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Yassine Elias Belarbi, Mohammed Yacine Ferroukhi, Nabil Issaadi, Philippe Poullain, Stéphanie Bonnet. Assessment of hygrothermal performance of raw earth envelope at overall building scale. *Energy and Buildings*, 2024, 310, pp.114119. 10.1016/j.enbuild.2024.114119 . hal-04541889

HAL Id: hal-04541889

<https://hal.science/hal-04541889>

Submitted on 11 Apr 2024

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Assessment of hygrothermal performance of raw earth envelope at overall building scale

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Abstract: Environmental challenges in the building sector have made raw earth a significant ecological alternative. The development of sustainable materials and a clear understanding of their behaviour are essential for sustainable construction. This work aims to respond to this societal issue. This investigation uses a HAM-BES cosimulation methodology that integrates dynamic thermal simulation code (TRNSYS) with a hygrothermal transfer model developed by Luikov and solved by Comsol Multiphysics. The study aims to investigate the energy needs of different building envelopes in several climates where there is raw-earth architecture. A comparison between a cob monolayer envelope and a polystyrene insulated polystyrene insulated brick multilayer envelope has been carried out. This study shows that the raw earth monolayer wall has a higher energy need for oceanic and tropical climate with, respectively, 14 and 19%. A decrease in demand has been found for the desert climate. Moreover, it was shown that the coupling of heat and mass transfers results in a notable reduction in energy demand that can reach 11.5% annually and up to 23% quarterly for tropical climate. These findings highlight the efficiency of raw earth materials and stress the importance of thoroughly understanding and incorporating heat and mass transfer dynamics in the evaluation of sustainability for biobased and earth-based construction materials.

Keywords: enta

1. Introduction:

Over the past few decades, the global demand for energy has not stopped growing, leading to a significant increase in energy consumption. Between 1971 and 2018, total final consumption increased from 4244 Mtoe to 9937 Mtoe according to the International Energy Agency (IEA). To respond to this major social and environmental issue, several regulations have been put in place as part of the global fight against global warming. At the international level, we can mention the Glasgow Conference on Climate Change (COP26) held in December 2021. This is the 26th session of the Conference of the Parties to the United Nations Convention on Climate Change, the 16th meeting of the parties to the Kyoto Protocol (CMP 16) and the third meeting of the parties to the 2015 Paris Agreement (referred to as CMA 3). The signatories of the treaty have set a global aim of limiting the temperature increase to below 2°C or even 1.5°C by 2100. One of the main sectors responsible for these harmful effects on our environment is the building sector. In fact, according to the IEA, the building sector (residential, nonresidential, and the construction industry) is responsible for nearly 36% of energy consumption and 39% of greenhouse gas emissions worldwide [1]. One of the materials responsible for these consequences is concrete. Indeed, the latter is the most important and widely used material in the building sector. Each year, about 10 million tons are poured, which corresponds to 320 kg per second [2].

To reduce the harmful influence of the building sector on our planet, one of the avenues considered is the development of materials that are less energy-consuming, more efficient, and more respectful of the environment. Within the framework of our study, we will be interested in raw-earth construction. This material is one of the oldest. The latter has been used since about 15000 BC at the beginning of the settlements of mankind, but its use was widely developed during the creation of the

first cities near the waterways [3]. Construction in raw earth is frequently associated with vernacular architecture because of the use of materials (raw earth, fibres, and other additions) depending on local availability. This architecture is different for each region or country. Almost 30% of the world's population lives on raw earth construction [4]. Moreover, 10% of the sites inscribed in the UNESCO are partly or totally composed of raw earth. Despite this, the use of raw earth has been marginalised, especially due to the overuse of concrete.

However, recently, there has been renewed interest in raw earth materials, not only for the purpose of restoring historical and cultural buildings but also because of their low environmental footprint. This is due to the significant reduction in environmental pollution induced by the use of raw earth to substitute conventional building materials. The advantages of raw earth are its abundance, its recyclability, and its good thermal inertia. Furthermore, the earth is a very good regulator of temperature and moisture and also limits the risk of medical conditions related to mould development [5]. Some hygrothermal properties have been characterised in few studies at the material scale showing the interesting properties of geobased materials with a notable MBV value that is, in general, according to the NORDTEST protocol, good or even very good (depending on the formulation) [6–13]. Variability of properties, specifically hygrothermal properties, is a notable problem with geosourced materials. Several studies have been carried out to address this issue, including the work of Tchiotsop et al. [14] focusing particularly on cob materials.

Apart from the studies presented above, few studies focus on raw earth properties on a material scale. Furthermore, to the best of our knowledge, no research has been done on the energy performance of envelopes or even buildings made of raw earth. Indeed, these studies focus mainly on the transient behaviour of the raw earth and neglect the exchanges that occur in the envelope and their interactions with the interior environments (moisture production, thermal regulation etc...) and the external environments (climatic solicitations). Nevertheless, some studies focused on the energy performance of buildings envelopes composed of biobased materials such as hemp concrete and the impact of mass transfer. Seng et al. [15] conducted research on the behaviour of hemp concrete under varying temperatures and humidity conditions. Temperature and humidity sensors were used for the experimental segment. Simulations using a heat and moisture transfer model were performed to analyse the coupling between heat and moisture transport within the wall. The authors found that temperature differences significantly influence moisture release and highlighted the impact of moisture adsorption on temperature variations within the wall. A study conducted by Busser et al. [16] focused on evaluating various simulation models, such as MATCH, UMIDUS, DELPHIN, and WUFI, used to predict heat and moisture transfer in porous building materials. This research highlights discrepancies between model predictions and experimental outcomes, particularly for materials with high moisture absorption or such as biobased materials, under dynamic conditions. The authors critically evaluate some of the assumptions inherent in these models, especially those related to the moisture storage capacity of the materials. They suggest that for increased accuracy of these models, a more comprehensive consideration of moisture convective transport, hysteresis effects, and the impact of temperature on moisture storage should be incorporated.

Earthen building techniques such as adobe, rammed earth, wattle and daub, and compressed earth blocks (CEB) have been used throughout history in different climatic conditions. The method on which we focus is named cob. This ancient technique involves combining unprocessed soil with water and occasionally incorporating biobased fibres. The mixture is then manipulated in a plastic form and moulded into spheres to build monolithic walls. In comparison to other earthen materials, cob has distinct characteristics. Its damp composition provides flexibility during construction, and while the material is ductile, it must be considered in the broader context of earthen construction methods without undue preference [17]. In addition, cob construction has two main advantages: the ease of the building process and the flexibility in design. Compared to other conventional construction methods, cob requires only

18 to 38% of the energy needed by conventional materials. Moreover, cob construction can reduce the impact of global climate change by a significant 75 to 82% during the manufacturing process. [18].

This study aims to evaluate the energy performance of two distinct wall configurations: a single-layer cob wall and a conventional multi-layered wall.. The analysis seeks to provide a clearer understanding of energy efficiency in structures constructed with raw and conventional materials, using numerical methods to investigate the hygrothermal behaviour of raw-earth buildings. In the present study, an advanced co-simulation approach is used with a comprehensive hygrothermal model to investigate the complex interactions between humidity and temperature within proposed wall configurations. A new aspect of this research is the evaluation of energy needs through two distinct methodologies: one incorporating mass transfer considerations and the other excluding them. This differentiation allows for a meticulous analysis that seeks to elucidate the potential impacts of mass transfer on the overall energy demands of building envelopes. The method provides precise assessments of the energy performance of theoretical cob and conventional constructions in various climatic scenarios, providing insight into the potential resilience and efficiency of these configurations in various environmental conditions.

First of all, the methodology will be presented with the HAM-BES cosimulation approach and experimental characterisation. Then we will focus on the results of energy needs for the cob configuration. The latter will be compared with a multilayer wall in several types of climate. We will then carry out a comparison between a HAM model and a thermal model to assess the impact of mass transfer on the energy needs of a cob wall.

2. Methodology:

2.1 HAM-BES Cosimulation Approach

Creating a multiscale computational methodology was important to better understand the behaviour of raw-earth walls in their surroundings. Cosimulation is one of the best strategies of all those devised in the literature. This method is based on the integration of a building dynamic thermal simulation tool with a phenomenological model of hygrothermal transfer through the envelope. Several cosimulation approaches are found in the literature [19–23]. However, these approaches do not consider some phenomenological phenomena such as thermo diffusion or the evolution of the hygrothermal properties depending on the moisture content. Some studies have highlighted the influence of moisture content on hygrothermal properties[24,25]. These assumptions make the model less accurate. In this study, the cosimulation method created by Ferroukhi et al. [26,27] was chosen. It was first applied to buildings made of hemp concrete to assess the influence of the hygrothermal behaviour of the material on the energy consumption of the entire building. 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 and validation of the developed co-simulation approach are detailed in the work by Ferroukhi et al. [26,27]. Fig.1 summarises the operating principle of the HAM-BES platform. The coupled heat and mass transfer model is based on Luikov theory [28] with the heat and moisture transfer variables being temperature (T) and vapour pressure (Pv). The system of non-linear equations given below describes the coupled heat and mass transfer model used.

$$C_{mi}(\omega)\rho_{si} \frac{\partial P_v}{\partial t} = (k_{mi}(\omega)\nabla P_v + k_{T_i}\nabla T) \quad (1)$$

$$C_{pi}\rho_{si} \frac{\partial T}{\partial t} = (\lambda_i(\omega)\nabla T + \alpha_i\nabla P_v) + L_v\rho_{si}\sigma_i C_{mi}(\omega) \frac{\partial P_v}{\partial t} \quad (2)$$

Where $C_m = \frac{\partial \omega}{\partial HR} \frac{1}{P_{sat}}$ where $I = 1, 2, \dots, n$ is the position of the wall layer (from the outside to inside), ω [kg/kg] is the water content, ρ_s [kg/m³] is the dry density, λ [W/(m·K)] is the thermal conductivity, C_p [J / (kg·K)] is the heat capacity, L_v [J/kg] is the phase change heat, k_m [kg / (m·s·Pa)] is the total moisture permeability, C_m [kg / (kg·Pa)] is the moisture storage capacity and P_{vsat} [Pa] is the saturated vapour pressure. α [m²/s] is the advection heat coefficient due to the water vapour pressure and σ represents the phase change criterion. k_T [kg/(m·s·K)] is the moisture transport caused by the temperature gradient. Concerning the boundary conditions (in particular the two sides of the wall in direct contact with the environment) the convective heat and mass transfer related to the indoor and outdoor air temperature and relative humidity has been taken into account. The equations below gather the boundary conditions:

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

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

The index 'amb' represents the indoor and outdoor environment, and the index 'surf' corresponds to the surface of the wall. h_m [kg/(m²·s·Pa)] and h_c [W/(m²·K)] represent the convective mass and heat exchange coefficients, respectively. q_{rad} [J/(m²·s)] and q_s [J/(m²·s)] are, respectively, the radiative heat flow density and the radiative heat gains density at the wall surfaces. The driving potentials are assumed to be continuous at the interfaces between the 'n' layers of different materials that make up the wall.

This model considers a strong moisture-heat coupling. It includes heat transfer by conduction, convection, and moisture phase transitions. For mass transport, it accounts for the effects of moisture diffusion and temperature changes on the distribution of water content in the wall. In addition, the model takes into account the variation of the most heat properties with the moisture content of the material. More details on the model and the validation process can be found in the work of Ferroukhi et al. [26,27,29].

The thermal behaviour at the building scale is modelled using TRNSYS software, in particular type 56 (TRNBuild). This multizone modelling is based on heat and moisture balances, integrating the contributions of the occupants, the heating and cooling systems, and the moisture and heat exchanges with the interior surfaces of the envelope. In fact, the HAM-BES coupling is carried out by using a more detailed heat and mass transfer mode (described below) to consider the moisture-heat coupling at two levels: the advection and thermal diffusion phenomena and the main properties (input data of the model) depending on the state of the material with regard to the thermal and hygric conditions. Figure 1 shows the operating principle of the platform.

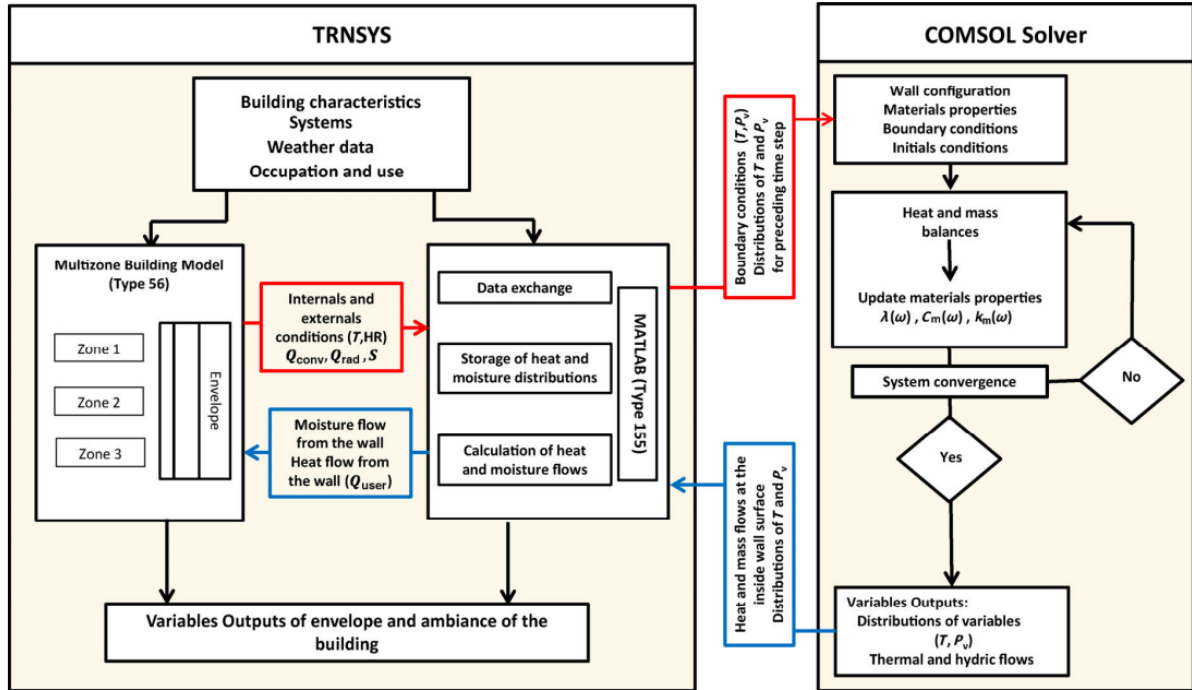


Figure 1 : HAM-BES platform operating principle [27]

2.2 Experimental Characterisation

The measurement of the hygrothermal properties of cob was performed, taking into account its evolution with the moisture content and the temperature except for the sorption curve measured at a constant temperature. 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. The method used are presented in the article by Belarbi et al. [13]. The formulation studied is made of raw earth and 3% by mass of straw fibres. This rate was previously found in the literature for cob [30–33]. The addition of vegetable fibres accelerates the drying process, reduces shrinkage cracks, and improves the cohesion and ductility of the material [34]. Straw was chosen because of its low thermal conductivity ranging between 0.06 and $0.08 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ [35]. Moreover, straw is a by-product of industrial agriculture that can be valorised in construction materials. Straw fibres have been added to reduce the thermal conductivity of the earthen composite.

As part of our study, we have characterised the hygrothermal properties of our raw material. The sorption isotherm is presented first, followed by the evolution of thermal conductivity as a function of temperature and relative humidity. Specific heat and water vapour permeability are shown. The dry density of our material is 1650 kg/m^3 .

The sorption isotherm of the studied material is presented in Figure 2. It was determined with the SPS-Pro Umid device (gravimetric method). The accuracy of this device is between $0.1 \mu\text{g}$ and $10 \mu\text{g}$. An internal reference helps to correct any shifts in the microbalance, ensuring good stability, even during long-term measurements that last over 24 hours. We conducted isotherm measurements at a temperature of $23 \text{ }^\circ\text{C}$, with humidity ranging from 0% to 90%.

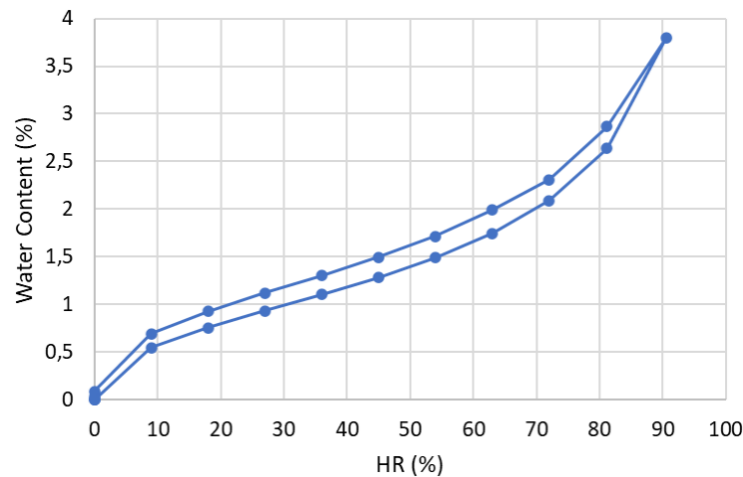


Figure 2 : Sorption isotherm of our composite of raw earth with straw

As can be seen on Figure 2, the water content remains moderate or low at high relative humidity with a maximum value lower than 4%. This value is higher than that of raw earth without straw. The water content of the straw is very high and can reach values of 25% [13]. It can be explained by the capillary condensation mechanisms that occur in the super-hygroscopic area. The measurement of water vapour permeability was carried out using the Gravitest® device, based on the dry cup method (ISO 12572 [36]). The test was carried out on three cylindrical specimens (diameter 8 cm and 2 cm thick). The obtained value of water vapour permeability at 23°C is $1,08 \times 10^{-11}$ kg/m.s.Pa.

The thermal conductivity was measured at various temperatures: 10 °C, 23 °C, and 40 °C using the Lambda-meter EP500e device. This device operates on the guarded hot plate technique, using Fourier's law in a steady state, in compliance with established standards [37,38]. Measurements are carried out under a temperature gradient of 15 °C, with the device's hot surface set at a specified reference temperature. Samples in a dry state (mass stabilisation at 50°C) and stabilised at a relative humidity of 50% were characterised at the 3 temperatures mentioned above. Figure 3 shows the evolution of the thermal conductivity depending on temperature and relative humidity. These results highlight an increase in thermal conductivity. This increase is linear, depending on the temperature. The specific heat capacity was measured using the Calvet calorimeter (NF EN 821-3 standard [39]) and the results depending on the temperature are shown in Figure 4. The samples tested are cylindrical in shape, with a diameter of 1 cm and an approximate length of 4 cm. The test is carried out over a temperature range of 0 °C to 35 °C.

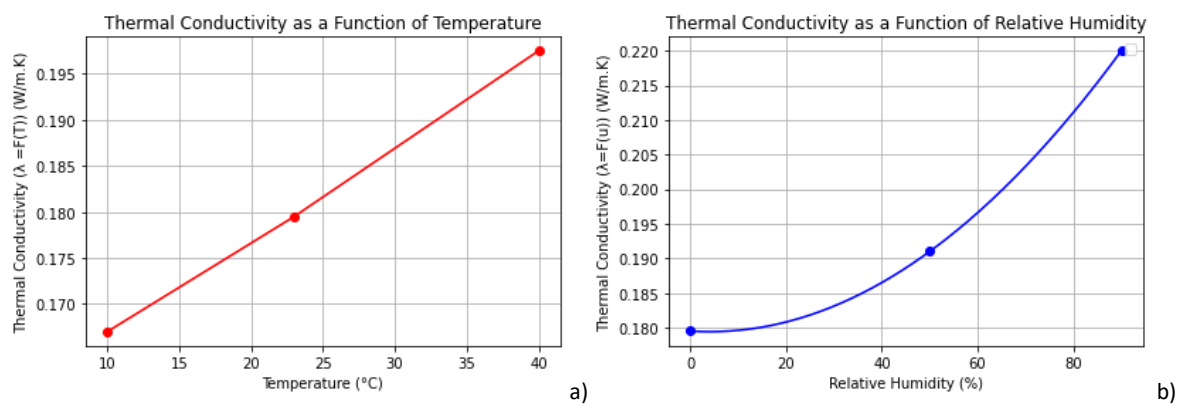


Figure 3 : Cob's thermal conductivity depending on the temperature and the Relative Humidity

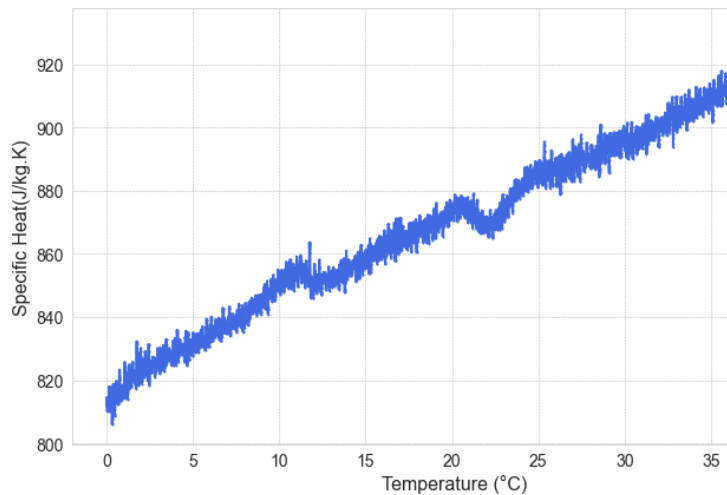


Figure 4 : Evolution of cob's specific heat depending on the temperature

2.3 Case Study

The aim of this case study is to compare the impact of a *single-layer raw earth envelope* with that of a *multilayer insulating wall*. To ensure a fair comparison, the 2 compared walls have the **same thermal resistance** ($3,34 \text{ m}^2 \cdot \text{K}/\text{W}$). The influence of cob raw earth on the overall hygrothermal and energy characteristics of a building was emphasised through a case study carried out within the framework of the IEA / Annex 41 project [40]. The study was conducted in a room (parallelepiped shape) with a volume of 50 m^3 (the side is 5m long on the east-west axis and 4m in north-south direction, for a total floor area of 20 m^2 . the wall height is 2.5m). A double glazed window with $1.41 \text{ m} \times 1.94 \text{ m}$ dimensions was included in the south wall.. The building is considered as one thermal zone in the co-simulation approach. The case study was conducted with a steady ventilation air exchange rate of 0.6 volume per hour. A scenario for moisture generation was established to simulate the typical moisture output of three individuals. This scenario includes a baseline moisture production rate of 25 grammes per hour, with peak outputs of 400 grammes per hour during the morning hours (6-8 AM) and 200 grammes per hour in the evening (4-10 PM). Indoor temperature and relative humidity were maintained within a range of 18-26 degrees Celsius and 40-60%, respectively, allowing natural fluctuations within these parameters. In this case study, hygrothermal control is considered on / off. The work of Woloszyn et al. [41] provides more specific information on the geometry of the room and the indoor hygrothermal regulations. Two wall configurations were modeled and Figure 5 illustrates the walls studied. Table 1 summarises the thermophysical and hygric properties considered as input data for the simulations. The properties of the materials used in conventional multilayer envelopes are derived from the work of Ferroukhi et al. [26] and Trechsel [42]. Hygrothermal transfer is considered throughout the building envelope, excluding the floor and roof, which have identical configurations for all simulations performed. This approach significantly reduces the computation time for an annual simulation. Importantly, this assumption does not compromise the final findings of the comparative analysis conducted in this study. Furthermore, to enhance the robustness of the conducted simulations, the initial conditions of the studied building envelopes are established following a two-year simulation of hygrothermal transfers, incorporating external climatic conditions. Indeed, the temperature and water vapour pressure distributions within the envelope, obtained at the end of the envelope hygrothermal transfer simulation, are adopted as the initial conditions for the annual simulation carried out at the whole building scale.

Table 1 : Thermophysical and hygric properties used as input data for the multilayer wall [26,42]

	Brick	Plaster	Polystyrene	Mortar
Density [kg/m^3]	1370	1360	20.4	1752
Water vapor permeability [$kg/(m.s.Pa)$]	1.42×10^{-11}	2.55×10^{-12}	1.87×10^{-12}	1.81×10^{-11}
Average moisture storage capacity (du/dRH) [kg/kg]	0.0047	0.0342	0.0021	0.0456
Thermal conductivity [$W/(m.K)$]	0.426	0.625	0.030	0.851
Heat capacity [$J/(K.kg)$]	856	867	1385	835

In order to investigate the impact of climatic conditions on the energy demands of buildings, we focused our study on three different climates (Figure 6) found in TRNSYS.

- a) oceanic climate of Nantes in France;
- b) desert climate of Riyadh in Saudi Arabia;
- c) tropical climate of Douala in Cameroon.

Nantes, located in the west of France, enjoys an oceanic climate. Summer temperatures are generally moderate and the use of air conditioning is less widespread. Riyadh is located in Saudi Arabia, which has a desert climate with extremely high temperatures, particularly during the summer months, which correspond to the second and third quarters of the year. The use of air conditioning is therefore very common, leading to high energy needs. Douala, in Cameroon, on the other hand, has a tropical climate with a relatively stable temperature throughout the year. To illustrate the specific requirements and challenges of each climate in terms of temperature and relative humidity, we have provided detailed visual data in Figure 6. This figure is essential to convey the different climatic stresses and their potential impact on a building's energy performance in different climatic conditions. Recognising the significance of mass transfer is essential to assess its varying effects on energy needs in diverse climate scenarios. In arid or certain temperate climates, where the influence of humidity on heat exchange is minimal, the exclusion of mass transfer in the estimation of energy demand can be considered insignificant. However, this approach is markedly inadequate for humid climates, such as those prevalent in Nantes and Douala. Maintaining a comfortable indoor environment in such regions requires a delicate equilibrium between temperature and humidity control, highlighting the importance of taking into account the coupling of heat and mass transfers. These assumptions are confirmed by Qin et al. research [43], which provides compelling evidence. By examining the different climates of Hong Kong and Paris, Qin et al. illustrate the increased energy demands required for thermal regulation in humid environments. Additionally, they validate the need to incorporate these mass transfer effects into precise predictions of energy needs.

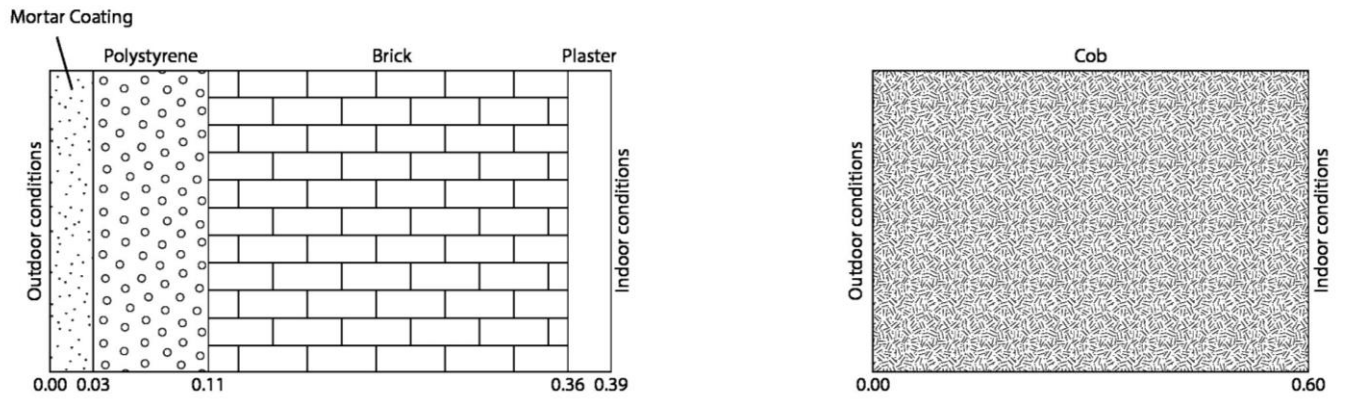
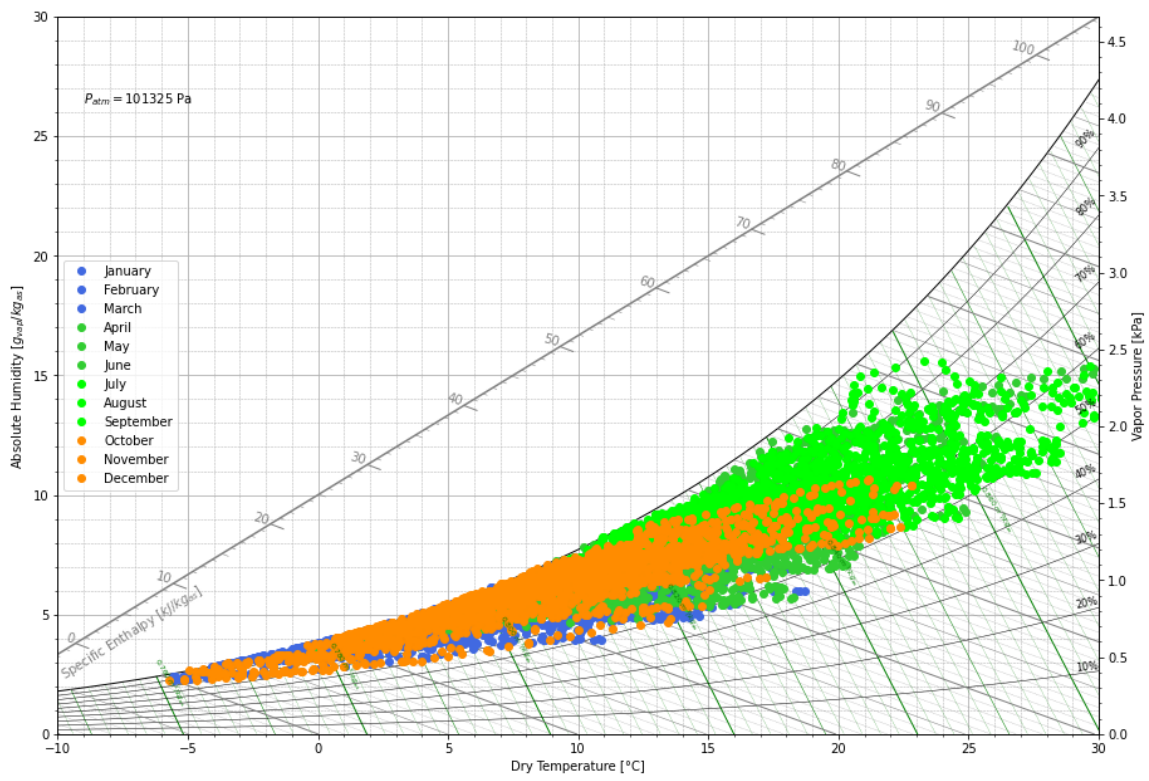
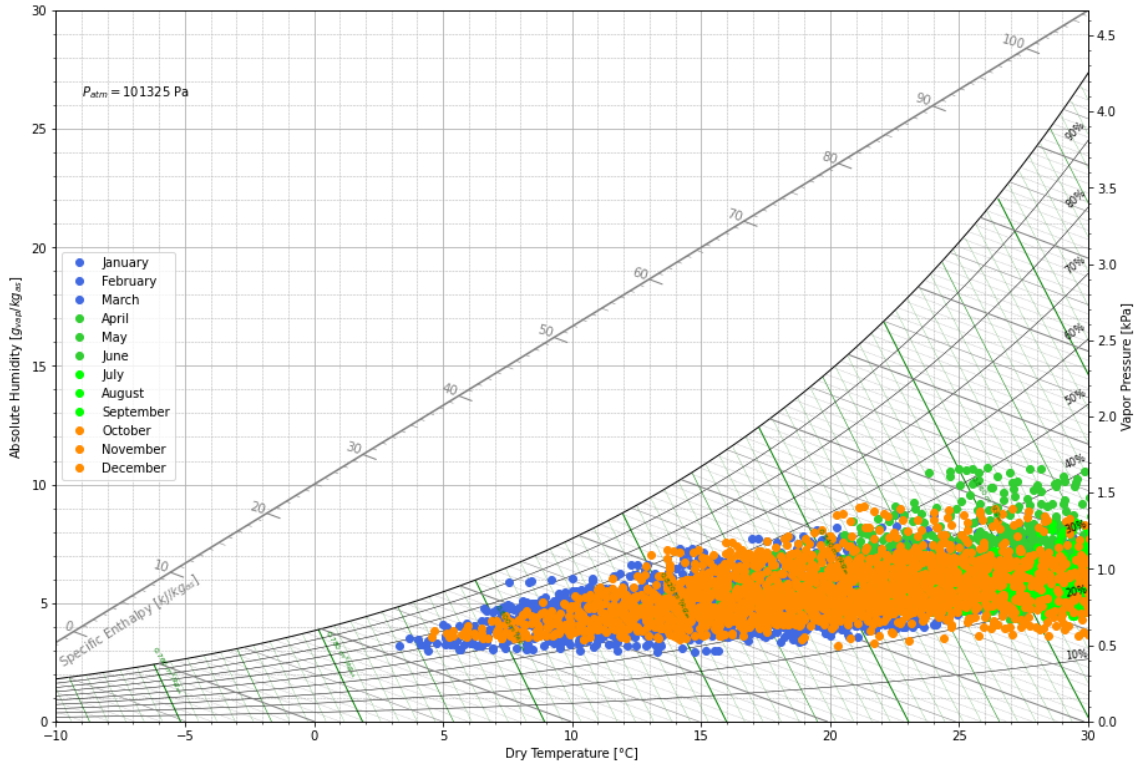


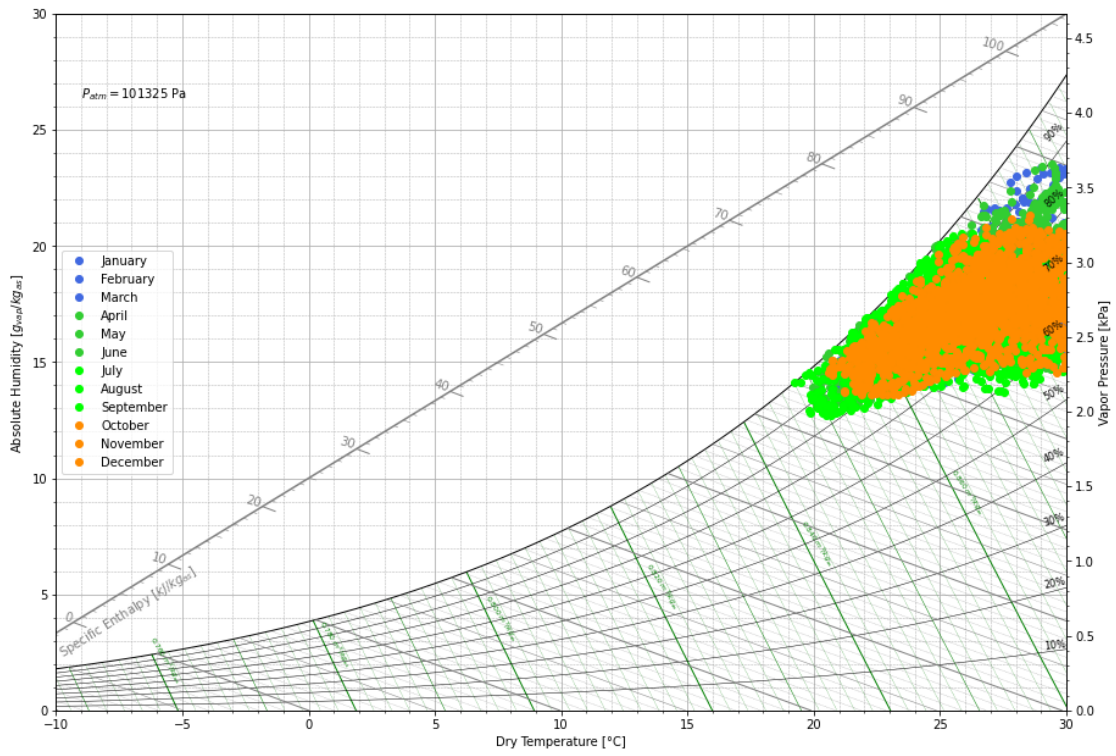
Figure 5 : Schemes of wall configurations with the multilayer wall on the left and the cob monolayer wall on the right (depth in m)



a)



b)



c)

Figure 6 : Annual weather files for Nantes (France) (a), Riyadh (Saudi Arabia) (b) and Douala (Cameroon) (c)

3. Results and Discussions

3.1 Comparison of a cob envelope with a conventional multilayer envelope

The simulations were carried out over a period of one year. The results are presented quarterly, starting in January, to provide an overall comparative analysis that highlights the hygrothermal impact of cob on the overall behavior of the building. Quarter 1 (Q1) corresponds to the period between January and March. Quarter 2 (Q2) corresponds to the period between April and June. Quarter 3 (Q3) corresponds to the period between July and September. And quarter 4 (Q4) corresponds to the period between October and December.

Figure 7 shows the quarterly energy needs of the building under study, contrasting the cob wall and the multi-layer wall in the three climates considered. The energy demand resulting from heating and cooling are represented. The data shows a striking variation in consumption depending on the climate. The climates of Riyadh and Douala are warmer than those of Nantes, resulting in significant differences in energy needs. In Riyadh and Douala, the main driver of energy needs is cooling, while in Nantes it is heating. We first focus on the case of the cob wall.

For the first quarter (Q1), Nantes recorded an energy need of 21.19 kWh/m², only due to heating requirements. This is 25% higher than Douala's consumption for cooling of 16,86 kWh/m² and more than 8 times higher than Riyadh's consumption of 2,23 kWh/m², which is low for this quarter, due to milder temperatures requiring less energy for heating.

The energy analysis reveals stark differences between Riyadh, Douala and Nantes. These differences are most pronounced in the second and third quarters. Riyadh, characterised by its desert climate, accounts for significant energy needs, with 27,64 kWh/m² in Q2, exceeding the consumption rates of both Douala and Nantes. Specifically, Riyadh's Q2 consumption is 70% higher than that of Douala and five times higher than that of Nantes, the latter experiencing relatively cool spring temperatures. In the third quarter, Riyadh's energy need escalates due to the high temperatures in June, July and August, reaching a peak of 36,87 kWh/m². This consumption is four times higher than in Douala and essentially much higher than in Nantes, where consumption is close to zero due to seasonal temperatures that negate the need for cooling. Douala, located in a tropical climate, has intermediate consumption values. Its energy demand is 250% higher than that of Nantes in Q2 and much higher in Q3, since consumption in Nantes is close to zero during this period. During the fourth quarter (Q4), the disparity in energy needs between the three climates is considerably reduced. Nantes registers an energy needs of 15.11 kWh/m², which is only about 23% higher than Douala's 12.26 kWh/m², and approximately 120% higher than Riyadh's consumption of 6.9 kWh/m². This relatively close range of energy demand, compared to previous quarters, likely results from a convergence of climatic conditions during this period, with Nantes transitioning from cold to mild temperatures, Douala experiencing lower temperatures, and Riyadh moving into its cooler season.

We will now shift our focus to the case of the multilayer wall, comparing it to the cob wall configuration.

Comparison of energy needs based on wall configuration provides important data. In the first quarter (Q1), the cob wall in Nantes registers a heating needs of 21.19 kWh/m², which is approximately 22% higher than the 17.34 kWh/m² needs observed for the multilayer wall. In Douala, the cob wall displays cooling needs of 16.86 kWh/m², about 17% more than the multilayer wall needs of 14,37 kWh/m². Riyadh shows a small difference between the cob (2.21 kWh/m²) and multilayer (2.30 kWh/m²) configurations but in this case, for cob, half of the needs are due to heating and cooling. For the multi-layer wall in Riyadh, the energy demand is linked by the cooling at 80%. For the second quarter (Q2), in Nantes, the cob wall is responsible for a demand of 4.45 kWh/m², about 39% more than the multilayer wall (3.18 kWh/m²). Douala also sees the cob wall consuming 15.92 kWh/m², approximately 25% more than the multi-layer wall that has an energy needs equal to 12.72 kWh/m². Riyadh registers a slight

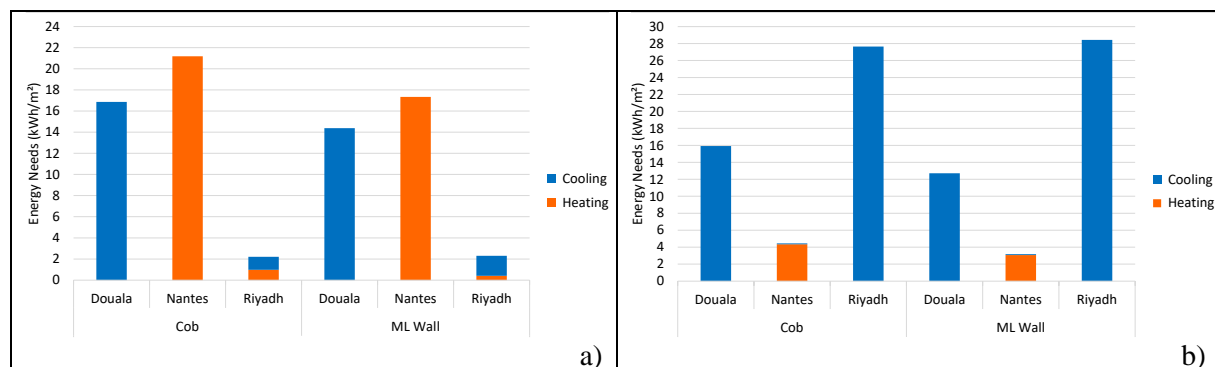
difference of 2.8 % in needs between the cob (27.64 kWh/m²) and multilayer (28.42 kWh/m²) walls. In the third quarter (Q3), Nantes registers needs of 0.83 kWh/m² for the cob wall, about 13% higher than the multi-layer wall's (0.74 kWh/m²). Douala has the cob wall consuming 10.27 kWh/m², roughly 24% more than the multi-layer wall's 8.29 kWh/m². In Riyadh, the cob wall consumes 36.87 kWh/m², marginally less than the multilayer wall's consumption of 37.6 kWh/m². In the fourth quarter (Q4), Nantes shows for the cob wall, a demand of 15.12 kWh/m², about 23% higher than the multilayer wall's 12.28 kWh/m². Douala registers similar needs for the cob (12.26 kWh/m²) and multilayer (12.09 kWh/m²) walls. In Riyadh, the cob wall has quarterly needs of of 6.95 kWh/m², about 9% less than the multilayer wall's 7.63 kWh/m². All these results, presented on Figure 7, highlight the variations between the cob wall, (monolayer structure without an insulating layer), and the multi-layer wall. Despite the differences, the cob wall shows needs rates that approach those of the insulated multilayer wall in some periods and climates such as Riyadh's climate. Table 2 and Table 3 summarise the energy needs for, respectively, cooling and heating. It appears that the consumption for cooling, in tropical and desert climates, is more important than the heating consumption in oceanic climate. Figure 8 corroborates this observation, clearly illustrating a measurable variance in energy needs between cob and multi-layer walls monthly.

Table 2 : Cooling energy needs for the 2 wall configurations and the 3 climates in kWh/m²

Quarter	Nantes		Riyadh		Douala	
	Cob	ML Wall	Cob	ML Wall	Cob	ML Wall
Q1	0	0	1.23	1.89	16.86	14.37
Q2	0.10	0.10	27.64	28.42	15.92	12.71
Q3	0.77	0.68	36.87	37.59	10.27	8.28
Q4	0	0	6.57	7.51	12.26	12.09
Total	0.87	0.78	72.31	75.41	55.31	47.45

Table 3 : Heating energy needs for the 2 wall configurations and the 3 climates in kWh/m²

Quarter	Nantes		Riyadh		Douala	
	Cob	ML Wall	Cob	ML Wall	Cob	ML Wall
Q1	21.18	17.33	0.97	0.41	0	0
Q2	4.34	3.07	0	0	0	0
Q3	0.06	0.06	0	0	0	0
Q4	15.11	12.28	0.39	0.11	0	0
Total	40.69	32.74	0	0.52	0	0



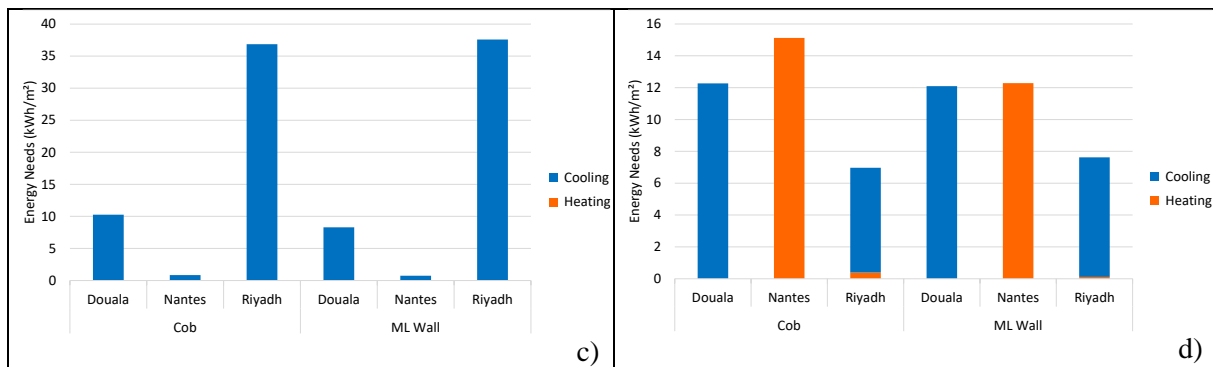


Figure 7 Total energy needs (a) first quarter (b) second quarter, (c) third quarter, and (d) fourth quarter depending on the climate for Cob configuration and Multi Layer Wall configuration

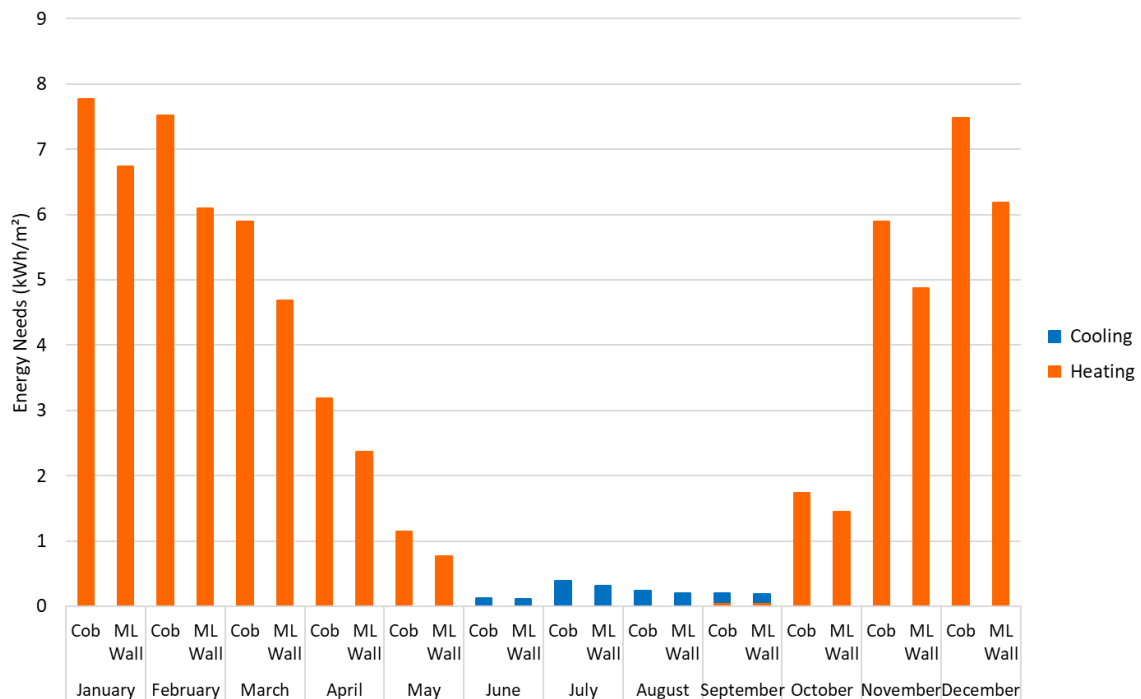


Figure 8 : Monthly total energy needs for Nantes climate

The hygrothermal performance of earthen building materials compared to multilayered envelopes under different climatic conditions is illustrated in the figure 9. Specifically, in the moderate climate of Nantes, graphs a.1 and a.2 demonstrate that the raw earth envelope (a.1) experiences significant fluctuations in absolute humidity, in response to temperature variations over time. The observed fluctuations point toward a dynamic interplay between the building envelope and indoor surroundings, with raw earth exhibiting an ability to absorb and release moisture. The graph depicts sharp peaks, highlighting the temporary aspect of these fluctuations and indicating phases of increased humidity that could lead to discomfort for several hundred hours. This is supported by the associated scale and colour gradient.

The multilayer envelope (a.2) exhibits exceptional stability, responding less noticeably to fluctuations in temperature over a prolonged period. This implies that the multilayered envelope could provide a more consistent indoor environment with reduced humidity peaks, which could promote comfort and reduce the risk of moisture-related problems within the building. For the arid climate of Riyadh, graphs b.1 and b.2 show significantly more stable and lower internal humidity profiles over time, in line with the arid conditions. These findings suggest that both the raw earth and the multilayer envelope can effectively maintain a stable indoor environment with minimal fluctuations in humidity levels, indicating that the management of internal moisture is less of a critical concern in such climates.

The case of Douala provides further evidence of this. Graph c.1 illustrates that the raw earth envelope is significantly affected by the elevated external relative humidity common in this area, leading to increased levels of internal absolute humidity for prolonged periods of time, probably several thousand hours per year. This long-lasting interaction may cause inconvenience and potential structural and health complications caused by biological growth. The multilayer envelope (c.2) appears to provide a more regulated internal environment, with fewer and shorter periods of high humidity, potentially increasing habitability and longevity in such a challenging climate.

These results highlight the dependence of hygrothermal performance on local climate and material selection. In tropical areas, a multilayered envelope can provide superior control, while in oceanic or desert climates, raw earth may be more suitable if internal humidity levels can be managed.

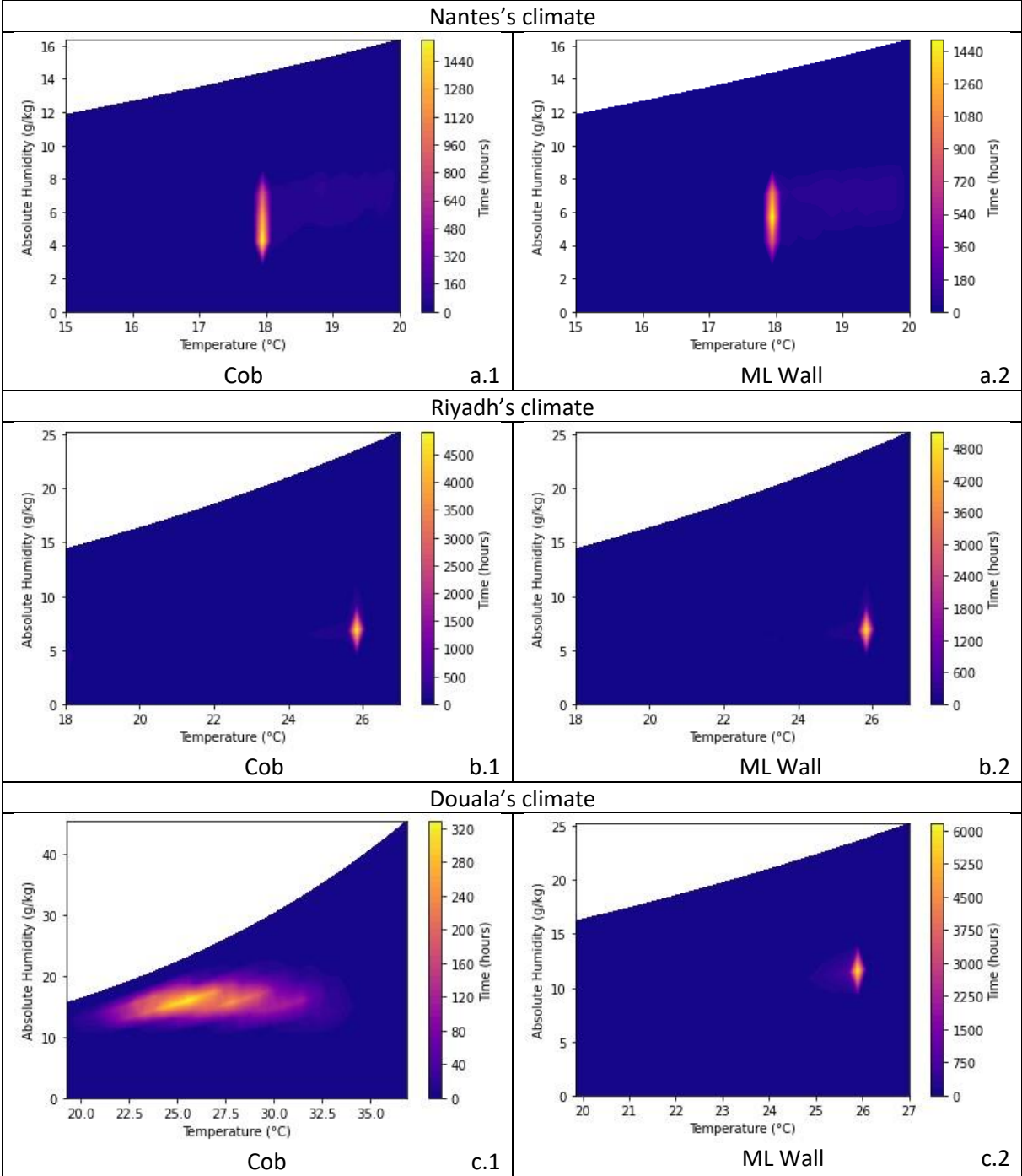


Figure 9 : Evolution of temperature and absolute humidity over a whole year for 1) Nantes's climate, 2) Riyadh's climate, 3) Douala's climate for a cob envelope (a) and a multilayer envelope (b).

3.2 Analysis of the impact of mass transfer on the energy needs

In this part of the paper, we investigate the influence of mass transfer on the energy needs patterns of the cob walls. The effect of mass transfer varies in various climate settings, including those that are dry, humid, cold, or hot. A comprehensive understanding of the mechanisms involved is crucial to refine the performance of building materials and even more so for bio-based and geosourced materials such as cob, specifically in enhancing energy efficiency across various climatic circumstances. We have compared the energy needs for the 3 different climates by comparing the cases *whether the mass transfer were carried out or not*. The results and analysis are shown in Figure 10. In the first quarter (Q1), the energy needs, taking into account only thermal transfers, were 22 kWh/m² in Nantes, 18.8 kWh/m² in Douala and 2.24 kWh/m² in Riyadh. This quarter represents winter in Nantes, which has an oceanic climate with cool winters, and in Riyadh, which has a desert climate with mild winters. In Douala, with its tropical monsoon climate, Q1 corresponds to the dry season. However, when heat and humidity (HAM) transfers are taken into account, energy needs decrease in all cities: 21.19 kWh/m² in Nantes (a decrease of 3.7%), 16.9 kWh/m² in Douala (a decrease of 10.1%) and 2.21 kWh/m² in Riyadh (a decrease of 1.3%). During the second quarter (Q2), which marks the arrival of spring in Nantes and Riyadh and the beginning of the rainy season in Douala, the energy needs under thermal transfer conditions were 4.49 kWh/m² in Nantes, 16.6 kWh/m² in Douala and 27.7 kWh/m² in Riyadh. Again, taking into account HAM transfers, energy needs decreased to 4.45 kWh/m² in Nantes (-0.9%), 15.9 kWh/m² in Douala (-4.2%) and 27.64 kWh/m² in Riyadh (-0.2%). The third quarter (Q3) is characterised by the continuation of the rainy season in Douala, while Nantes and Riyadh enter their respective summer seasons. During this period, the energy needs in the thermal transfer scenario were 0.98 kWh/m² in Nantes, 11.25 kWh/m² in Douala and 37 kWh/m² in Riyadh. When HAM transfers were included, the energy needs values decreased to 0.83 kWh/m² in Nantes (a reduction of 15.3%), 10.27 kWh/m² in Douala (a reduction of 8.7%) and 36.87 kWh/m² in Riyadh (a reduction of 0.4%). During the fourth quarter (Q4), Nantes and Riyadh enter the autumn season and Douala enters the dry season. The energy needs under thermal transfer conditions were 15.32 kWh/m² in Nantes, 15.92 kWh/m² in Douala and 6.95 kWh/m² in Riyadh. With HAM transfers, energy demand was 15.12 kWh/m² in Nantes (a reduction of 1.3%), 12.26 kWh/m² in Douala (a reduction of 24.4%) and 6.95 kWh/m² in Riyadh (no change). Inclusion of Heat and Moisture (HAM) transfers in the annual data analysis had a significant impact on energy needs at all sites, with the largest impact seen in Douala. In Nantes, known for its temperate maritime climate with mild winters and relatively cool summers, the implementation of HAM transfers led to an annual reduction in energy needs of about 5.3% compared to simulations using only thermal transfers. This reduction suggests that in climates similar to those in Nantes, the inclusion of HAM transfers can improve the energy performance of buildings. The effect of HAM transfers was particularly pronounced in Douala, which experiences significant humidity fluctuations between the dry season (humidity between 40% and 85%) and the rainy season (humidity between 60% and 90-95%). Annual energy needs were reduced by approximately 11.9% compared to thermal-only simulations. This significant reduction underscores the critical role of HAM transfers in improving energy efficiency in tropical climates and suggests the potential of geosourced materials, such as cob, to modulate humidity levels in buildings.

In contrast, Riyadh, which is characterised by a hot desert climate with mild winters and extremely hot summers and general low humidity, showed a small reduction in annual energy needs of approximately 0.5% when HAM transfers were considered. This finding suggests that in climates with less drastic humidity variations, the impact of HAM transfers on the overall energy efficiency of buildings may be less significant.

In summary, these results indicate that the inclusion of mass transfer, in addition to heat transfer, can significantly affect the estimated energy needs of buildings, especially in climates with significant humidity variations. This finding highlights the importance of considering HAM transfers when predicting energy demand, especially in the context of traditional building materials such as cob. These

results are in line with those of Qin et al. [43] who have focused on the impact of mass transfer on the energy needs for various climates such as Hong Kong and Paris for a concrete wall.

The impact of mass transfer on energy needs is inextricably linked to the management of humidity and temperature in buildings, which are critical elements in the dynamics of thermal comfort and energy requirements for heating and cooling. During cold periods, in high humidity environments such as Hong Kong or Douala, the air is charged with a significant amount of water vapour. When this air encounters colder surfaces in a building, a process of condensation occurs, releasing latent heat that warms the indoor environment. This condensation plays an active role in natural temperature regulation, reducing the need for additional heating. On the other hand, in hot weather, the evaporation of water from internal surfaces can have a natural cooling effect. This effect is particularly important in humid climates where humidity levels are high. In more temperate or colder climates, such as Paris or Nantes, this evaporation phenomenon is less pronounced because the air is generally less humid. As a result, mass transfers have less influence on the thermal regulation of buildings and taking them into account results in a less pronounced reduction in energy needs. It is important to note that the inclusion of mass transfer can help to improve indoor air quality. Indeed, regulating humidity can prevent the growth of mould and other air quality problems, thereby promoting a healthier indoor environment.

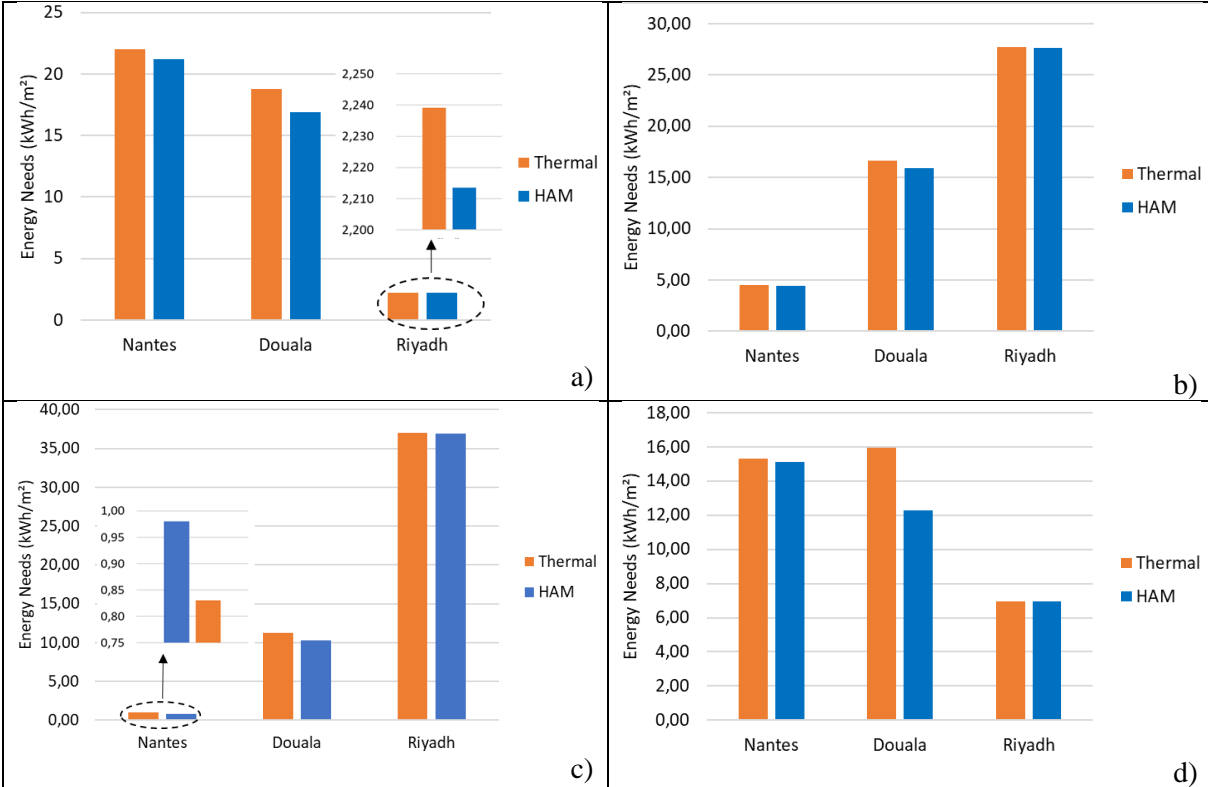


Figure 10 : Total energy needs in the ambience (a) first quarter (b) second quarter, (c) third quarter, and (d) fourth quarter depending on whether HAM or only thermal transfers are taken into account

4. Conclusion

In our study, we evaluated the energy needs of two different wall configurations in different climates. This analysis allowed us to effectively compare a single-layer raw earth (cob) wall with a conventional multilayer wall including insulation. The results show that the cob envelope requires 24-35% more energy than the multilayer envelope in both oceanic and tropical climates, which were represented by Nantes and Douala, respectively. The high energy demand is mainly due to the need for heating in Nantes' oceanic climate and cooling in Douala's tropical setting. However, the cob wall has a slight advantage in efficiency, with a 3% lower energy demand than the multilayer wall in the arid climate of Riyadh. The higher energy demand is primarily due to the less optimal mass transfer in the cob construction in humid climates like Douala, which is a key determinant of overall energy efficiency.

In warmer climates such as Douala and Riyadh, we observed a higher energy demand for cooling, as opposed to heating in the climate of Nantes. Our investigation showed that though cob and multilayer walls display comparable temperature and humidity outlines in Nantes and Riyadh, this wasn't the scenario in Douala. The cob walls in Douala demonstrated considerable inconsistencies, underscoring the obstacles created by high levels of humidity in tropical regions.

By including mass transfer considerations in our analysis, a significant reduction in energy demand was observed - just over 5% in Nantes and nearly 12% in Douala. These results are in line with the findings of Qin et al. [43], who discovered a 6.5% reduction in heating demand in Paris and a 15% reduction in cooling needs in the tropical climate of Hong Kong.

The research highlights the potential effectiveness of cob as a single material, compared to multilayered structures. This is especially crucial in developing countries, where construction mainly depends on concrete blocks. Raw earth, particularly cob proves to be a persuasive substitute when paired with a bio-sourced insulator like hemp concrete. It presents a sustainable, climate-resilient, and efficient building approach that accommodates the environmental and climatic subtleties of these regions. Thus, it widens the prospect for environmentally friendly and energy-efficient construction practices.

Acknowledgments

Authors are grateful to the Agence de la transition écologique (ADEME) and Pays de la Loire Region (in France) for supporting this work.

Conflicts of Interest

The authors declare no conflict of interest.

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