IEA EBC - Annex 86 - Energy Efficient Indoor Air Quality Management in Residential Buildings

Impact of VOC and moisture buffering capacities of bio-based building materials on IAQ and indoor RH: the case of hemp concrete

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IEA Annex 86 Webinars- Smart materials- 12 Oct. 2021

Goal for building design

- Hygrothermal comfort → One passive way by using hygroscopic materials (release or adsorb water vapor depending on the surrounding air conditions)
- Indoor air quality (IAQ)
- Acoustical and visual comforts

Use of vegetable particles (hemp shives, flax shives, straw bales, etc.) as building material aggregates:

- *bio-based materials*
- *low embodied energy*

Rape (rapeseed)

Hemp

Hemp
availability in the world

France is the first producer of hemp in Europe

Flax

Miscanthus

Bamboo

National availability (France)

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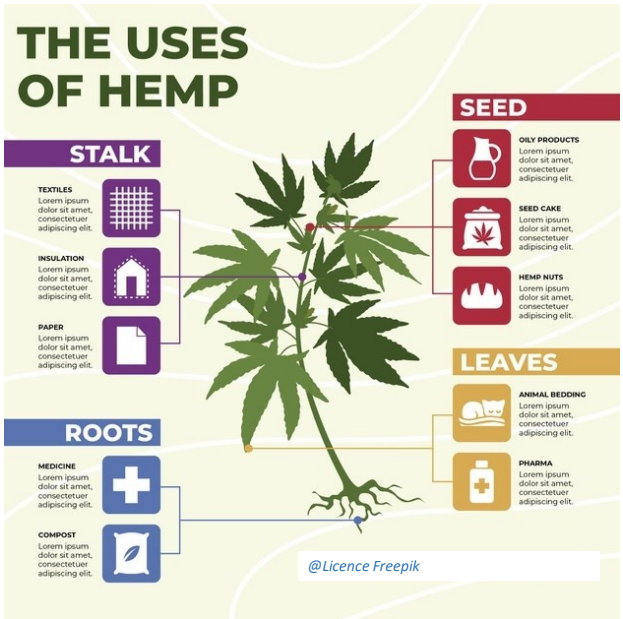

Back to history

Hemp mortar discovered in *Merovingian bridge* *built in the 6th century* *in Saint Céneri le Gérei, in France*

Now: hemp concrete

- ✓ **environmentally friendly building material**
- ✓ **reference bio-based material**

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Impact of VOC and moisture buffering capacities of bio-based building materials on IAQ and thermal comfort

Valorization of Hemp in building construction

Hemp

partly decorticated hemp stalk

Hemp shiv

Fiber

Hemp concrete

Hemp plaster

Hemp insulation

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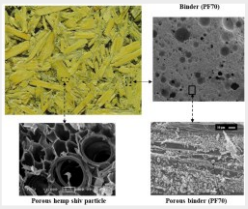
mCHAMPS-BBMS

The multi-scale approach to Coupled Heat, Air, Moisture and Pollutants Simulations in Bio-based Building Materials and Systems

Microscopic scale



Microscopic properties of components

Material scale

Properties (anisotropy)
Thermal
Physical
Moisture
Pollutant (VOC)

Wall scale

Hygrothermal and VOC behavior

Experimental study
Model validation

Room and house scale

Hygrothermal performance, thermal comfort et indoor air quality (QAI: VOC, CO2…), Energy consumption
Numerical and experimental studies
Model validation

HygroPo-BBM

Homogenization method

CHAMPS-BBM

mCHAMPS-BBMS

Implemented properties

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English version

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mCHAMPS-BBMS

The multi-scale approach to Coupled Heat, Air, Moisture and Pollutants Simulations in Bio-based Building Materials and Systems

What is the impact of VOC and moisture buffering capacities of hemp concrete building envelope on IAQ and indoor RH?

Wall scale

Hygrothermal and VOC behavior

Experimental study
Model validation

Room and house scale

Hygrothermal performance, thermal comfort et indoor air quality (QAI: VOC, CO2…), Energy consumption
Numerical and experimental studies
Model validation

CHAMPS-BBM

mCHAMPS-BBMS

Homogenization method

Implemented properties

English version

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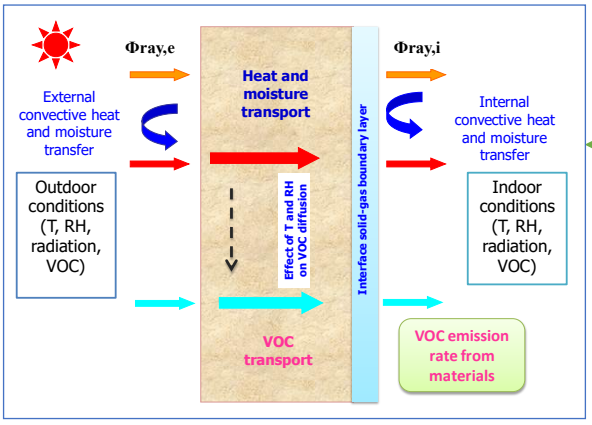
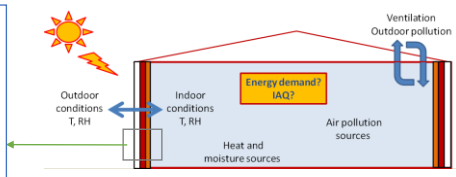
CHAMPS-Bio Model

Development and Validation of a Coupled Heat, Air, Moisture and Pollutant Simulation Model Dedicated to Bio-based Materials





- Heat and moisture transport in building materials
- Adsorption or desorption heat due to water vapor sorption in building materials
- Diffusion and sorption of VOC
- **Taking into account of impact of T and RH on VOC diffusion and sorption** (if data are available)
- **Focusing on Biobased building materials**

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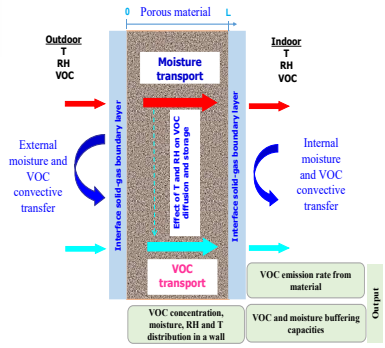
CHAMPS-Bio model



Selected references

- *J.R. Philip, D.A. De Vries, Moisture movement in porous materials under temperature gradients, Trans. Am. Geophys. Union 38 (2) (1957) 222–232.*
- *J.S. Zhang, Combined heat, air, moisture, and pollutants transport in building environmental systems, JSME International Journal, Series B 48 (2) (2005) 1–9.*
- *N. Mendes, F.C.Winkelmann, R.Lamberts, P.C.Philippi. Moisture effects on conduction loads. Energy Build. 35 (7) (2003), 631–644.*
- *A.D. Tran Le, C. Maalouf, T.H. Mai, E. Wurtz, F. Collet, Transient hygrothermal behaviour of a hemp concrete building envelope, Energy Build. 42 (2010) 1797–1806.*
- *A.D. Tran Le, JS. Zhang, Z. Liu, D Samri, T. Langlet. Modeling the similarity and the potential of toluene and moisture buffering capacities of hemp concrete on IAQ and thermal comfort, Building and Environment, 188,2021,107455.*
- *etc.*

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Governing moisture balance equation and boundary conditions

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(D_T \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}\left(D_\theta \frac{\partial \theta}{\partial x}\right)$$

$$-\rho_l\left(D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x}\right)\Big|_{x=0,e} = h_{M,e}\left(\rho_{ve,a,e} - \rho_{ve,s,e}\right) \quad \text{external surface (x=0)}$$

$$-\rho_l\left(D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x}\right)\Big|_{x=L,i} = h_{M,i}\left(\rho_{ve,s,i} - \rho_{ve,a,i}\right) \quad \text{internal surface (x=L)}$$

Energy balance equation and boundary conditions

$$\rho_0 C p_m \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_{app} \frac{\partial T}{\partial x}\right) + L_v \rho_l\left(\frac{\partial}{\partial x}\left(D_{T,v} \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}\left(D_{\theta,v} \frac{\partial \theta}{\partial x}\right)\right)$$

$$-\lambda_{app} \frac{\partial T}{\partial x} - L_v \rho_l\left(D_{T,v} \frac{\partial T}{\partial x} + D_{\theta,v} \frac{\partial \theta}{\partial x}\right)_{x=0,e} = h_{T,e}\left(T_{a,e} - T_{s,e}\right) + L_v h_{M,e}\left(\rho_{ve,a,e} - \rho_{ve,s,e}\right) + \Phi_{ray,e}$$

$$-\lambda_{app} \frac{\partial T}{\partial x} - L_v \rho_l\left(D_{T,v} \frac{\partial T}{\partial x} + D_{\theta,v} \frac{\partial \theta}{\partial x}\right)\Big|_{x=L,i} = h_{T,i}\left(T_{s,i} - T_{a,i}\right) + L_v h_{M,i}\left(\rho_{ve,s,i} - \rho_{ve,a,i}\right) - \Phi_{ray,i}$$

Pollutants transport equation and boundary conditions

$$\frac{\partial C_m}{\partial t} = \frac{\partial}{\partial x}\left(D_m \frac{\partial C_m}{\partial x}\right)$$

$$-D_m \frac{\partial C_m}{\partial x}_{x=0,e} = h_{m,e}\left(C_{a,e} - C_{as,e}\right) \qquad -D_m \frac{\partial C_m}{\partial x}_{x=L,i} = h_{m,i}\left(C_{as,i} - C_{a,i}\right)$$

For pollutants model, at the material-air interface, we assume an instantaneous equilibrium between VOC concentration (mg/m3) in the air near material surface (Cas) and the one in the surface layer (Cms)

$$C_{ms} = K.C_{as}$$

Energy and mass balance equations for room air

$$\rho_l C_p V \frac{\partial T}{\partial t} = \Phi_{West} - \Phi_{East} + \Phi_{South} - \Phi_{North} + \Phi_{Bottom} - \Phi_{Top} + \Phi_{Ventilation} + \Phi_{Source}$$

$$V \frac{\partial \rho_v}{\partial t} = Q_{mWest} - Q_{mEast} + Q_{mSouth} - Q_{mNorth} + Q_{mBottom} - Q_{mTop} + Q_{mVentilation} + Q_{mSource}$$

$$V \frac{\partial C_i}{\partial t} = Q(C_{a,e} - C_{a,i}) + AE + G_{VOC\_Source} \quad \text{Where} \quad E = h_{m,i}\left(C_{as,i} - C_{a,i}\right)$$

The Simulation Problem Analysis and Research Kernel (SPARK)* BERKELEY LAB

**SPARK: E.F. Sowell, P. Haves, Efficient solution strategies for building energy system simulation, Energy Build. 33 (2001) 309–317.*

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CHAMPS-Bio model validation (1)

Case of a particleboard: prediction of VOC emission rate

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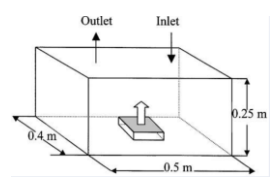
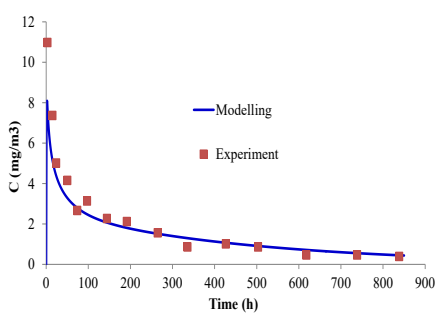
- Experimental setup consists of a small test chamber (0.4*0.5*0.25 m3) with a pollutant emitting panel material inside
- Particleboard with dimension 0.212x0.212x0.0159 m3
- Test conditions: T=23°C, RH=50%, Air change rate= 1 1/h

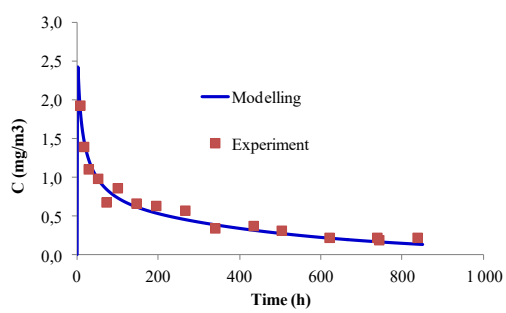
Age: 0



Reference: X. Yang, Q. Chen, J.S. Zhang, R. Magee, J. Zeng, C.Y. Shaw, Numerical simulation of VOC emissions from dry materials, Build. Environ. 36 (10) (2001) 1099–1107.



Validating for TVOC concentration emitted from the particleboard



Validating for Hexanal concentration emitted from the particleboard

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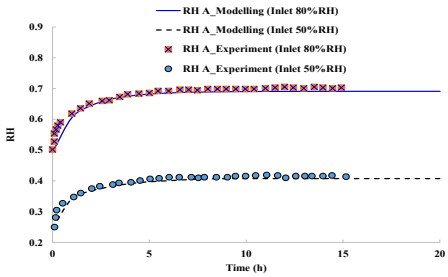
CHAMPS-Bio model validation (2)

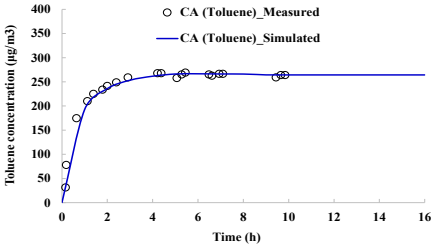
CHAMPS-Bio model has been validated recently

- ✓ **In framework of Fulbright Scholar program in 2020 (Commission Fulbright Franco-Américaine and Hauts-de-France region,FR)**
- ✓ **In collaboration with BEESL lab, Syracuse University, USA (referent Pr. ZHANG Jensen)**
- ✓ **Model validation with two indoor typical VOCs (*Formaldehyde and Toluene*) based on experimental results obtained with calcium silicate (Xu and Zhang 2011*)**



Model validation for moisture diffusion model

Impact of humidity on VOC behavior of porous materials and on IAQ : important to study



Model validation for Toluene (TOL)

A.D. Tran Le, JS. Zhang, Z. Liu, D Samri, T. Langlet. ***Modeling the similarity and the potential of toluene and moisture buffering capacities of hemp concrete on IAQ and thermal comfort****, Building and Environment, 188,2021,107455.*

A.D. Tran Le, JS. Zhang, Z. Liu. ***Impact of humidity on formaldehyde and moisture buffering capacity of porous building material****, Journal of Building Engineering, 36, 2021, 102114, ISSN 2352 7102.*

**Xu. J., Zhang, JS. An experimental study of relative humidity effect on VOCs' effective diffusion coefficient and partition coefficient in a porous medium. Build Environ 46 (2011), 1785-96.*

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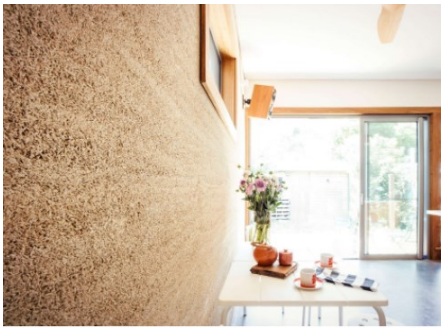
Effect of toluene and moisture buffering capacities of hemp concrete wall on indoor relative humidity and toluene concentration

Hemp concrete

well known in the literature

- ✓ used widely in the world
- ✓ low environmental impact
- ✓ good compromise between insulation and thermal inertia
- ✓ **high moisture buffering capacity**



Similarity between VOC and moisture buffering?
If yes, what is the impact of pollutant (VOC) buffering capacity on IAQ?

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Effect of toluene and moisture buffering capacities of hemp concrete wall on indoor relative humidity and toluene concentration

- Reference room: V=5*4*2.5 m^3
- Ventilation rate of 0.72 ACH (Air Changes per Hour)
- Exposed surface area S=25 m^2
- A toluene source scheme : 12 hours of 1000 µg/h followed intermittently 12 hours of 0 µg/h
- Room is occupied by two persons from 8.00 am to 17.00 pm (the water vapor source is 142 g/h).

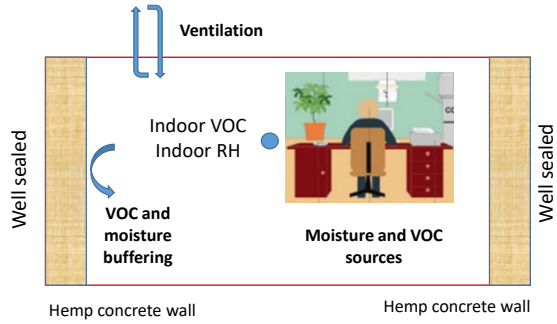
$K_{m,TOL}$	$D_{m,TOL}$ (m^2/s)
550	5.5×10^{-9}

Hygric properties of hemp concrete to model toluene properties.

Dry density (kg/m^3)	Total porosity (%)	Open porosity (%)	μ_{wv}	Sorption isotherm (GAB model parameters)
450	78	66	5	$w_m = 0.02$; $C_{GAB} = 7$; $K_{GAB} = 0.89$

Hygrothermal properties of hemp concrete measured by many research teams (selected references):

- F. Collet, J. Chamoin, S. Pretot, C. Lanos, Comparison of the hygric behaviour of three hemp concretes, Energy Build. 62 (2013) 294–303.
- R. Walker, S. Pavía, Moisture transfer and thermal properties of hemp–lime concretes, Construct. Build. Mater. 64 (2014) 270–276.
- M. Rahim, O. Douzane, A.D. Tran Le, G. Promis, B. Laidoudi, A. Crigny, et al., Characterization of flax lime and hemp lime concretes: hygric properties and moisture buffer capacity, Energy Build. 88 (2015) 91–99.
- T. Colinart, P. Glouannec, Temperature dependence of sorption isotherm of hygroscopic building materials. Part 1: experimental evidence and modeling, Energy Build. 139 (2017) 360–370.
- Etc.



- **Model with buffering capacity (BC model)**
- **Model without buffering capacity (Without-BC model)**

Toluene properties of hemp concrete

Reference: A.D. Tran Le, JS. Zhang, Z. Liu, D Samri, T. Langlet. **Modeling the similarity and the potential of toluene and moisture buffering capacities of hemp concrete on IAQ and thermal comfort**, *Building and Environment*, 188,2021,107455.

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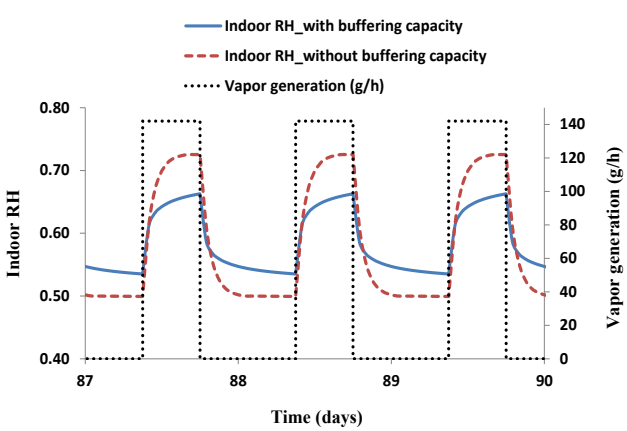
Effect of toluene and moisture buffering capacities of hemp concrete wall on indoor relative humidity and toluene concentration

Effect of moisture sorption capacity of hemp concrete on indoor RH



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Peak reduced factor-PRF

RH_0 : without buffering capacity
RH: with buffering capacity

$$PRF = \frac{RH_0 - RH}{RH_0}$$

Maximum values
- **BC** model: 66.3% RH
- **Without-BC** model: 72.5% RH
- ***PRF_{RH}*=8.6 %**

Amplitude reduced factor-RFa

$$RF_a = \frac{A_0 - A}{A_0}$$

A and A0 amplitudes of indoor relative humidity variation with and without moisture buffering capacity

RFa value of 43.4%: moisture buffering capacity can reduce the indoor RH variation amplitude by 43.4%.

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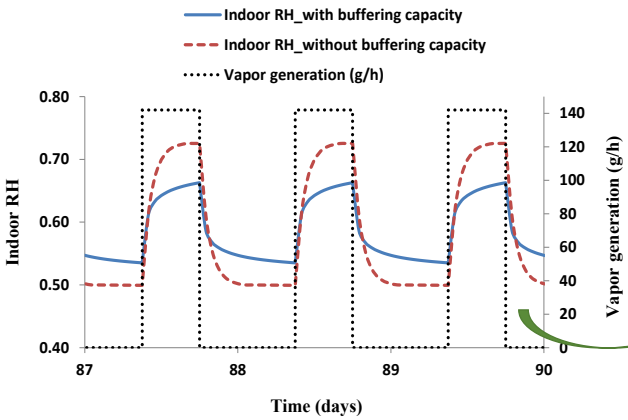
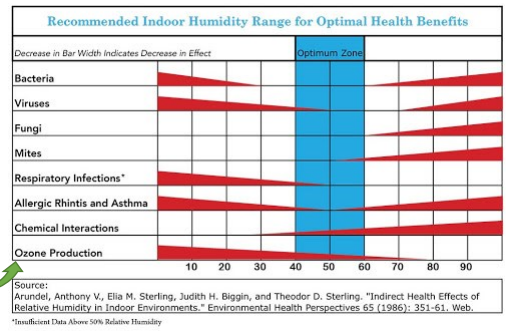
Effect of toluene and moisture buffering capacities of hemp concrete wall on indoor relative humidity and toluene concentration

Discussion: Effect of moisture sorption capacity of hemp concrete on health benefits





Moisture buffering capacity
passive way to keep the variation in RH between threshold levels

- ✓ **Hygrothermal comfort**
- ✓ **Health benefits**

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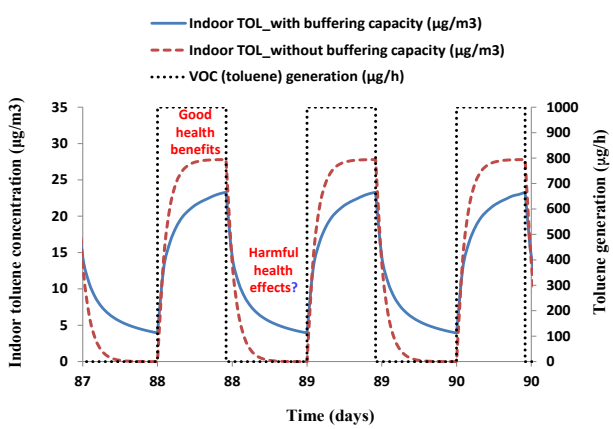
Effect of toluene and moisture buffering capacities of hemp concrete wall on indoor relative humidity and toluene concentration

Effect of toluene (TOL) sorption capacity of hemp concrete on indoor toluene concentration



Similarity between VOC and moisture buffering

Peak reduced factor-PRF

C_0 : *without buffering capacity*
C: *with buffering capacity*

$$PRF = \frac{C_0 - C}{C_0}$$

Maximum values
- **BC** model: 23.6 µg/m³
- **Without-BC** model: 27.8 µg/m³

***PRF_{TOL}* = 15%**

Cumulative Exposure Reduction Factor, ERFc

takes into account the concentration reduction and exposure time

$$\text{ERFc} = \int_0^t PRF\,dt$$

The ERFc for toluene is 210.5% for 12 h exposure

Health benefits?

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Reference: A.D. Tran Le, JS. Zhang, Z. Liu, D Samri, T. Langlet. **Modeling the similarity and the potential of toluene and moisture buffering capacities of hemp concrete on IAQ and thermal comfort**, *Building and Environment*, 188,2021,107455.

Effect of toluene and moisture buffering capacities of hemp concrete wall on indoor relative humidity and toluene concentration

Conclusions

- ✓ **Similarity between toluene (VOC) and moisture buffering capacities of hemp concrete** (a reference bio-based building material)
- ✓ **Impact of buffering capacities (toluene-VOC and moisture) of hemp concrete on indoor RH and IAQ: important to study**

  VOC buffering capacity: special attention at health benefits?

- ○ **Needed further experiments and analyses**
- ○ **If confirmed: buffering capacity toward moisture/pollutant (VOC) as an approach to improving IAQ as well as hygrothermal performance of buildings in future standards and design**

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Amiens, Hauts-de-France region, FRANCE

Thank you for your attention

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