



**HAL**  
open science

# Assessment of hygrothermal performance of hemp concrete compared to conventional building materials at overall building scale

Fares Bennai, Mohammed Yacine Ferroukhi, Ferhat Benmahiddine, Rafik Belarbi, Armelle Nouviaire

## ► To cite this version:

Fares Bennai, Mohammed Yacine Ferroukhi, Ferhat Benmahiddine, Rafik Belarbi, Armelle Nouviaire. Assessment of hygrothermal performance of hemp concrete compared to conventional building materials at overall building scale. *Construction and Building Materials*, 2022, 316, pp.126007. 10.1016/j.conbuildmat.2021.126007 . hal-03619493

**HAL Id: hal-03619493**

**<https://hal.science/hal-03619493v1>**

Submitted on 16 Jun 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Assessment of hygrothermal performance of hemp concrete compared to conventional building materials at overall building scale

Fares Bennai<sup>a</sup>, Mohammed Yacine Ferroukhi<sup>b</sup>, Ferhat Benmahiddine<sup>c,d</sup>, Rafik Belarbi<sup>c,d,\*</sup>, Armelle Nouviaire<sup>c</sup>

<sup>a</sup> Université de Lorraine, CNRS, Arts et Métiers ParisTech, LEM3, F-57000 Metz, France

<sup>b</sup> Univ Lyon, ENISE, LTDS UMR CNRS 5513, 58 Rue Jean Parot, F-42023, St-Etienne Cedex, France

<sup>c</sup> LaSIE UMR 7356 CNRS, La Rochelle Université, Avenue Michel Crépeau, CEDEX 1, F-17042 La Rochelle, France

<sup>d</sup> 4evLab, LaSIE, CNRS, EDF R&D, La Rochelle Université, Avenue Michel Crépeau, CEDEX 1, F-17042 La Rochelle, France

## ARTICLE INFO

### Keywords:

Hemp concrete  
Hygrothermal behaviour  
HAM-BES coupling  
Energy consumption  
Building envelope

## ABSTRACT

The aim of this paper is to analyse the impact of hemp concrete on the overall hygrothermal behaviour of the building when it used as an infill layer in the envelope of wood-frame structures. Three wall configurations were considered in different climates. Then, a hygrothermal co-simulation approach was used to integrate the model of coupled heat and moisture transfer through multilayered walls in a dynamic thermal simulation tool for the building. The material properties which constitute the input parameters for the model were determined experimentally, according to the hygrothermal state of the material. The results showed that hemp concrete significantly reduces the energy consumption of the building and has better insulation properties than the two conventional building materials: brick and aerated concrete. This is justified by the good hygrothermal properties of this bio-based material, especially its high thermal resistance of  $3.08 \text{ K.m}^2/\text{W}$  compared to  $0.88 \text{ K.m}^2/\text{W}$  of brick and  $2.28 \text{ K.m}^2/\text{W}$  of aerated concrete. In addition, for the three climates considered, the thermal comfort of the hemp concrete envelope is significantly improved. This material also allows stabilisation of relative humidity levels in the ambient air by naturally regulating the hygrometry, to ensure better ambience. The study shows that hemp concrete has interesting hygrothermal properties. Thus, this material can be used massively in the construction field in order to meet the requirements of the current standards which aim to reduce the energy and environmental impacts of dwelling and office building.

## 1. Introduction

Global energy demand continues to grow and the energy consumption curve keeps increasing. This leads to the depletion of natural resources and results in the amplification of pollution, including that related to Greenhouse Gas (GHG) emissions. Consequently, as part of the Paris Agreement, the European Union committed to reducing these emissions by 40% compared to 1990 levels [1] and to increasing energy efficiency by 27% (all by 2030) [2].

It is clear, therefore, that the building sector can positively contribute to improving energy and environmental conditions by limiting GHG emissions and the energy consumption of buildings. One way to limit the environmental impact of buildings is to use bio-based building materials [3]. This will significantly reduce energy consumption and GHG emissions by providing better hygrothermal comfort in the buildings.

In this context, the use of bio-based building materials becomes an unavoidable solution, as it allows us to respond to current environmental problems [4,5]. Among these bio-based materials, hemp concrete, which is a mixture of hemp shives and binder [6–12]. This material, which is environmentally friendly, allows the storage of carbon [13]. On the other hand, hemp concrete can cover several uses in buildings, depending on the formulation used [14,15]. The available literature has shown that hemp concrete has very interesting hygrothermal [14,16–19] and acoustic [20] properties compared to classic building materials. Indeed, this vegetable particle-based material has a low thermal conductivity [21,22] and, therefore, a significant insulation capacity which could improve the thermal behaviour of buildings.

The hygric behaviour of hemp concrete shows a high value of water vapour permeability [14] as well as a significant moisture storage capacity [12]. In addition, it has a high humidity regulation capacity due

to its excellent moisture buffer capacity (MBV) [23,24]. On the other hand, several studies have shown that the hygrothermal properties of hemp concrete allow it to reduce the daily changes in relative humidity, limit energy consumption [25] and maintain hygrothermal comfort in buildings [26]. Many experimental and numerical investigations have been reported on hemp concrete [17,22,24,27–31]. The results show a good thermal inertia for hemp concrete walls [28] and emphasised the ability of hemp concrete to dampen external weather conditions by showing good results for indoor temperature and relative humidity [32].

However, the works cited above focus on the transient behaviour of hemp concrete and neglect the exchanges that occur in the envelope and their interactions with indoor environments (thermal regulation, moisture production, etc.) and outside environments (climatic solicitations).

In this regard, the objective of this paper is to analyse the impact of hemp concrete on the global hygrothermal behaviour of buildings in different climates (temperate, hot and humid, cold and wet) by proposing a multi-scale numerical approach: experimental characterization at the material scale and numerical analysis at the envelope and building scales.

Indeed, this approach is based on the work of Ferroukhi et al. [33,34], where a co-simulation method was developed that allowed integration of models that coupled heat and moisture transfer through multi-layered walls through a dynamic thermal simulation tool. This makes it possible to integrate modelling of the coupled hygrothermal behaviour of hemp concrete and its hygric and thermal contributions into the heat and mass balances of the indoor zone. Consequently, the energy consumption of buildings could be predicted with more accuracy, as well as the comfort of the occupants. Also, to ensure more precision in the proposed work, an experimental characterisation campaign of the main hygric and thermal properties of hemp concrete was carried out in order to define the input parameters of the numerical model, focusing on the evolution of these properties as a function of the water content of the material.

## 2. Methodology

In this section, the multi-scale numerical and experimental approach is described. Furthermore, a case study was undertaken in order to highlight the impact of hemp concrete on the hygrothermal behaviour of the whole building.

### 2.1. HAM-BES co-simulation approach

To better understand the behaviour of hemp concrete walls in their environment, developing a numerical and experimental multiscale approach proved to be necessary. Of all the approaches developed in the literature, co-simulation is one of the most effective methods. This approach is based on the integration of a phenomenological model of hygrothermal transfer through a building envelope using a dynamic thermal simulation tool.

In the literature, several authors [35–39] have proposed different co-simulation approaches. However, the developed models generally lack precision from a phenomenological point of view, where phenomena such as thermo-diffusion and the variation of the hygrothermal properties, according to the moisture content of the material, are not considered.

In this paper, the co-simulation approach developed by Ferroukhi et al. [33,34] was used to assess the impact of hemp concrete on whole-building hygrothermal behaviour. The dynamic HAM-BES co-simulation platform (HAM: Heat, Air and Moisture transfer BES: Building Energy Simulation) is based on a dynamic exchange of data at each time step between a dynamic thermal model (compiled using TRNSYS) and a hygrothermal transfer model (implemented using Comsol Multiphysics). The implementation of the developed co-simulation method and its validation are detailed in the work of Ferroukhi et al. [33,34]. Fig. 1 summarises the operating principle of the HAM-BES platform.

The coupled heat and mass transfer model used is represented in the system of non-linear equations given below. This model is based on the Luikov theory [40], the temperature ( $T$ ) and vapour pressure ( $P_v$ ) representing the heat and moisture transfer variables.

$$C_m(\omega)\rho_s \frac{\partial P_v}{\partial t} = \text{div}(k_m(\omega)\nabla P_v + k_{T_i}\nabla T) \quad (1)$$

$$C_p\rho_s \frac{\partial T}{\partial t} = \text{div}(\lambda_i(\omega)\nabla T + \alpha_i\nabla P_v) + L_v\rho_s\sigma_i C_m(\omega) \frac{\partial P_v}{\partial t} \quad (2)$$

Where:  $C_m = \frac{d\omega}{dHRR} \frac{1}{P_{sat}}$  where  $i = 1, 2, \dots, n$  is the wall layer position (from the outside to inside),  $\omega$  [kg/kg] is the water content,  $\rho_s$  [kg/m<sup>3</sup>] is the dry density,  $\lambda$  [W/(m·K)] is the thermal conductivity,  $C_p$  [J/(kg·K)] is the heat capacity,  $L_v$  [J/kg] is the heat of phase-change,  $k_m$  [kg/(m·s·Pa)] is

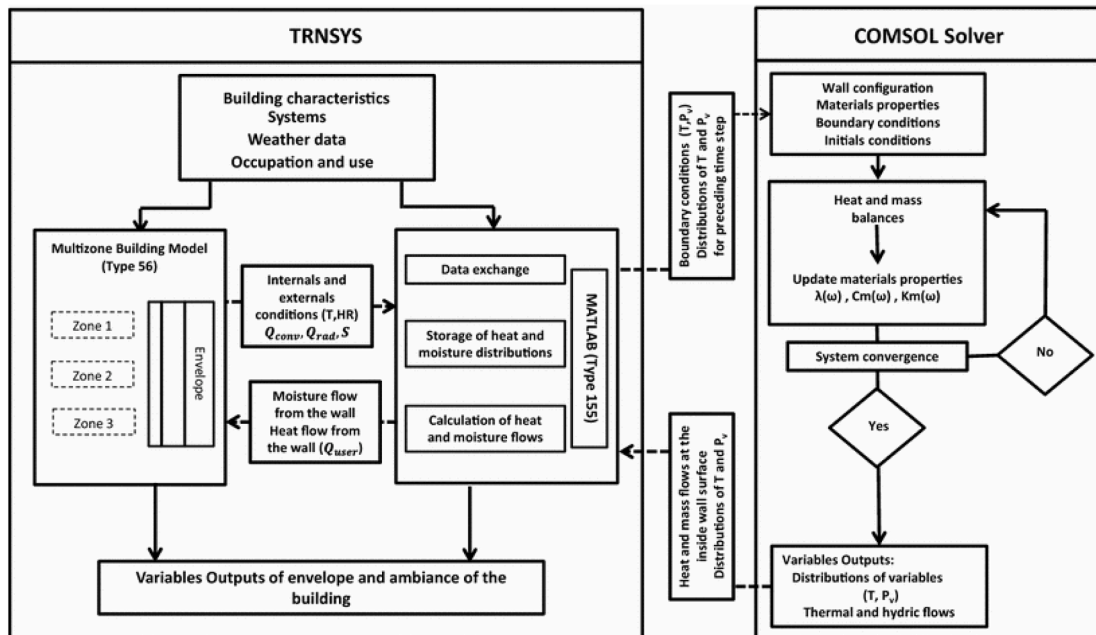


Fig. 1. HAM-BES platform operating principle [34].

the total moisture permeability,  $C_m$ : [kg/(kg·Pa)] is the moisture storage capacity, and  $P_{vsat}$  [Pa] is the saturated vapour pressure.  $\alpha$  [m<sup>2</sup>/s] is the advection heat coefficient due to water vapour pressure and  $\sigma$  represents the phase change criterion.  $k_T$  [kg/(m·s·K)] is the moisture transport caused by the temperature gradient.

Concerning the boundary conditions (particularly at both of the wall sides in direct contact with the ambience), the convective heat and mass exchanges related to the indoor and outdoor conditions were taken into consideration, mainly temperature and air humidity. The boundary conditions are summarised in the following equations:

$$k_m(\omega)\nabla P_v + k_T\nabla T = h_m(P_{vamb} - P_{vsurf}) \quad (3)$$

$$\lambda(\omega)\nabla T + \alpha\nabla P_v = h_c(T_{amb} - T_{surf}) + (1 - \sigma)L_v h_m(P_{vamb} - P_{vsurf}) \quad (4)$$

The ‘amb’ index represents the internal and external ambience and the ‘surf’ index is the surface of the wall.  $h_m$  [kg/(m<sup>2</sup>·s·Pa)] and  $h_c$  [W/(m<sup>2</sup>·K)] represent the convective mass and heat exchange coefficients, respectively. The driving potentials are assumed to be continuous at the interfaces between the ‘n’ layers of different materials constituting the wall.

In this model, strong hygrothermal coupling was considered. Heat transfer, thermal conduction and advection was considered, as well as the heat contribution due to the moisture phase change. For the mass transport, the impact of moisture diffusion and temperature variation on the water content distribution in the wall were considered. Furthermore, the variation of hygrothermal properties as a function of the water content of the material was considered in this modelling. More details of the model and the validation process are presented in the work of Ferroukhi *et al.* [33,34].

The thermal behaviour at the building scale is modelled using TRNSYS software, in particular the Type 56 (TRNBuild). This multi-zone modelling is based on the establishment of thermal and hygric balances integrating the contributions of occupants, heating and cooling systems and hygrothermal exchange with the indoor envelope surface. Indeed, the HAM-BES coupling is implemented by substituting the simple thermal (conduction) and hygric (Buffer Storage Humidity [Klein *et al.* 2010]) transfer TRNSYS model through the envelope by the more detailed heat and mass transfer model (described below) which considers a hygrothermal coupling at two levels: advection and thermos-diffusion phenomena as well as the variation of the main properties (input data of the model) according to the thermal and hygric condition of the material.

## 2.2. Experimental Characterisation

As part of the numerical and experimental approach developed in this work, the characterisation of the hygrothermal properties of hemp concrete was an essential step. Indeed, the hygrothermal transfer model used in the HAM-BES co-simulation platform is based on phenomenological modelling, where the degree of accuracy of the prediction is conditioned by a reliable evaluation of the input data.

Construction materials are often exposed to variable hygrothermal conditions and their properties change according to their hygric and thermal condition, particularly for highly permeable materials such as hemp concrete. Therefore, part of our study was dedicated to the experimental characterisation of the intrinsic hygric and thermal properties of hemp concrete (according to its hygrothermal state) using standard laboratory methods. It should be noted that the hemp concrete studied in this paper had a porosity of 72.38% and a dry density of about 480 kg/m<sup>3</sup>. The mass percentages used for the formulation (wall application) have been chosen according to the professional rules for the execution of hemp concrete and mortar structures (Shives: 14%, Lime: 36% and Water: 50%).

Fig. 2 illustrates the isotherm sorption curve of the studied material, as determined by a volumetric method using the Belsorp aqua3 device.

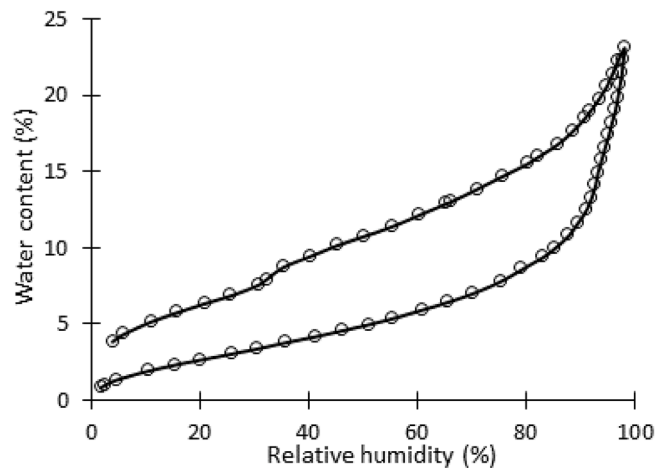


Fig. 2. Water vapour sorption isotherm curve of the studied hemp concrete at 25 °C.

This method is based on the measurement of the volume of adsorbed or desorbed moisture by the material [14,33]. The sorption isotherm curve shows that the water content of hemp concrete increases gradually and becomes important at high relative humidities. This behaviour is due to the capillary condensation mechanisms that occur in the super hygroscopic zone. The storage capacity of the material, which is an important parameter of the presented hygrothermal transfer model, was evaluated from the slope of the sorption isotherm curve.

The water vapour permeability is the second essential property in the hygric characterisation of the studied material. It was evaluated with the EN ISO 12572 standard method, using Gravitest® equipment. Both dry permeability (3% inside the cup and 50% outside the cup) and wet permeability (93% inside the cup and 50% outside the cup) were evaluated under isothermal conditions at 23 °C (see Table 1). An increase in the water vapour permeability was observed with an increase in moisture gradient.

Concerning the thermal properties, thermal conductivity was measured under stationary conditions using the standard guarded hot plate method, according to EN 12664 and EN 12667 standards. The measurement was carried out using the  $\lambda$ -Meter® EP 500.

Fig. 3 illustrates the evolution of the thermal conductivity of hemp concrete as a function of the temperature  $F(T)$  and the water content  $F(u)$  of the material. The results show a linear increase of the thermal conductivity according to the temperature test variation. On the other hand, the hygric state of the material had a significant impact on the thermal conductivity values of hemp concrete. An increase in thermal conductivity of 125% between the dry and saturated states was observed. This behaviour is due to the material’s high porosity and high moisture storage capacity, particularly in high-hygroscopic conditions.

In addition to the thermal conductivity, the specific heat capacity of the studied material was analysed using a Calvet BT 2.15 calorimeter. This device is equipped with Calvet 3D sensors that completely surround the sample and allow accurate measurement of heat exchanges to be made during the test.

Fig. 4 illustrates the specific heat capacity variation of hemp concrete as a function of its temperature and water content. Indeed, an increase of 9% in specific heat capacity was observed between 5 and 35 °C. More pronounced variation of the specific heat capacity was observed

Table 1  
Water vapour permeability of the hemp concrete studied.

	Wet cup	Dry cup
Water vapor permeability (kg/m.s.Pa)	$2.01 \times 10^{-11}$	$1.13 \times 10^{-11}$
Diffusion resistance factor	9.67	17.35

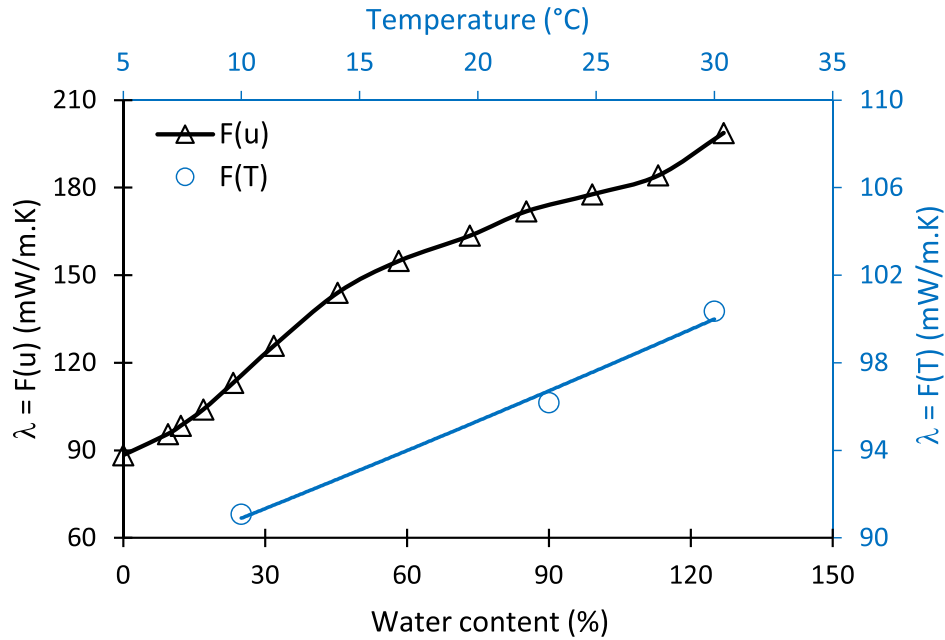


Fig. 3. Evolution of thermal conductivity, of hemp concrete, as a function of water content and temperature.

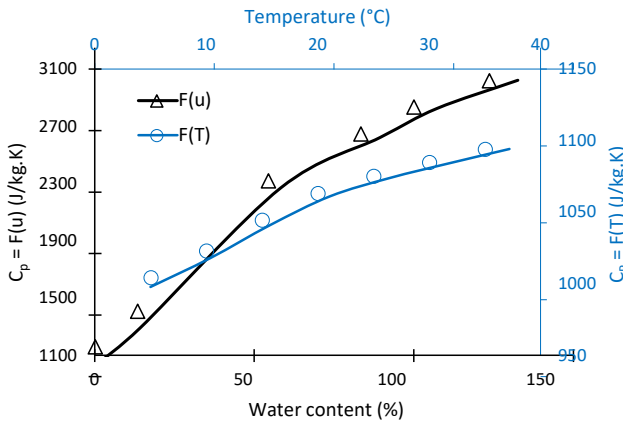


Fig. 4. Evolution of specific heat, of hemp concrete, as a function of water content and temperature.

between the dry and the saturated states. A rise of 150% was recorded (1161 J/kg.K in the dry state and 3021 J/kg.K in the moisture-saturated state).

More details on the experimental devices used and the testing protocols adopted are mentioned in the works of Bennai *et al.* [14] and Ferroukhi *et al.* [33]. The dry state is an unrealistic state because building materials are often exposed to variable climatic conditions. This is why variations in the input parameters of the coupled heat and mass transfer model as a function of the hygrothermal state of the material was considered at the modelling stage.

The hygric and thermal properties of the other materials (brick, aerated concrete, plaster and exterior plaster) were derived from the works of Ferroukhi *et al.* [33] and Trechsel [41]. These properties constitute the input parameters of the hygrothermal prediction model, they are summarized in Table 2. Note that for hemp concrete, the evolution of thermal conductivity and specific heat as a function of water status and temperature has not been taken into account in the numerical simulations.

Table 2

Hygric and thermal properties of the studied conventional materials.

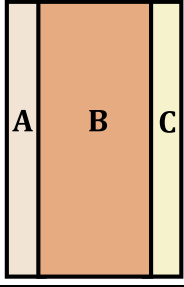
	Brick	Aerated concrete	Plaster	Exterior plaster
Density [kg/m <sup>3</sup> ]	1670	550	1360	1752
Water vapor permeability [kg/(m.s.Pa)]	1.42E-11	6.02E-11	2.55E-12	1.81E-11
Average moisture storage capacity ( $du/dRH$ ) [kg/kg]	0.0047	0.0641	0.0342	0.0456
Thermal conductivity [W/(m.K)]	0.426	0.138	0.625	0.851
Heat capacity [J/(K.kg)]	856	840	867	830

### 2.3. Case study

In order to highlight the impact of hemp concrete on the overall hydrothermal and energy behaviour of the building, a case study was carried out in the context of the IEA / Annex 41 project [42]. The room has a volume of 50 m<sup>3</sup> and a wall surface of 67 m<sup>2</sup> (without floor, door or windows). The room is equipped with a thermal control system, ventilation and a humidity generator. This case study was performed with a constant ventilation air exchange rate of 0.6 h<sup>-1</sup>. To simulate the moisture production of three people in the room, a moisture supply scenario was imposed with a basic production of 25 g·h<sup>-1</sup> with spikes of 400 g·h<sup>-1</sup> between 6 am and 8 am and 200 g·h<sup>-1</sup> between 16 h and 22 h. The indoor temperature and relative humidity are set between [18 °C–26 °C] and [40%–60%] respectively and left free in these ranges. More details concerning the geometry and indoor hydrothermal regulations are available in Woloszyn work [43]. Three wall configurations coated with interior and exterior plaster were modelled and Table 3 summarises the composition of the studied walls. The interest of this case study is to compare the impact of hemp concrete, at the building scale, to other conventional materials when this biobased material is used as a wall infill (in wood framing for example). In order to have a consistent comparison, the same wall configuration is required. The differences obtained for energy consumption and comfort will necessarily be attributed to the only variant of this configuration (infill wall).

To highlight the impact of environmental conditions, the case study

**Table 3**  
Studied wall configurations.

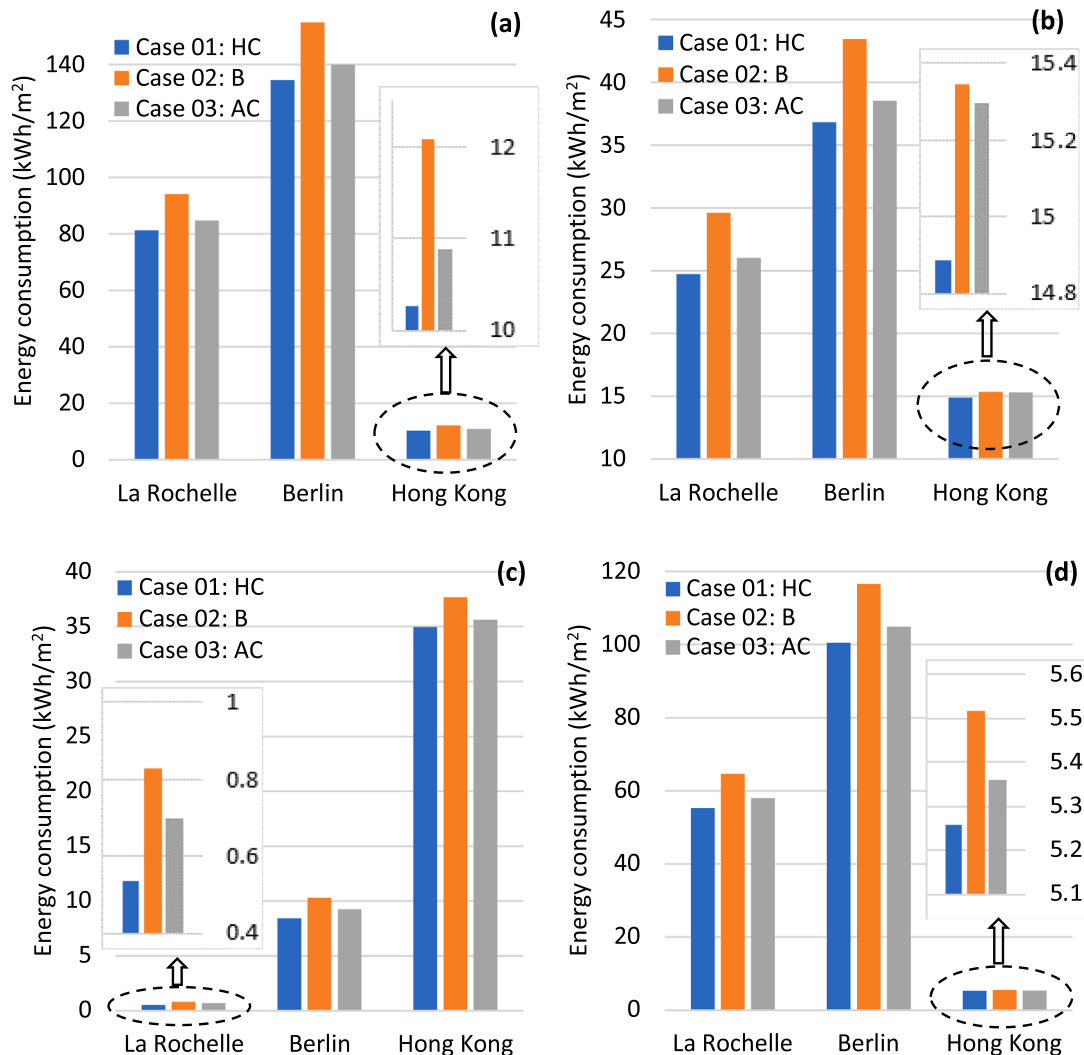
Wall configuration	Materials	Thickness (m)		
	A	Exterior plaster	0.03	
	B	Case 1	Hemp Concrete (HC)	0.30
		Case 2	Brick (B)	0.30
		Case 3	Aerated Concrete (AC)	0.30
	C	Plaster	0.03	

was undertaken for three different climates: the temperate ocean climate of La Rochelle, a hot and humid climate of Hong Kong and a cold and wet climate of Berlin. Simulations were performed over a period of one year with a hourly time step.

### 3. Results and discussion

The proposed HAM - BES dynamic co-simulation approach considers the model of coupled heat, air and moisture transfers in the envelope. Indeed, this approach allowed us to study the hygrothermal behaviour of the whole building in more detail. The simulations were carried out over a period of one year. The results are presented in quarters beggins from January in order to get a global comparative analysis allowing to highlight the hygrothermal impact of hemp concrete over all building behaviour.

Fig. 5 shows the quarterly energy consumption of the case study building zone for the different walls and in each considered climate. These results show a variation in consumption depending on the material and the considered climate. Indeed, the climates of Berlin and La Rochelle are relatively colder than that of Hong Kong, which is why we observed energy consumption in these two climates in quarters 1, 2 and 4 (the energy consumption is exclusively a heating demands for La Rochelle and Berlin climates). In contrast, during the third quarter of the year, the need for air conditioning in Hong Kong's climate led to higher energy consumption (For this hot and humid climate the cooling demand is clearly high then the heating ones). In addition, we note that for the three climates considered, the use of hemp concrete in the envelope reduces the energy consumption of the building. A difference of 16% total energy consumption was observed in Berlin between brick and



**Fig. 5.** Total energy consumption in the ambience (a) first quarter (b) second quarter, (c) third quarter, and (d) fourth quarter.

hemp concrete buildings. Indeed, the energy consumption of the building decreases using hemp concrete, which has a significant economic gain (not negligible economic gain). Hemp concrete is a filling material with particularly interesting insulation properties; it ensures better energy performance regardless of the climate considered.

Fig. 6 illustrates the thermal gains of the envelope walls in different climates for each quarter of the year. The values can be negative in the case of a heat loss (heat flow leaving the envelope) or positive in the case of a penetration of heat through the walls (heat flow entering the envelope). For cold climates, such as La Rochelle and Berlin (as well as the 1st and 4th quarter of Hong Kong), we note that the losses and heat gains in hemp concrete are significantly lower than those of brick and aerated concrete. For example, for the first quarter, increases in heat losses of 18.03%, 18.25% and 10.79% between hemp concrete and brick were observed for the La Rochelle, Berlin and Hong Kong climates, respectively. On the other hand, concerning overheating in summer, there is an increase in heat input of 51% and 17% of the brick compared to hemp concrete, respectively during the 2nd and 3rd quarters in Hong Kong. These results show that hemp concrete significantly contributes to improving the thermal comfort of the habitat, compared to brick and aerated concrete. These results can be justified by the good hygrothermal properties of this bio-based material, especially its high thermal resistance that allows reducing heat loss in cold climates and overheating in hot climates as shown in Table 4. In addition, hemp concrete

**Table 4**

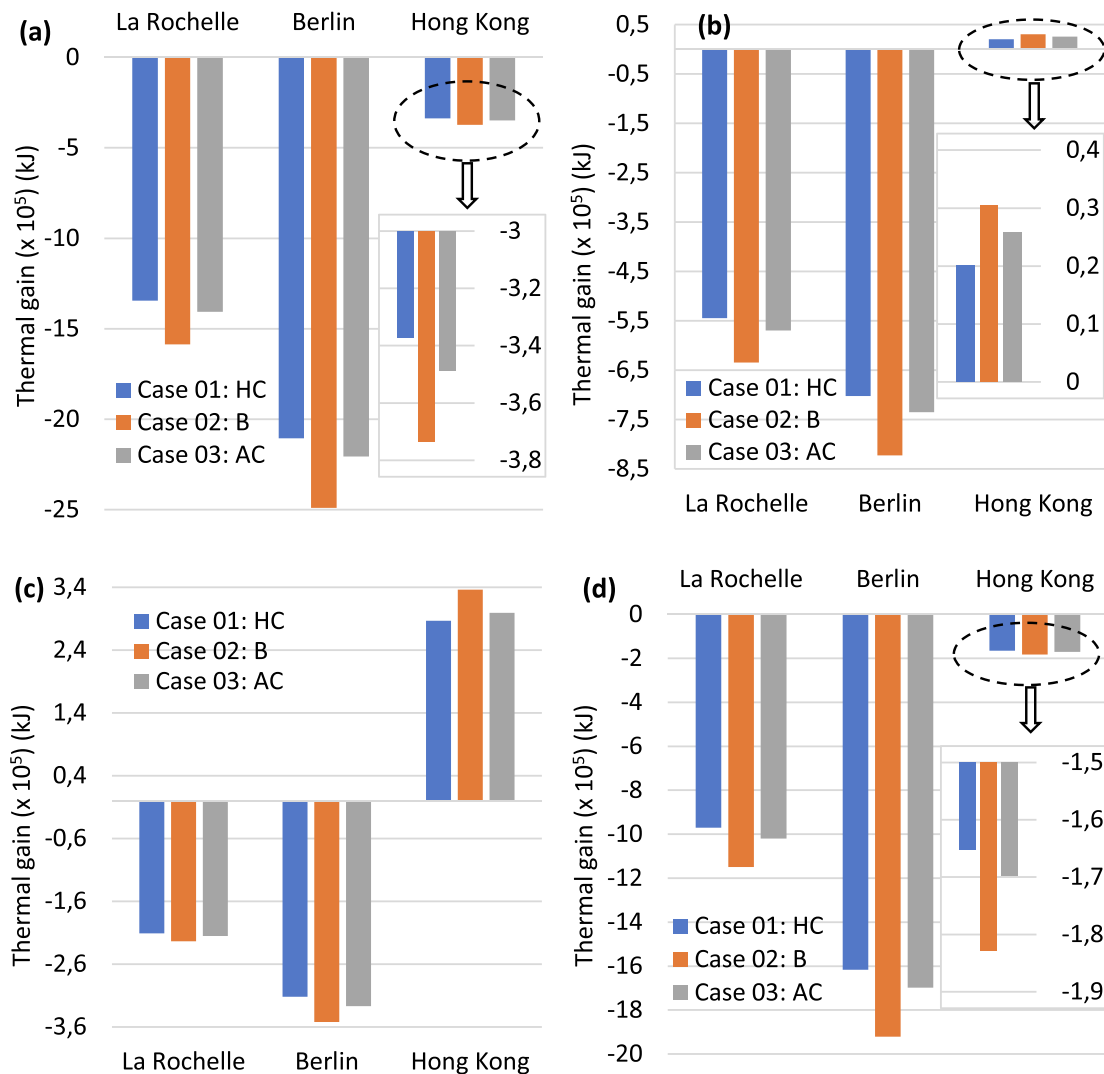
Total thermal resistance of the studied materials.

Materials	Hemp concrete	Brick	Aerated concrete
Thermal resistance(K.m <sup>2</sup> /W)	3.08	0.88	2.28

recovers solar gain in winter and reduces discomfort of the envelope in summer due to its interesting thermal inertia.

Evaluation of the hygrothermal comfort inside the ambience was also performed. Fig. 7 indicates the number of hours of the year for which the temperatures of the ambience are less than or equal to 18 °C. This set-point temperature has been chosen as the comfort limit temperature below which the heating system should be activated. The results are presented for the considered envelope walls in the three climates.

The results shown in Fig. 7 confirm the energy consumption and thermal gains of the envelope. It can be seen that, for all three climates, there is better thermal comfort in the case of hemp concrete (an increase of 13% in the number of hours of brick compared to hemp concrete in Hong Kong). Indeed, hemp concrete has a better physical capacity to maintain its temperature due to its thermal inertia. This property of hemp concrete allows minimisation of the thermal contributions required to maintain a constant temperature of the material. On the other hand, this plant fibre material also has the ability to dampen external temperature variations [32]. All of these parameters strongly



**Fig. 6.** Thermal gains (a) first quarter (b) second quarter, (c) third quarter, and (d) fourth quarter.

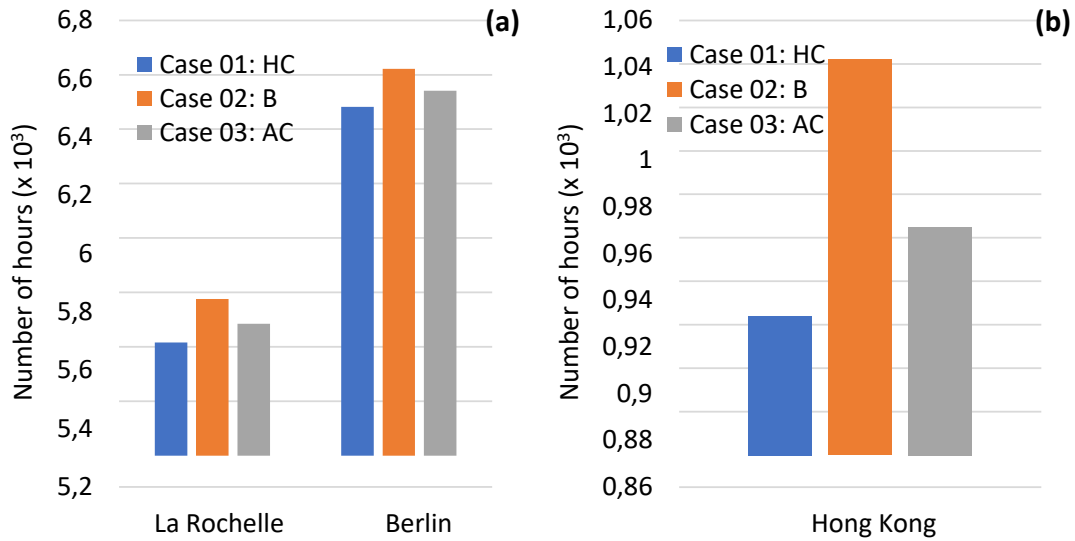


Fig. 7. Number of hours at an ambient temperature  $\leq 18^\circ\text{C}$

contribute to the improvement of thermal comfort in the hemp concrete envelope.

The co-simulation platform enables dynamic integration of the coupled heat and moisture transfer model in multilayer walls (HAM) in the Building Thermal Model (BES). Consequently, the quality of hygric comfort prediction is improved. Fig. 8 illustrates the number of hours for which the relative humidity values inside the envelope are greater than or equal to 65% in La Rochelle, Berlin and Hong Kong. This set relative humidity defines the upper limit of hygrometric comfort [34].

It should be noted that, for all climates, the hemp concrete envelope has a better hygric comfort, this is followed by aerated concrete and then brick construction. Indeed, a high degree of humidity in the building strongly contributes to the appearance of the problems of condensation and mould on the walls, which are harmful to the sanitary comfort of the habitable ambience. In terms of relative humidity, it can be seen that the number of hours where the relative humidity is above the indoor comfort limit show an increase of up to 5% between the walls of hemp concrete and brick. Indeed, hemp concrete is a great way to passively dampen daily variations in relative humidity. Hemp concrete is a

breathable material and it has very good hygrometric capacity. This means that it is an excellent hygrometric ambience regulator according to the classification proposed by the Nordtest project. This property is justified by a moisture buffer value (MBV) of greater than 2 [12].

In order to highlight the hygrothermal impact of hemp concrete, a dynamic thermal simulation (without consideration of the coupled heat and mass transfers) has been performed for case 01: HC for the La Rochelle climate. For this simulation, the thermal conductivity and the specific heat are considered in the dry state of the material. The thermal and hygrothermal gains (in flux density) are represented in the Fig. 9.

The results presented in Fig. 9 highlight the hygrothermal impact of the studied hemp concrete. This observation is more pronounced in the winter period when the thermal gradient (on both sides of the envelope) is significant (Fig. 9a.1). In the summer period, the hygrothermal impact is less significant (Fig. 9a.2). Indeed, a higher thermal gain in the hygrothermal simulation case compared to the only thermal simulation is observed. This is necessarily due to the effect of moisture over thermal transfer at two levels. The first, concerns the consideration of the thermal properties variation according to the hygric state of the hemp

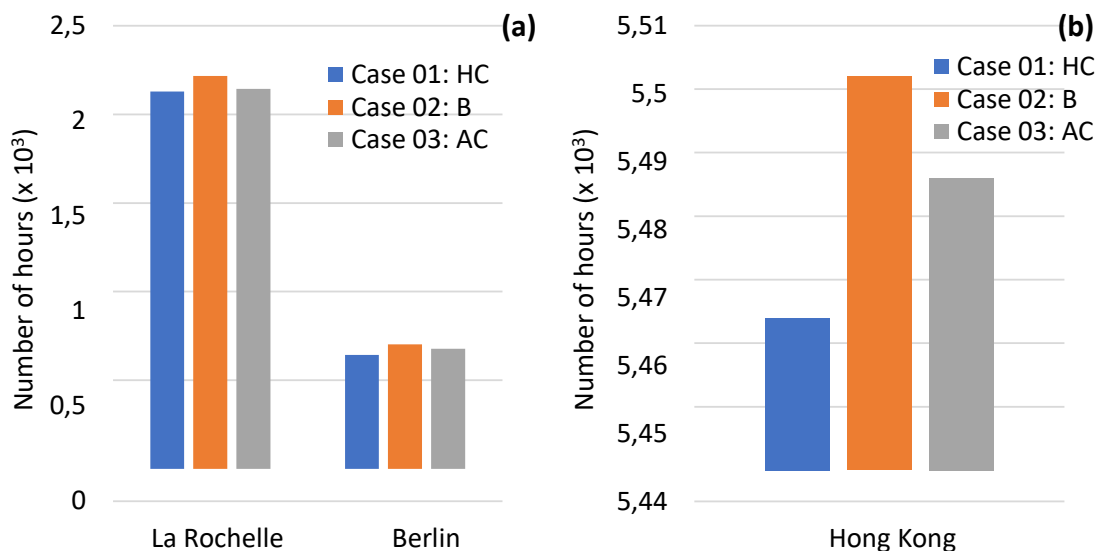
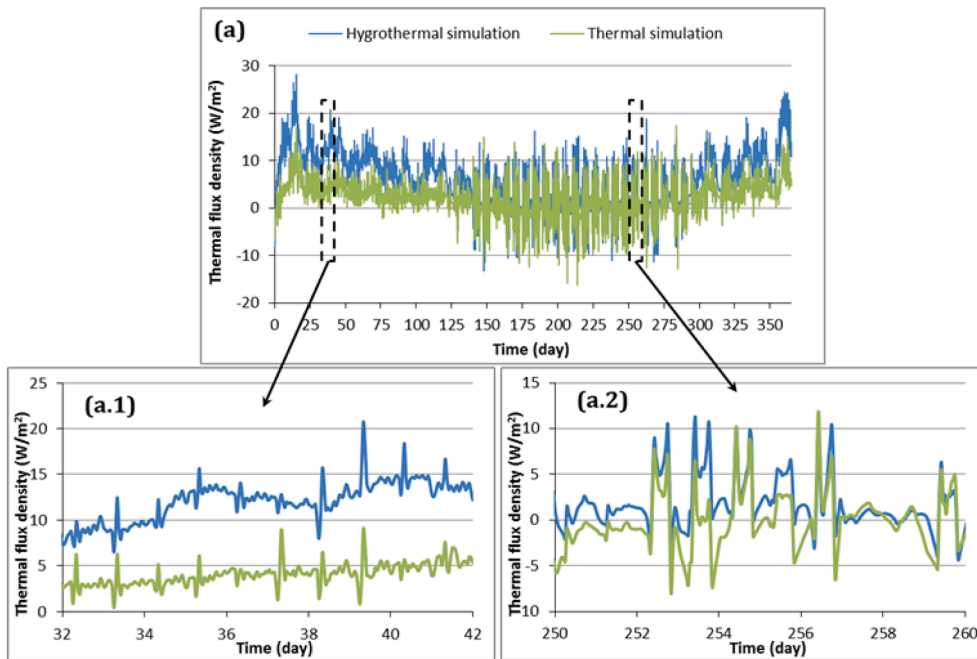
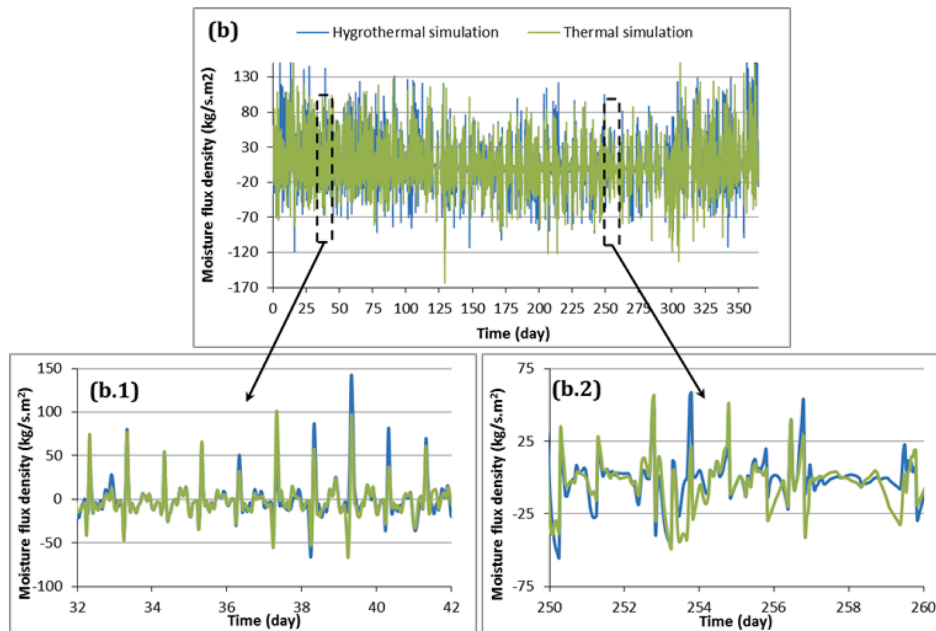


Fig. 8. Number of hours at an ambient relative humidity  $\geq 65\%$





a. Thermal Flux density at the inner envelope surface



b. Hygic flux density at the inner envelope surface

Fig. 9. Thermal and moisture flux density at the inner envelope surface: hygrothermal and thermal simulations.

concrete. The second level is related with the consideration of the advection phenomenon (heat transfer caused by the moisture transport).

Concerning the moisture transport, the hygrothermal impact is not noticed. The two proposed simulations (hygrothermal and thermal simulations) show similar hygric gains (Fig. 9b). This result confirms that the thermo-diffusion phenomenon (mass transfer due to thermal transfer) is negligible in this case study.

#### 4. Conclusion

This study focused on the hygrothermal and energetic performance of hemp concrete. Three building envelopes were built using hemp concrete, brick and aerated concrete. Their performance was considered in different climates: La Rochelle, Berlin and Hong Kong. First of all, an experimental characterisation of the hygrothermal properties of hemp concrete was performed. It focused on studying the impact of the hygrothermal state of this hygroscopic material on these intrinsic properties. The results showed that the hemp concrete properties are

strongly influenced by its hygric and thermal state.

The HAM-BES dynamic co-simulation platform was then used to ensure dynamic interaction during the modelling of hygrothermal transfers in the envelope. Particular attention was paid to variations in the material properties as a function of the hygrothermal state; this led to an improvement in the precision of the results.

The results showed an increase in energy consumption for the building cases using aerated concrete and brick. Hemp concrete has better insulation properties and significantly reduces the energy demand of the envelope. Indeed, the use of hemp concrete is an effective way to improve the thermal comfort of buildings, in both winter and summer. The study also showed that hemp concrete is not just a simple insulator. It associates the various comfort parameters, such as thermal inertia and the management of the water vapour contained in the air. This allows to lower the temperature to comfortable levels and contributes to the improvement of comfort felt inside habitats. In addition, the ability of this vegetable-based material to naturally dampen variations in relative humidity and outdoor temperature can contribute to the stabilisation of the relative humidity level in the ambient air, without consuming energy.

Hemp concrete offers the possibility for significant energy savings with a high level of comfort. It can be an inescapable solution for new construction or renovation projects.

#### CRedit authorship contribution statement

**Fares Bennai:** Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Mohammed Yacine Ferroukhi:** Investigation, Validation, Writing – original draft, Writing – review & editing. **Ferhat Benmahiddine:** Validation, Writing – review & editing, Visualization. **Rafik Belarbi:** Conceptualization, Writing – review & editing, Supervision, Validation. **Armelle Nouviaire:** Visualization, Validation.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Acknowledgements

The Region and the European Union support the project < CPER-FEDER Bâtiment durable Axis 2 MADUR Project: High-performance building materials with low environmental impact, sustainable and resilient > within the framework of the « Operational Program FEDER/FSE 2015-2020 and Energy saving certificate program of the Ministry of Ecological and Solidarity Transition “SmartReno support” 2019-2021.

#### References

- [1] P. Tobin, N.M. Schmidt, J. Tosun, C. Burns, Mapping states' Paris climate pledges: Analysing targets and groups at COP 21, *Global Environ. Change* 48 (2018) 11–21, <https://doi.org/10.1016/j.gloenvcha.2017.11.002>.
- [2] M. Sinka, P. Van den Heede, N. De Belie, D. Bajare, G. Sahmenko, A. Korjakins, Comparative life cycle assessment of magnesium binders as an alternative for hemp concrete, *Resour. Conserv. Recycl.* 133 (2018) 288–299, <https://doi.org/10.1016/j.resconrec.2018.02.024>.
- [3] J. Glass, A.R.J. Dainty, A.G.F. Gibb, New build: Materials, techniques, skills and innovation, *Energy Policy* 36 (12) (2008) 4534–4538, <https://doi.org/10.1016/j.enpol.2008.09.016>.
- [4] M. Pervaiz, M.M. Sain, Carbon storage potential in natural fiber composites, *Resour. Conserv. Recycl.* 39 (4) (2003) 325–340, [https://doi.org/10.1016/S0921-3449\(02\)00173-8](https://doi.org/10.1016/S0921-3449(02)00173-8).
- [5] K. Ip, A. Miller, Life cycle greenhouse gas emissions of hemp–lime wall constructions in the UK, *Resour. Conserv. Recycl.* 69 (2012) 1–9, <https://doi.org/10.1016/j.resconrec.2012.09.001>.
- [6] F. Bennai, C. El Hachem, K. Abahri, R. Belarbi, Microscopic hygric characterization of hemp concrete by X-ray microtomography and digital volume correlation, *Energy Build.* 216 (2020) 105000, <https://doi.org/10.1016/j.enbuild.2020.105000>.
- [7] R. Belarbi, F. Bennai, M.Y. Ferroukhi, C. El Hachem, K. Abahri, A. Diouri, A. Boukhari, L. Ait Brahim, L. Bahi, N. Khachani, M. Saadi, J. Aride, A. Nounah, Multiscale modelling for better hygrothermal prediction of porous building materials, *MATEC Web Conf.* 149 (2018) 02005, <https://doi.org/10.1051/mateconf/201814902005>.
- [8] A.D. Tran Le, J.S. 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, *Build. Environ.* 188 (2021) 107455, <https://doi.org/10.1016/j.buildenv.2020.107455>.
- [9] M.P. Sáez-Pérez, M. Brümmer, J.A. Durán-Suárez, Effect of the state of conservation of the hemp used in geopolymer and hydraulic lime concretes, *Constr. Build. Mater.* 285 (2021) 122853, <https://doi.org/10.1016/j.conbuildmat.2021.122853>.
- [10] M.S. Abbas, F. McGregor, A. Fabbri, M.Y. Ferroukhi, The use of pith in the formulation of lightweight bio-based composites: Impact on mechanical and hygrothermal properties, *Constr. Build. Mater.* 259 (2020) 120573, <https://doi.org/10.1016/j.conbuildmat.2020.120573>.
- [11] M.S. Abbas, E. Gourdon, P. Glé, F. McGregor, M.Y. Ferroukhi, A. Fabbri, Relationship between hygrothermal and acoustical behavior of hemp and sunflower composites, *Build. Environ.* 188 (2021) 107462, <https://doi.org/10.1016/j.buildenv.2020.107462>.
- [12] F. Benmahiddine, F. Bennai, R. Cherif, R. Belarbi, A. Tahakourt, K. Abahri, Experimental investigation on the influence of immersion/drying cycles on the hygrothermal and mechanical properties of hemp concrete, *J. Build. Eng.* 32 (2020) 101758, <https://doi.org/10.1016/j.jobee.2020.101758>.
- [13] R. Walker, S. Pavia, R. Mitchell, Mechanical properties and durability of hemp–lime concretes, *Constr. Build. Mater.* 61 (2014) 340–348, <https://doi.org/10.1016/j.conbuildmat.2014.02.065>.
- [14] F. Bennai, N. Issaadi, K. Abahri, R. Belarbi, A. Tahakourt, Experimental characterization of thermal and hygric properties of hemp concrete with consideration of the material age evolution, *Heat Mass Transf.* 54 (4) (2018) 1189–1197, <https://doi.org/10.1007/s00231-017-2221-2>.
- [15] F. Benmahiddine, R. Cherif, F. Bennai, R. Belarbi, A. Tahakourt, K. Abahri, Effect of flax shives content and size on the hygrothermal and mechanical properties of flax concrete, *Constr. Build. Mater.* 262 (2020) 120077, <https://doi.org/10.1016/j.conbuildmat.2020.120077>.
- [16] M. Rahim, O. Douzane, A.D. Tran Le, G. Promis, T. Langlet, Characterization and comparison of hygric properties of rape straw concrete and hemp concrete, *Constr. Build. Mater.* 102 (2016) 679–687, <https://doi.org/10.1016/j.conbuildmat.2015.11.021>.
- [17] F. Benmahiddine, R. Belarbi, J. Berger, F. Bennai, A. Tahakourt, Accelerated Aging Effects on the Hygrothermal Behaviour of Hemp Concrete: Experimental and Numerical Investigations, *Energies* 14 (2021) 7005, <https://doi.org/10.3390/en14217005>.
- [18] A. Rima, K. Abahri, F. Bennai, C. El Hachem, M. Bonnet, Microscopic estimation of swelling and shrinkage of hemp concrete in response to relative humidity variations, *J. Build. Eng.* 43 (2021) 102929, <https://doi.org/10.1016/j.jobee.2021.102929>.
- [19] Y. Zouaoui, F. Benmahiddine, A. Yahia, R. Belarbi, Hygrothermal and Mechanical Behaviors of Fiber Mortar: Comparative Study between Palm and Hemp Fibers, *Energies* 14 (2021) 7110, <https://doi.org/10.3390/en14217110>.
- [20] O. Kinnane, A. Reilly, J. Grimes, S. Pavia, R. Walker, Acoustic absorption of hemp–lime construction, *Constr. Build. Mater.* 122 (2016) 674–682, <https://doi.org/10.1016/j.conbuildmat.2016.06.106>.
- [21] A. Bourdot, T. Moussa, A. Gacoin, C. Maalouf, P. Vazquez, C. Thomachot-Schneider, C. Bliard, A. Merabtine, M. Lachi, O. Douzane, H. Karaky, G. Polidori, Characterization of a hemp-based agro-material: Influence of starch ratio and hemp shive size on physical, mechanical, and hygrothermal properties, *Energy Build.* 153 (2017) 501–512, <https://doi.org/10.1016/j.enbuild.2017.08.022>.
- [22] F. Bennai, K. Abahri, R. Belarbi, Contribution to the Modelling of Coupled Heat and Mass Transfers on 3D Real Structure of Heterogeneous Building Materials: Application to Hemp Concrete, *Transp Porous Med.* 133 (2) (2020) 333–356, <https://doi.org/10.1007/s11242-020-01426-9>.
- [23] M. Rahim, O. Douzane, A.D. Tran Le, G. Promis, B. Laidoudi, A. Crigny, B. Dupre, T. Langlet, Characterization of flax lime and hemp lime concretes: Hygric properties and moisture buffer capacity, *Energy Build.* 88 (2015) 91–99, <https://doi.org/10.1016/j.enbuild.2014.11.043>.
- [24] T. Jami, S.R. Karade, L.P. Singh, A review of the properties of hemp concrete for green building applications, *J. Cleaner Prod.* 239 (2019) 117852, <https://doi.org/10.1016/j.jclepro.2019.117852>.
- [25] C. Maalouf, C. Ingrao, F. Scrucca, T. Moussa, A. Bourdot, C. Tricase, A. Presciutti, F. Asdrubali, An energy and carbon footprint assessment upon the usage of hemp–lime concrete and recycled-PET façades for office facilities in France and Italy, *J. Cleaner Prod.* 170 (2018) 1640–1653, <https://doi.org/10.1016/j.jclepro.2016.10.111>.
- [26] A. Shea, M. Lawrence, P. Walker, Hygrothermal performance of an experimental hemp–lime building, *Constr. Build. Mater.* 36 (2012) 270–275, <https://doi.org/10.1016/j.conbuildmat.2012.04.123>.
- [27] E. Latif, R.M.H. Lawrence, A.D. Shea, P. Walker, An experimental investigation into the comparative hygrothermal performance of wall panels incorporating wood fibre, mineral wool and hemp–lime, *Energy Build.* 165 (2018) 76–91, <https://doi.org/10.1016/j.enbuild.2018.01.028>.
- [28] B. Moujalled, Y. Ait Ouméziane, S. Moissette, M. Bart, C. Lanos, D. Samri, Experimental and numerical evaluation of the hygrothermal performance of a

- hemp lime concrete building: A long term case study, *Build. Environ.* 136 (2018) 11–27, <https://doi.org/10.1016/j.buildenv.2018.03.025>.
- [29] C. Maalouf, A.D.T. Le, S.B. Umurigirwa, M. Lachi, O. Douzane, Study of hygrothermal behaviour of a hemp concrete building envelope under summer conditions in France, *Energy Build.* 77 (2014) 48–57, <https://doi.org/10.1016/j.enbuild.2014.03.040>.
- [30] T. Colinart, D. Lelievre, P. Glouannec, Experimental and numerical analysis of the transient hygrothermal behavior of multilayered hemp concrete wall, *Energy Build.* 112 (2016) 1–11, <https://doi.org/10.1016/j.enbuild.2015.11.027>.
- [31] L. Wang, H. Lenormand, H. Zmamou, N. Leblanc, Effect of variability of hemp shiv on the setting of lime hemp concrete, *Ind. Crops Prod.* 171 (2021) 113915, <https://doi.org/10.1016/j.indcrop.2021.113915>.
- [32] G. Costantine, C. Maalouf, T. Moussa, G. Polidori, Experimental and numerical investigations of thermal performance of a Hemp Lime external building insulation, *Build. Environ.* 131 (2018) 140–153, <https://doi.org/10.1016/j.buildenv.2017.12.037>.
- [33] M.Y. Ferroukhi, K. Abahri, R. Belarbi, K. Limam, Integration of a hygrothermal transfer model for envelope in a building energy simulation model: experimental validation of a HAM–BES co-simulation approach, *Heat Mass Transf.* 53 (6) (2017) 1851–1861, <https://doi.org/10.1007/s00231-016-1944-9>.
- [34] M.Y. Ferroukhi, R. Djedjig, K. Limam, R. Belarbi, Hygrothermal behavior modeling of the hygroscopic envelopes of buildings: A dynamic co-simulation approach, *Build. Simul.* 9 (5) (2016) 501–512, <https://doi.org/10.1007/s12273-016-0292-5>.
- [35] A.W.M. van Schijndel, Integrated modeling of dynamic heat, air and moisture processes in buildings and systems using SimuLink and COMSOL, *Build. Simul.* 2 (2) (2009) 143–155, <https://doi.org/10.1007/s12273-009-9411-x>.
- [36] R. Djedjig, E. Bozonnet, R. Belarbi, Analysis of thermal effects of vegetated envelopes: Integration of a validated model in a building energy simulation program, *Energy Build.* 86 (2015) 93–103, <https://doi.org/10.1016/j.enbuild.2014.09.057>.
- [37] M. Steeman, A. Janssens, H.J. Steeman, M. Van Belleghem, M. De Paepe, On coupling 1D non-isothermal heat and mass transfer in porous materials with a multizone building energy simulation model, *Build. Environ.* 45 (4) (2010) 865–877, <https://doi.org/10.1016/j.buildenv.2009.09.006>.
- [38] D. Cóstola, B. Blocken, J. Hensen, External coupling between BES and HAM programs for whole-building simulation, Glasgow, IBPSA, 2009, pp. 316–323.
- [39] M. Steeman, M. Van Belleghem, M. De Paepe, A. Janssens, Experimental validation and sensitivity analysis of a coupled BES–HAM model, *Build. Environ.* 45 (10) (2010) 2202–2217, <https://doi.org/10.1016/j.buildenv.2010.04.003>.
- [40] A.V. Luikov, Heat and Mass Transfer in Capillary-Porous Bodies, in: *Advances in Heat Transfer*, Elsevier, 1964: pp. 123–184. <http://linkinghub.elsevier.com/retrieve/pii/S0065271708700984> (accessed February 27, 2017).
- [41] H.R. Trechsel (Ed.), *Moisture analysis and condensation control in building envelopes*, ASTM, West Conshohocken, PA, 2001.
- [42] P. Ruut, C. Rode, Common exercise 1–case 0A and 0B revised, IEA Annex 41 (2004).
- [43] M. Woloszyn, C. Rode, Annex 41, Subtask 1: Modelling principles and common exercises, Draft Final Report for the ECBCS Executive Committee of the International Energy Agency. (2008).