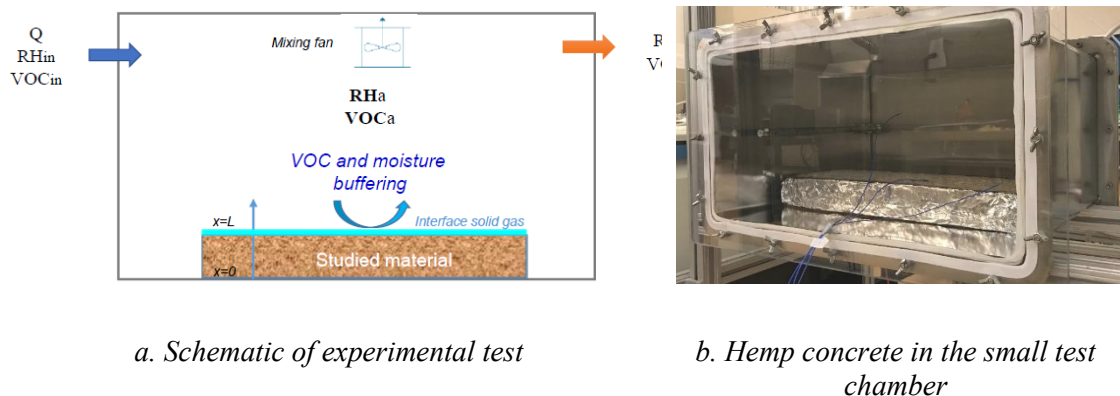


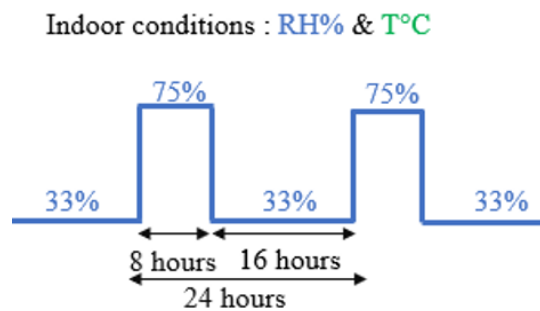
Figure 1: Schematic of experimental test (a) and small test chamber test (b) for toluene test of hempcrete

Experimental study of hygric behavior of hempcrete

The moisture buffer capacity of hempcrete was measured experimentally according to the

Nordtest protocol proposed in – Rode et al., [2005] using a climate chamber (Fitoclima 300) of LTI laboratory/UPJV in France shown in *Figure 2*. This climate chamber can control the temperature and the relative humidity in the range from -45°C to 180°C with an accuracy of 0.5°C , and 10% to 98 % of RH, with an accuracy of 2 %RH. During the test, the temperature is kept constant at 23°C as recommended in the Nordtest protocol. The regulation of temperature and relative humidity can be verified using the sensor of the climate chamber and was carried out automatically.

A hempcrete sample with dimensions $19 \times 11.5 \times 5 \text{ cm}^3$ was prepared in which the exposed area of the surface material is higher than the value recommended in the Nordtest protocol. The back and edges of the hempcrete sample were sealed with aluminum tape (so only a surface of $19 \times 11 \text{ cm}^2$ is open to water vapor diffusion) and then placed in the climatic chamber. In order to minimize the perturbation of temperature and relative humidity in the climate chamber, when the mass has reached equilibrium, the specimen was weighted three times during the absorption period and three times during desorption period using a balance with 0.001 g resolution (0-750 g).



Indoor RH variation in the climate chamber
($T=23^{\circ}\text{C}$)

Climate chamber

Figure 2: Schematic of moisture buffering capacity test of hemp concrete.

PHYSICAL MODEL AND MOISTURE/TOLUENE PROPERTIES OF HEMP CONCRETE

A coupled pollutant and moisture simulation model presented in Figure 3 [24] permitting the study of the moisture and pollutant behavior of porous building materials was used. In this model, due to the multilayer adsorption of water vapor, we assumed that the water vapor sorption is described by the sorption isotherm curve. Regarding toluene, it is modelled by the partition coefficient because it is generally considered as monolayer

adsorption. The model includes moisture and VOC diffusion, moisture and VOC sorption, impact of RH and T on moisture and VOC diffusion/sorption, boundary condition between indoor/outdoor air and building envelope surfaces, etc.

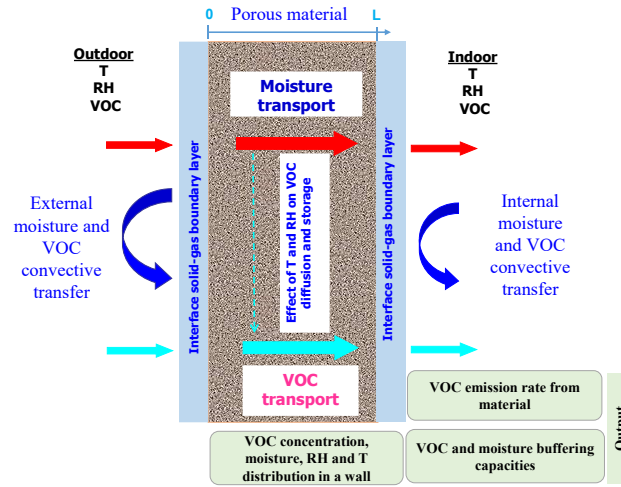


Figure 3: Schematic of coupled moisture and VOC transport model in a wall presented in – Tran Le et al., [2021].

Coupled moisture, air and pollutant transport in porous building material

In this article, it assumed that VOC and moisture diffusion in materials are due to the VOC and moisture concentration gradients, respectively, while the chemical reactions are neglected.

Considering the one-dimensional diffusion in a dry material with homogeneous diffusivity, the VOC transport within the wall can be described with [30;31] :

$$\frac{\partial C_{m,VOC}}{\partial t} = \frac{\partial}{\partial x} \left(D_{m,VOC} \frac{\partial C_{m,VOC}}{\partial x} \right) \quad (1)$$

Where $C_{m,VOC}$ is VOC concentration in the material (kg/m^3), $D_{m,VOC}$ is the diffusion coefficient of the VOC in the material (m^2/s), x is abscissa (m) and t is time (s).

It is considered that the equilibrium between the concentration of VOC in a material ($C_{m,VOC}$) and the concentration in air ($C_{a,VOC}$) is defined by the partition coefficient $K_{m,VOC}$. Therefore, at the material-air interface, we assume an instantaneous equilibrium between VOC concentration (kg/m^3) in the air near material surface ($C_{a,VOC,s}$) and the one in the surface layer ($C_{m,VOC,s}$). They are related by the following equation:

$$C_{m,VOC,s} = K_{m,VOC} \cdot C_{a,VOC,s} \quad (2)$$

The following boundary conditions are applied for the external ($x=0$) and internal ($x=L$) surfaces of the wall, respectively:

$$-\left(D_{m,VOC} \frac{\partial C_{m,VOC}}{\partial x}\right)_{x=0,e} = h_{m,VOC,e} (C_{a,VOC,e} - C_{a,VOC,s,e}) \quad (3)$$

$$-\left(D_{m,VOC} \frac{\partial C_{m,VOC}}{\partial x}\right)_{x=L,i} = h_{m,VOC,i} (C_{a,VOC,s,i} - C_{a,VOC,i}) \quad (4)$$

Where $C_{a,VOC,i}$ and $C_{a,VOC,e}$ are VOC concentration in the room air and outside (kg/m^3); $C_{a,VOC,s,i}$ and $C_{a,VOC,s,e}$ are VOC concentrations in the air near internal and external surfaces (kg/m^3); $h_{m,VOC,e}$ and $h_{m,VOC,i}$ are convective VOC transfer coefficients (m/s) for the external and internal surfaces, respectively.

Regarding the hygric model, considering the moisture content in material as driving force, the moisture transport can be described by the one-dimensional diffusion (– Philip and De Vries, [1957]):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left(D_{m,wv} \frac{\partial \theta}{\partial x} \right) \quad (5)$$

Where θ is moisture volumetric content in the material (m^3 of water/ m^3 of material), $D_{m,wv}$ is diffusion coefficient of the moisture in the material (m^2/s) which is determined by the following equation [32;33]:

$$D_{m,wv} = \delta_{wv} \frac{P_{v,sat}}{\rho_w} \frac{1}{\partial \theta / \partial RH} \quad (6)$$

$\partial \theta / \partial RH$ is the slope of the sorption isotherm curve designating the relationship between the moisture content and the relative humidity (RH) at a constant temperature, δ_{wv} is water vapor permeability of material ($\text{kg}/(\text{m.s.Pa})$), ρ_w is the density of water (kg/m^3), $P_{v,sat}$ the saturation pressure of water vapor (Pa).

Concerning the sorption isotherm, the Guggenheim-Anderson-deBoer (GAB) model [34], extended from Langmuir and BET theories [35;36], is used to describe the sorption curve of studied material. The GAB model can be written as follows:

$$w = \frac{w_m C_{GAB} K_{GAB} RH}{(1 - K_{GAB} RH)(1 + K_{GAB} C_{GAB} RH - K_{GAB} RH)} \quad (7)$$

Where RH is relative humidity, w is the moisture content (kg of moisture/kg of material), w_m is the monolayer moisture content value, C_{GAB} and K_{GAB} are energy constants of GAB model.

At the material-air interface, it is assumed that there is an instantaneous equilibrium between water vapor concentration (kg/m^3) in the air near material surface ($C_{a,wv,s}$) and the one in the surface layer ($C_{m,wv,s}$). The boundary conditions can be written as follows, for the external ($x=0$) and internal ($x=L$) surfaces of the wall, respectively:

$$-\left(\rho_w D_{m,wv} \frac{\partial \theta}{\partial x}\right)_{x=0,e} = h_{m,wv,e} (C_{a,wv,e} - C_{a,wv,s,e}) \quad (8)$$

$$-\left(\rho_w D_{m,wv} \frac{\partial \theta}{\partial x}\right)_{x=L,i} = h_{m,wv,i} (C_{a,wv,s,i} - C_{a,wv,i}) \quad (9)$$

Where $C_{a,wv,i}$ and $C_{a,wv,e}$ are water vapor concentrations in the room air and outside (kg/m^3), and $h_{m,wv,e}$ and $h_{m,wv,i}$ are convective water vapor transfer coefficients (m/s) for the external and internal surfaces.

The mass transfer coefficient strongly depends upon the characteristics of the airflow at the material surface and may be measured directly or indirectly (– Axley, [1991]). Note that a theoretical relationship between $h_{m,wv}$ and $h_{m,VOC}$ has been established allowing to determine the convective mass transfer coefficient of VOC ($h_{m,VOC}$) from the convective mass transfer coefficient of water vapor $h_{m,wv}$ (or inversely) using the diffusion coefficients of VOC and water vapor [24].

Model for a room

In order to model the indoor VOC concentration and relative humidity in the room, the nodal method has been used, which considers the room as a perfectly mixed zone characterized by moisture and pollutant concentrations. The nodal method involves equations for moisture/pollutant (VOC) mass balance and equations describing mass transfer through the walls, additional convection between inside wall surfaces and room ambiance. The water vapor/VOC concentration in the room is determined by the water vapor/VOC transfer from interior surfaces, water vapor /VOC production rate and the gains or losses due to air infiltration, natural and mechanical ventilation, sources due to room occupants as well as the moisture/VOC buffering capacity of other indoor elements (such as furniture, woolen carpet, etc.). This yields to the following mass balance equation for water vapor/VOC:

$$V \frac{\partial C_{a,i}}{\partial t} = Q(C_{a,o} - C_{a,i}) + \sum A \cdot h_{m,i} (C_{as,i} - C_{a,i}) + G \quad (10)$$

Where $C_{a,i}$ is the VOC/water vapor concentration at time t (kg/m^3), $C_{a,o}$ is outdoor ventilation air, V is volume space (m^3); A is exposed area of the material (m^2), Q is the

air flow rate into and out of the room (m^3/s), G is the generation rate of VOC/water vapor in the room (kg/s).

To solve the above-mentioned equation system, the numerical solution is based on the finite difference technique with an implicit scheme. The Simulation Problem Analysis and Research Kernel (SPARK) suited to efficiently solve differential equation systems has been used – Sowell and Haves, [2001]; – Mendonça et al., [2002]; – Wurtz et al., [2006].

Toluene and moisture properties of hempcrete

The toluene and moisture properties of hempcrete were determined by fitting the numerical and experimental results. Regarding the experimental work, the toluene concentration (228 ± 15 ppb) has been injected into the test chamber while air temperature and relative humidity of the inlet air were maintained at 23°C and 50% RH. The toluene (TOL) concentration in the test chamber (*Figure 1*) was used to determine toluene properties of hempcrete. Concerning the moisture properties, they were determined based on the sample mass variation for the test realized in the climate chamber (*Figure 2*).

The mean free path of toluene is equal to 14.3 nm [9]. In the study of [37], the mean pore diameter in hemp concrete is about 780 nm, therefore molecular diffusion dominates for toluene. Concerning water vapor, its mean free path is 100 nm, the molecular diffusion is predominant in hempcrete compared to Knudsen diffusion which is also expected to occur.

The initial toluene concentrations C_0 in hemp concrete specimen is equal to 0 ($\mu\text{g}/\text{m}^3$) because this material is clean. Figure 4 shows the comparison of the experimental and numerical results of indoor toluene (TOL) concentration in the small test chamber with these parameters: partition coefficient $K_{m,\text{TOL}}=150$ and diffusion coefficient $D_{m,\text{TOL}}=2.5 \times 10^{-9} \text{ m}^2/\text{s}$. As it can be seen, a very good agreement between the numerical model and experimental results for adsorption and desorption periods has been obtained. Note that in the previous publication by [24], the predicted theoretical values of another hemp lime concrete produced in France were $K_{m,\text{TOL}}=550$ and $D_{m,\text{TOL}}=5.5 \times 10^{-9} \text{ m}^2/\text{s}$.

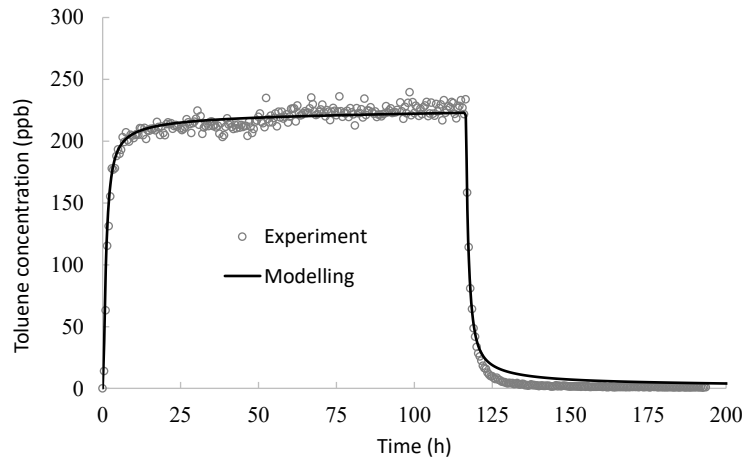


Figure 4: Comparison of experimental and numerical results of indoor toluene (TOL) concentration in the small chamber

Regarding moisture properties of hempcrete, the sorption properties and water vapor permeability were determined by fitting the numerical and experimental mass variations obtained in the climate chamber test. Using the moisture properties proposed in Table 1, a good agreement between the experimental and numerical results was obtained (Figure 5). Note that the proposed values are consistent with the ones obtained for other hemp concretes in the literature ([38;39]).

The toluene and moisture parameters which have been previously determined for hempcrete are summarized and regrouped in Table 1. These parameters will be used for the simulations in the following section focusing on the impact of moisture and toluene buffering capacities of hempcrete on IAQ and indoor RH variation.

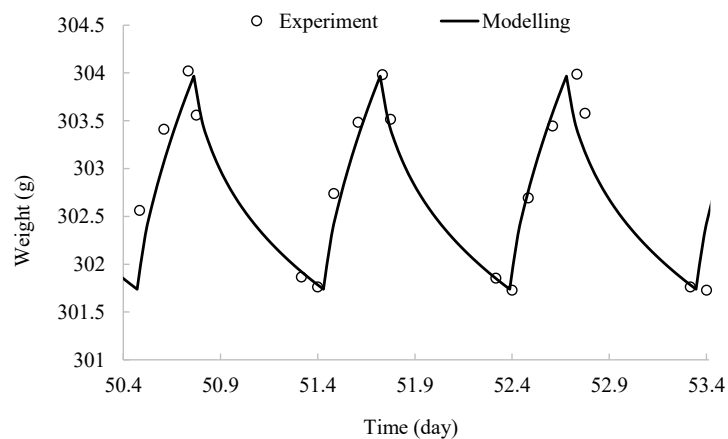


Figure 5: Comparison of experimental and numerical results of the sample mass variation in the climate chamber

Density (kg/m ³)	K _{m,TOL}	D _{m,TOL} (m ² /s)	δ _{wv} kg/(m.s.Pa)	Sorption isotherm (GAB model parameters)
298	150	2.5×10 ⁻⁹	5.57×10 ⁻¹¹	w _m =0.029; C _{GAB} =7; K _{GAB} =0.99

Table 1: Toluene (TOL) and moisture properties of hempcrete used for the simulation.

IMPACT OF MOISTURE AND TOLUENE BUFFERING CAPACITIES OF HEMP CONCRETE

The objective of this study is to analyze quantitatively the effect of moisture and toluene sorption on IAQ and indoor RH variation using the numerical model presented in the above section.

Description of studied room and simulation conditions

In order to carry out a quantitative study, we define a reference office room which is depicted in Figure 6:

- The office room has a space area of 3×4 m² and a volume of 30 m³.
- A total exposed surface area S=25 m² of hempcrete (moisture and toluene interactions between indoor air and building materials are taken into account) is considered.
- The hempcrete wall has a thickness of 20 cm.
- The ventilation uses the external conditions in which the outdoor temperature and relative humidity are 20°C and 50 %, respectively.
- The office room is occupied by one person from 8.00 am to 17.00 pm and the water vapor source is 72 g/h.
- Air velocity over the wall of 0.15 m/s which is a typical designed value in buildings.

Concerning the numerical solution, the hempcrete wall is divided into 25 nodes and the time step is 240s. Only interaction (moisture/toluene) between the internal exposed surface of hempcrete wall and indoor air is taken into account; the other faces of the material are considered “well sealed”. The initial relative humidity is 50% RH and the initial toluene concentrations C₀ in hemp concrete is 0 (μg/m³) because it is considered as a clean material. To study the effect of toluene buffering capacity of hempcrete, a toluene

source scheme is considered: 12 hours of 1000 $\mu\text{g}/\text{h}$ followed by 12 hours of 0 $\mu\text{g}/\text{h}$ intermittently. In this paper, two models have been considered: the first one is buffering capacity model (**BC** model) which takes into account the moisture and toluene sorption capacities; the second one is **Without-BC** model (model without buffering capacity) which neglects the moisture and toluene sorption capacities.

The hygric and pollutant properties of hempcrete presented in Table 1 were used for the simulation. The room temperature is constant and kept at 20°C. An outdoor toluene concentration of 0 mg/m^3 and a ventilation rate of 0.6 ACH determined based on the ventilation rate required in the French office buildings are considered.

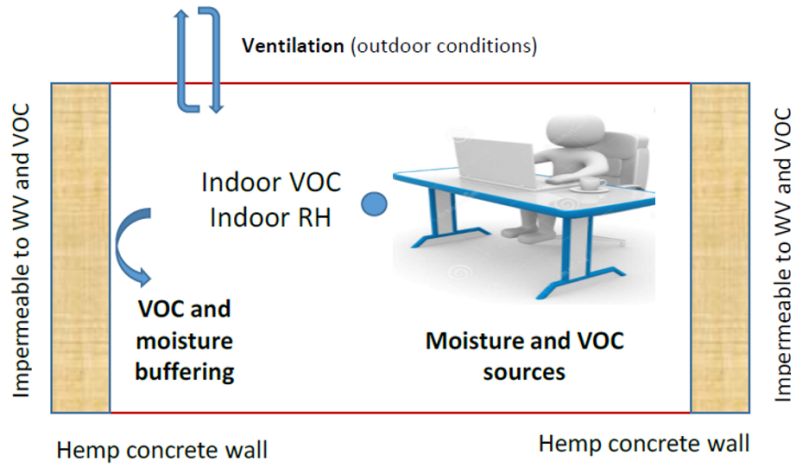


Figure 6: Studied reference office room

Results and discussion

The results of the simulations using the two models considering and neglecting the moisture/pollutant buffering capacity are presented in Figure 7 and Figure 8. In addition, Table 2 presents the analysis results obtained from the simulation at equilibrium. It can be seen in Figure 7 that the effect of the toluene buffering capacity of hempcrete on indoor toluene variation is significant. A parameter called “*peak reduced factor-PRF*” which is calculated from the indoor concentration obtained by **Without-BC** and **BC** models (C_0 corresponds to the case without buffering capacity) is defined as follows:

$$PRF_{VOC} = \frac{c_0 - c}{c_0} \quad (11)$$

The PRF_{VOC} value allows to quantify the VOC buffering capacity of building materials and is very useful for IAQ analysis and design. Regarding the values of indoor pollutant

concentration at the equilibrium state, the maximum values of **BC** and **Without-BC** models are 51.5 and 55.5 $\mu\text{g}/\text{m}^3$, respectively (Table 2) (so a PRF_{TOL} of 8 %). Note that PRF_{TOL} value depends on the exposure time. Regarding the IAQ analysis, it is very interesting to define a parameter called “*Cumulative Exposure Reduction Factor, ERFc*” (unit is %·h)” that takes into account both the concentration reduction and the exposure time:

$$ERF_c = \int_0^t PRF dt \quad (12)$$

In this studied case, the ERFc for toluene is 151.6 %·h for 12 hours exposure.

To quantify the impact of VOC buffering capacity of building material on indoor VOC concentration in a period of time, and for a specific room, another index called “*cumulative Exposure Reduction Quantity, ERQc* (unit is g)” is defined as follows:

$$ERQ_c = \int_0^t (C_0 - C) V dt \quad (13)$$

Within 12 hours exposure, the ERQc of toluene calculated is 2.26 g which represents 18.8% of the quantity of toluene generated during 12 hours (which is equal to 12 g). The results obtained show that taking into account the capacity of toluene sorption results in damping the peak of indoor toluene concentration and thus contributes to improving indoor air quality.

Regarding the variation of the indoor relative humidity, the results are presented in Figure 8 and Table 2. It can be seen that the moisture buffering capacity of hempcrete allows to dampen the indoor relative humidity variation. Numerically, at the equilibrium state, the maximum indoor RH values decrease from 73 % to 64.9 % RH ($PRF_{RH}=11$ %) for **Without-BC** and **BC** models, respectively. To quantify the hygric buffering capacity of building materials, a parameter called “*amplitude reduced factor- RF_a* ” which is calculated from the amplitude of indoor relative humidity variation with and without moisture buffering capacity (A_0 corresponds to the case without moisture capacity) is defined as follows:

$$RF_a = \frac{A_0 - A}{A_0} \quad (15)$$

The RF_a value obtained showing that the moisture buffering capacity of hempcrete can reduce the indoor RH variation amplitude by 61.7 %.

Indoor Toluene ($\mu\text{g}/\text{m}^3$)			Indoor RH (%)		
Amplitud			Amplitud		
TOL min	TOL max	e	RH min	RH max	e

Without-BC

model	0	55.5	55.5	50	73	23
BC model	3.2	51.1	47.8	56.1	64.9	8.8

Table 2: Effect of toluene and moisture buffering capacities of hempcrete on indoor toluene concentration and indoor RH

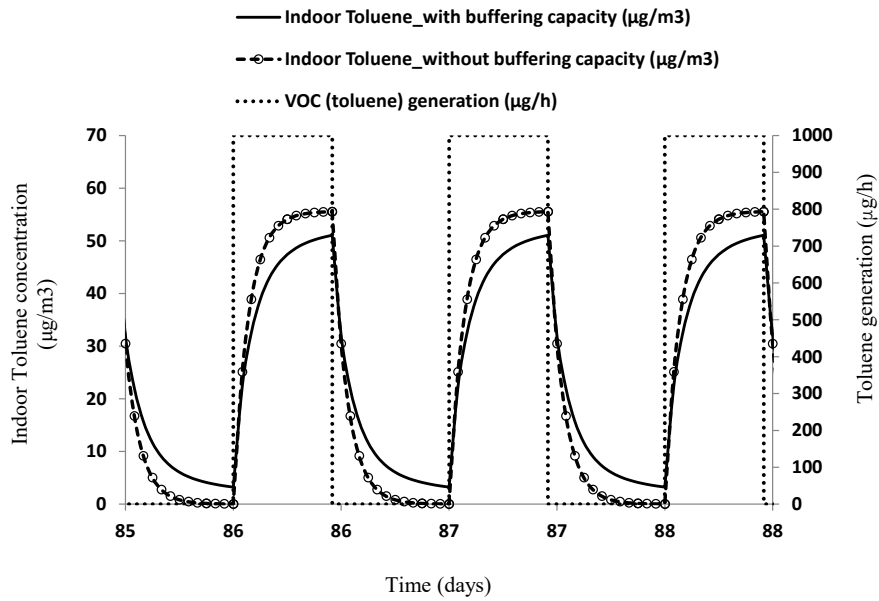


Figure 7: Effect of toluene (TOL) sorption capacity of hempcrete on indoor toluene concentration

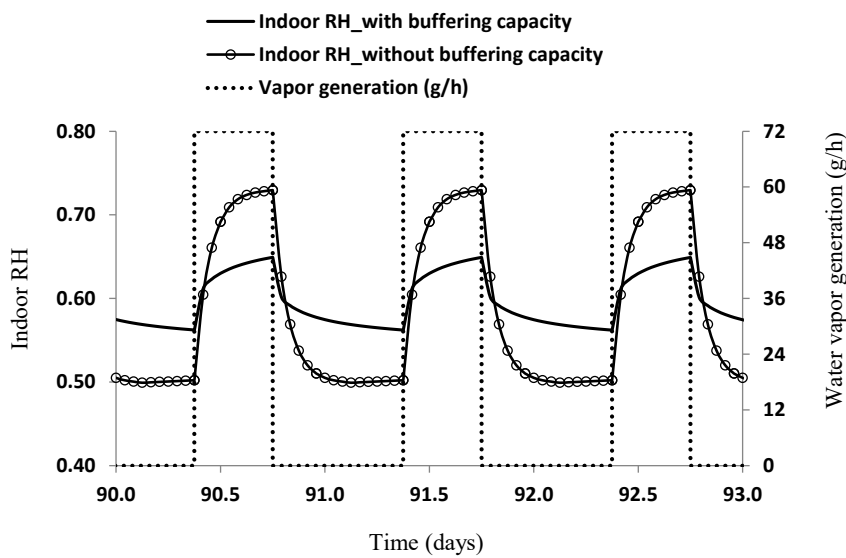


Figure 8: Effect of moisture buffering capacity of hempcrete on indoor RH variation

Note that the buffering capacity is fully utilized when hempcrete is directly exposed to indoor air. In the case that hempcrete wall is rendered/plastered with finishing material, it is suggested to use the moisture and VOC permeable internal plaster. Regarding the material selection process in building design, it is very useful to study the effect of the loading ratio defined by the ratio of the exposed surface area (A) of hemp concrete to the volume of the studied room (V) on IAQ and hygric performance. Therefore, the simulation has been done with different loading ratios from 0 to 1 with a step of 0.2 (so an exposed surface varies from 0 to 30 m² with a step of 5 m²). Figure 9 and Table 2 show the effect of the exposed surface and the loading ratio on indoor toluene and other parameters (PRF_{TOL}, ERF_C and ERQ_C). It can be seen that the impact of the loading ratio is significant. The higher the loading ratio, the more PRF_{TOL} because more toluene molecules can be adsorbed by hempcrete during the adsorption period. Numerically, when the loading ratio decreases from 1 to 0.5, the ERQ_C decreases from 2.6 g to 1.47 g and the PRF_{TOL} decreases from 9.4 % to 5 %.

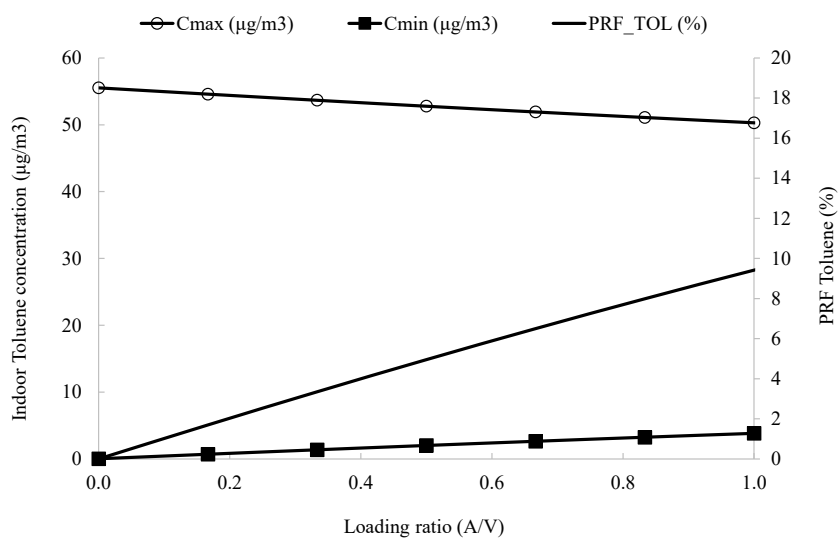


Figure 9: Effect of loading ratio (m²/m³) of hempcrete on indoor toluene concentration and PRF

A (m²)	Loading ratio A/V (m²/m³)	C_{max} (µg/m³)	C_{min} (µg/m³)	Amplitude (µg/m³)	PRF_{TOL} (%)	ERFc (%.h)	ERQc (g VOC)
0	0.0	55.5	0.0	55.5	0.0	0	0
5	0.2	54.6	0.7	53.9	1.7	36.2	0.53
10	0.3	53.7	1.4	52.3	3.3	69.2	1.02
15	0.5	52.8	2.0	50.8	5.0	99.2	1.47
20	0.7	51.9	2.6	49.3	6.5	126.6	1.88
25*	0.8	51.1	3.2	47.8	8.0	151.6	2.26
30	1.0	50.3	3.8	46.5	9.4	174.7	2.60

*Reference case

Table 3: Impact of exposed surface (A) and loading ratio

Regarding the impact of loading ratio on indoor RH variation, the results obtained are presented in Figure 10 and Table 4. It can be observed that increasing loading ratio results in decreased amplitude variation of indoor RH and increased RF_{a,RH} (%) and PRF_{RH} (%). Numerically, when the loading ratio varies from 0 (moisture buffering is neglected) to 1, RF_{a,RH} (%) varies from 0 to 65.8 % and PRF_{RH} (%) varies from 0 to 11.5%, respectively. The results obtained suggest that the use of pollutant and moisture buffering capacity of materials is a good solution in building design to improving IAQ as well as hygrothermal performance of buildings.

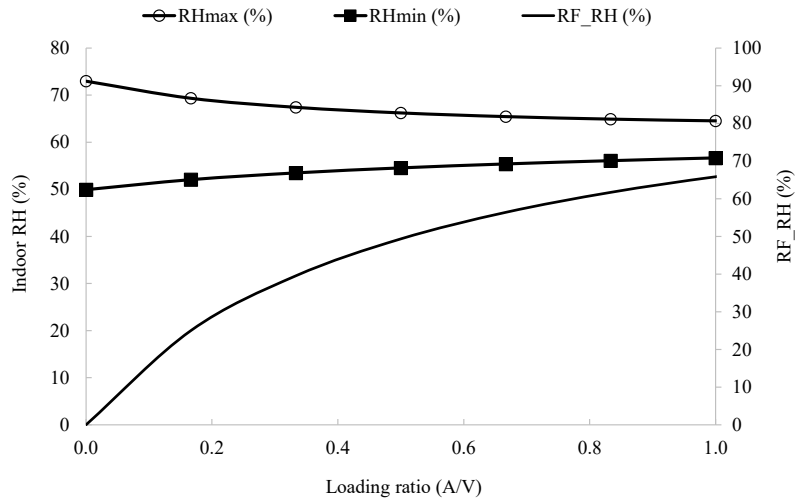


Figure 10: Effect of loading ratio (m^2/m^3) of hempcrete on indoor RH and RF_{RH} (%)

A (m^2)	Loading	RH_{max}	RH_{min}	Amplitude	$\text{RF}_{\text{a,RH}}$	PRF_{RH}
	ratio S/V (m^2/m^3)					
0	0.00	73.0	50.0	23.0	0.0	0.0
5	0.17	69.3	52.1	17.3	25.0	5.0
10	0.33	67.4	53.5	13.9	39.6	7.6
15	0.50	66.2	54.6	11.7	49.3	9.2
20	0.67	65.4	55.4	10.0	56.4	10.3
25*	0.83	64.9	56.1	8.8	61.7	11.0
30	1.00	64.5	56.7	7.9	65.8	11.5

*Reference case

Table 4: Impact of exposed surface (A) and loading ratio on hygric performance of hempcrete

CONCLUSION

The objective of this article is to study the impact of toluene, a typical indoor VOC, and moisture buffering capacities of hempcrete on IAQ and indoor RH. A validated coupled moisture and pollutant transport simulation model which has been implemented in SPARK, an object-oriented program suited to complex problems, was applied to evaluate the toluene and moisture buffering of hempcrete. Different indices (*Peak Reduced Factor-PRF*, *cumulative Exposure Reduction Factor-ERFc*, *cumulative Exposure Reduction Quantity*, *amplitude Reduced Factor-RFa*) have been defined and proposed for possible application in future standards or studies that consider moisture and VOC buffering concept in the passive design of buildings. The numerical model has been applied to the reference office room. The results obtained show that taking into account the sorption capacity toward moisture and toluene of hempcrete is necessary to predict indoor RH and IAQ properly. Finally, the obtained results highlight that the use of hempcrete with a high loading ratio is one of passive ways to improve the indoor air quality and thermal comfort in buildings.

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NOMENCLATURE

A	Exposed area of the material	m ²
C	Concentration	kg/m ³
C _{a,o}	Outdoor ventilation air	kg/m ³
C _{a,wv,e}	Water vapor concentrations in the outside	kg/m ³
C _{a,wv,i}	Water vapor concentrations in the room air	kg/m ³
D _{m,VOC}	Diffusion coefficient of the VOC in the material	m ² .s ⁻¹
D _{m,wv}	Mass transport coefficient associated to a moisture content gradient	m ² .s ⁻¹
h _{m,wv,i}	Convective water vapor transfer coefficient for the internal	m/s

	surface	
$h_{m,wv,e}$	Convective water vapor transfer coefficient for the external surface	m/s
$h_{m,VOC,e}$	Convective VOC transfer coefficient for the external surface	m/s
$h_{m,VOC,i}$	Convective VOC transfer coefficient for the internal surface	m/s
$K_{m,VOC}$	Partition coefficient for VOC	-
ERFc	Cumulative Exposure Reduction Factor	%h
PRF	Peak reduced factor	%
ERQc	cumulative Exposure Reduction Quantity	g
$P_{wv,sat}$	Saturation pressure of water vapor	Pa
Q	Flow rate	m ³ /s
RH	Relative humidity	-
T	Temperature	K
t	Time	s
V	Volume space	m ³
w	Moisture content	kg.kg ⁻¹
w_m	Monolayer moisture content	kg.kg ⁻¹
x	Abscissa	m
θ	Moisture volumetric content	m ³ .m ⁻³
μ_{wv}	Vapor diffusion resistance factor	-
δ_{wv}	Water vapor permeability of material	kg/(m.s.Pa)

Subscripts

e= external

m= material

i= internal

wv= water vapor

IAQ= Indoor Air Quality

VOC= Volatile Organic Compounds

TOL=Toluene

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