Thermal Performance and Characterization of a Sawdust-raw Earth Material for Building Application and Behaviour

Ryad Bouzouidja$^{1,2}$, Tingting Vogt Wu$^{1,2}$, Abraham Samuel$^{1,2,3}$, Jacinta Dsilva$^4$, Jasmina Locke$^4$, Mehdi Sbaita$^{1,2}$

$^1$Univ. Bordeaux, CNRS, Bordeaux INP, I2M, UMR 5295, F-33400, Talence, France
$^2$ Arts et Métiers Institute of Technology, CNRS, Bordeaux INP, Hesam Universite, I2M, UMR 5295, F-33400 Talence, France
$^3$ Amity School Architecture & Planning Amity University Dubai Dubai, United Arab Emirates
$^4$ SEE Institute, Dubai, United Arab Emirates

Abstract

In a context of global warming and climate change, ensuring thermal comfort in summer conditions is one of the most important priorities for scientists and building designers. It is crucial to ensure the well-being of occupants, whether in a private or professional setting, considering the importance of occupants' productivity and health. The most common material used in the building sector is concrete, which is responsible for emitting greenhouse gas emissions (GES). An alternative to tackle GES is to use, for example, biosourced raw earth material. The analysis of this study shows that air conditioning consumption can be significantly reduced with compressed earth bricks (CEB) for a west-facing façade.

The objective of this study was to evaluate the impact of mud bricks on the thermal behaviour of a west-facing wall in a very hot Middle Eastern climate (Dubai) during late summer (October 2019 period). The first step involved modelling this behaviour with Comsol Multiphysics software. The results showed that the model accurately describes the thermal behaviour very well ($R^2=0.88$ to 0.97) compared to the measured data. This work explains the effect of using a bio-based material with sawdust (3%, 5% and 10%) in reducing the thermal amplitude and improving the thermal phase shift from the outside to the inside during a month of October (late summer in the Dubai region, United Arab Emirates). The result corresponds to a decrease in the thermal amplitude of damping factors by about 65% and a thermal phase shift of 6 hours 24 minutes between the walls equipped with CEB.

Highlights

- Compressed earth blocks-enhanced building envelope under extreme United Arab Emirates conditions is investigated.
- Finite Element Model is used to simulate the impact of CEB.
- The utilisation of digital tools, such as Comsol®, can help in simulating the behaviour of raw earth blocks under different temperatures, and moisture levels, providing valuable insights into their thermal behaviour.
- Modelling raw earth blocks also facilitate the creation of innovative and aesthetically pleasing designs.

Introduction

Construction sector contributes to the world's greenhouse gas emissions and consumes nearly 36% of global energy (according to the International Energy Agency, 2020). Concrete, primarily made with Portland cement, is the most widely used building material, accounting for over 25 billion tons (Afroughsabet et al., 2018; Cristino et al., 2021). Concrete finds extensive use in various industries, including construction of physical infrastructures such as bridges, dams, buildings, and tunnels (Yang et al., 2018).

However, the extensive use of concrete has strained natural resources in recent years (Tiwari et al., 2016). To reduce energy consumption in buildings without compromising performance or structure, alternative solutions are necessary. Balancing cost and reducing the carbon impact of concrete presents a challenge.

Calculating the carbon footprint of concrete is complex, as determining the amount of carbon dioxide emitted per unit of production for major structural materials is not straightforward. Reinforced concrete, the most commonly used type, has a high carbon impact (Shao et al., 2023). Nevertheless, identifying the carbon footprint of concrete remains a complex task. Strategies to minimize the use and environmental impact of concrete include reducing, reusing, and recycling, with biosourced concrete being a widely adopted solution globally due to its ease of implementation and the availability of biosourced products such as hemp, wood sawdust, or raw earth.

The utilisation of raw earth as a building material offers a range of environmental, social, and economic benefits. Unlike traditional construction materials, processing and handling of raw earth require significantly less energy (i.e. 440 kWh m$^3$ compared to 1300 kWh m$^3$), with the manufacture of compressed earth blocks using only one-third of the energy required to produce conventional fired bricks (Little and Morton, 2001). While concrete is known for its ability to support self-standing walls and low thermal inertia, it has a drawback in terms of heat transfer capabilities due to its high thermal conductivity (Asadi et al., 2018).

To enhance the thermal and mechanical properties of raw earth, methods such as chemical and physical stabilisation are applied (Losini et al., 2021). Physical stabilisation involves granular correction and the addition of fibres (Vatani Oskouei et al., 2017). For several years, the scientific literature around raw earth bricks has been
constantly increasing (Turco et al., 2021). Researchers and scientists are focusing on energy modelling and control to develop strategies that will reduce energy consumption in buildings. According to the literature review, ongoing studies are investigating the mechanical and hygrothermal performance of compressed earth bricks with sawdust (Robert et al., 2021). In the study of (Beckett et al., 2017), the thermal performance of a residential building made with rammed earth was simulated using the BERS Pro v4.3 software, commonly used in Australia. However, this analysis did not account for the combined effects of heat and moisture transfer. Other investigations in the literature have also focused on the heat transfer properties of rammed earth walls, using various commercial software packages such as TRANSYS, Comsol, Design Builder, among others (Giuffrida et al., 2021; Jiang et al., 2020).

This study aims to maximise the potential of local resources, such as earth and hemp, in construction materials as a means to address housing issues and reduce energy consumption. In addition, the objective of the present investigation is to illustrate an approach that relies on the building envelope's design to enhance thermal comfort and diminish energy consumption in an existing structure. Specifically, the study aims to optimise thermal comfort in a building made from local materials, identify less energy-intensive materials to improve energy efficiency, and promote ecological and environmental protection.

**Case Study Building**

In order to evaluate the impact of the implementation of bio-based materials such as compressed mud bricks in the building envelope under extreme conditions, a case study building in the United Arab Emirates (UAE) was considered. Dubai experiences a Tropical and Subtropical Desert Climate (Bwh climate in the Köppen Geiger classification system (Kottek et al., 2006)).

August is the warmest month of the year, with an average air temperature of 35°C. The average lowest recorded temperature is 18°C (January). The wettest months are January, February and March, with 45 mm of precipitation on average. The building selected in this study is a house called BaityKool from a Solar Decathlon 2018 competition. The house is located 35 km from Dubai (Figure 1).

In selecting this case study, the intention was to consider the behaviour of an exposed wall on the west facade in a very hot climatic region. Also, in order to provide a good overview of the impacts of using raw earth in the context of improving the building performance by using a material with a reduced carbon impact compared to clay brick and concrete.

**Weather conditions**

Data (outdoor temperature and rainfall quantity) from the weather station were obtained over a 10 days period during October 2019 (Figure 2).

Outdoor temperature (±0.3°C accuracy), relative humidity (±2% accuracy) probes (Silicon PN Junction Diode and film capacitor), wind speed (± 0.83 m s\(^{-1}\) accuracy) and solar irradiance (CMP6 Kipp & Zonen) (sensitivity 5 to 20 μV W\(^{-1}\) m\(^{-2}\)) were also installed.

These probes were connected to a data logger (Vantage Pro v2) powered by a battery connected to a solar panel (10F accumulator). Temperature values were recorded with a 10-min time step between 17 October 2019 and 27 October 2019. During this period, the outdoor temperature varied from 21.0 to 41.0°C, with an average value of 29.8 °C, and no rainfall were observed. The end
of October 2019 demonstrated very warm weather. The outdoor temperature reached 41.0°C on 25 October. This period (17-27 October 2019) was selected to evaluate the thermal behaviour of the CEB during very warm weather. Only the west façade was studied. The composition of the selected wall is presented in Table 1 and Figure 3. The wall is composed from the inside to the outside of a sheet of recycled material (Barrisol®), which serves as vapor barrier and sound reducer. It is followed by a layer of raw earth-based bricks and a layering of rigid and semi-rigid wood fibre insulation (STEICO®), sandwiched between a massive cross-laminated timber (CLT) panel, a vapour barrier based on kraft and a reflective sheet that controls the passage of vapour between the outside and the inside of the building.

The instrumentation of the wall is composed of hybrid temperature and hygrometry sensors hygrometry sensors SHT85 (accuracy ± 0.1°C and ± 1.5% respectively).

Due to datalogger and probes issue, ultra-high-performance concrete (UHPC) and Air gap (AG) were not studied.

\[ T = \text{the temperature (°C), } \rho = \text{the density (kg m}^{-3}), \text{ } \text{Cp} = \text{the heat capacity of the wall (J kg}^{-1} \text{K}^{-1}), \text{ } U = \text{the velocity (m s}^{-1}), \text{ } \text{t} = \text{the time (s).} \]

In Equation (1) and (2), heat transfer in solids is described by conduction. 

\[ \lambda \frac{\partial T}{\partial t} + \nabla \cdot q = 0 \]  

where,  

\[ q = -\nabla (\lambda T) \]  

\[ q_{\text{conv}} = h_{\text{ext}} \cdot (T_{\text{out}} - T) \]  

\[ q_{\text{conv}} \] is the convective heat flux (W m\(^{-2}\)), \( h_{\text{ext}} \) is the convective heat coefficient (W m\(^{-2}\) K\(^{-1}\)). \( T_{\text{out}} \) is defined as the outdoor temperature (°C).

It is expected that the boundary conditions can be of the following categories:

- At the surface of the wall considered as outdoor condition, Mixed Dirichlet/Neumann condition (\( T_s \)) and \( q_s \) is applied (Forkel et al., 1970):

\[ q_{\text{conv}} = h_{\text{ext}} \cdot (T_{\text{out}} - T) \]  

- Inside boundary condition is defined by internal convective condition (\( h_{\text{int}} = 8 \text{ W m}^{-2} \text{ K}^{-1} \)) and internal air ambient temperature \( T_{\text{in}} \) (°C):

\[ q_{\text{conv}} = h_{\text{int}} \cdot (T_{\text{int}} - T) \]  

- An initial temperature between 30.2°C (outdoor) to 32.8°C (inside) was assumed for the entire domain.

- COMSOL employs by default the correlation by (Lloyd and Moran, 1974), as cited by (Incropera et al., 1996), to evaluate natural convection between CEB surface and the inside air.

COMSOL Multiphysics software was used to evaluate the behaviour of the temperature field over the time within the CEB over time using a finite element scheme. The solution was found for a time step of 10-min for the time period from 17 to 27 October 2019, using a MUMPS solver, a solver for finite element applications. A 48-hour (17 to 18 October 2019) period was necessary to initialise the simulation.

The wall-oriented West was modelled with a rectangular block of 60 cm wide (Figure 4). As mentioned before, the thickness of the concrete slab poured on top was 38 mm. A relatively “fine” mesh was used, with nearly 13,118 elements in it, with an average area of 0.18 cm\(^2\) (Figure 4).
Validation and evaluation process

Two phases were used to evaluate the influence of the sawdust:

- Phase #1, validation process of the model using experimental data without adding sawdust into the brick named CEB0.
- Phase #2, evaluation process of adding sawdust to the mix (CEB3, CEB5, and CEB10). Only numerical results are available. These properties are considered as constant and are given in Table 2. A previous study has been conducted on characterisation of CEB with adding wood sawdust (Bouzouidja et al., 2023).

Table 2: Physical characteristics of the used material. $^d$, $^*$, $^*$ are defined as the different formulations (CEB0, CEB3, CEB5, and CEB10 respectively).

<table>
<thead>
<tr>
<th>Property</th>
<th>Ratio (%)</th>
<th>Initial water content (wt%)</th>
<th>$\rho$ (kg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>75$^d$;72$^<em>$; $^d$ 65$^</em>$</td>
<td>70$^*$</td>
<td>1.2</td>
</tr>
<tr>
<td>Clay</td>
<td>20</td>
<td>0.1</td>
<td>610</td>
</tr>
<tr>
<td>Cement</td>
<td>5</td>
<td>0.036</td>
<td>370</td>
</tr>
<tr>
<td>Sawdust</td>
<td>0$^<em>$;3$^</em>$; $^<em>$ 5$^</em>$; 10$^*$</td>
<td>0.036</td>
<td>252</td>
</tr>
</tbody>
</table>

Table 3 also presents the thermal properties of the CEB layer.

Results of the validation phase

Figure 5 shows the temperature of the CEB0 and the CLT, respectively.

The temperatures predicted by the model for the CEB0 closely match the measured temperatures ($R^2$=equal to 0.97). During the night, the difference between the predicted and observed temperature is approximately 0.05°C at midnight. During the daytime, a difference of around 0.25°C (at 8:00 am and noon) (Figure 5a).

A similar pattern can be observed for the CLT (Figure 5b), with a temperature difference of approximately 0.5°C between the predicted and monitored values.

Table 3: Description of the thermal compressed earth blocks (CEB) materials’ properties. “CEB0”, “CEB3”, “CEB5”, “CEB10” are defined as the ratio of sawdust in the compressed earth bricks (0%, 3%, 5%, 10% respectively).

<table>
<thead>
<tr>
<th>Code</th>
<th>$\lambda$ (W m$^{-1}$ K$^{-1}$)</th>
<th>$\rho$ (kg m$^{-3}$)</th>
<th>$C_p$ (J kg$^{-1}$ K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEB0</td>
<td>1.200</td>
<td>1936.3</td>
<td>1093.9</td>
</tr>
<tr>
<td>CEB3</td>
<td>1.1641</td>
<td>1749.3</td>
<td>1177.9</td>
</tr>
<tr>
<td>CEB5</td>
<td>0.8539</td>
<td>1732.5</td>
<td>1128.7</td>
</tr>
<tr>
<td>CEB10</td>
<td>0.7660</td>
<td>1715.9</td>
<td>1061.4</td>
</tr>
</tbody>
</table>
The modelling of the wall is given by taking into account the case study of the weather conditions of the month of October described in Figure 2. The previous modelling results are based on CEB0 layer properties. We then evaluated the damping factor and the thermal phase shift time. The damping factor is the ratio of the amplitudes of the indoor and the outdoor temperatures (ISO 13786:2017 Standards). The lower the damping factor, the lower the internal temperatures are. It is determined by the Equation (5):

$$ f = \frac{\Delta T_{in}}{\Delta T_{ex}} $$  \hspace{1cm} (5)

where, $\Delta T_{in}$ and $\Delta T_{ex}$ are the amplitudes of the internal and external temperatures respectively. These properties of the wall are important because they allow in characterising the internal environment. They are evaluated according to the indoor and outdoor temperatures and provide information on the behaviour of the west façade. The thermal phase time is the time needed for the indoor temperature to reach its maximum from the moment when the outdoor temperature is considered to be at its maximum. It evolves with the inertia of the building and is determined by the Equation (6):

$$ \phi = t_{in,max} - t_{ex,max} $$  \hspace{1cm} (6)

where, $\phi$ is the thermal phase shift time (h), $t_{in,max}$ and $t_{ex,max}$ are the times (h) at which the peaks of internal and external temperatures are reached.

Figure 7 shows the damping factors and the thermal phase shift time of the walls with different CEB configuration (CEB0, CEB3, CEB5, and CEB10) as a function of the thickness of the internal mass storage. It is possible to notice a slight increase in the damping factors of the different values for ratios of the sawdust by 3%. Whereas in terms of time shift, we notice a small decrease by 6 mins.

This study has shown the potential of a detailed simulation to investigate the influence of biosourced material as compressed earth blocks (CEB) such on control-oriented models. Moreover, detailed simulations enable to conduct studies in extreme weather conditions. Our research team intends to investigate the effect of mixing sawdust (with different proportion 3%; 5%, and 10%) and raw earth material on the performance of wall oriented west. The results show that the model used represents very well the behaviour ($R^2= 0.88$) of a wall equipped with CEB.

### Conclusion

This study also made it possible to determine, using a numerical model validated experimentally, the values of the time of thermal dephasing, the damping factors according to the quantity of sawdust for a wall equipped with compressed raw earth brick. It appears in these conditions that the contribution of sawdust from 3% is sufficient to reduce the time of phase shift and mitigate the damping factor. However, the values are quite low to increase the thermal comfort during the heat wave.
Acknowledgements

The authors would like to thank TELLUS CERAM Company for providing the compressed earth bricks. We would like to thank the BaityKool team (www.Baitykool.com) for providing us the data. We would like to thank our colleagues from Institute de of Mechanical and Engineering (I2M) Bernard Sobles for its inputs.

References


