Modeling Energy Consumption in a Single-Family House in South Tyrol: Comparison Between Hemp Concrete and Clay Bricks

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Abstract

The built environment generates nearly 40 % of annual global CO_2 emissions. To reduce these emissions, alternative materials able to store CO_2 have started to be used in the construction sector. In the case of hemp concrete, part of this storage occurs during its service life leading to a potential decrease of indoor CO_2 levels. Assuming that CO_2 is used to control ventilation rates in certain buildings, the use of this material might lead to lower ventilation requirements and, thus, reduced energy consumption. The aim of this work was to develop an energy model including the CO_2 sequestration capability of hemp concrete to estimate the potential energy savings derived from its use in a typical residential building in South Tyrol with CO_2-based demand controlled ventilation. This result was later compared with the energy consumption of the same building made of clay bricks and the influence of air infiltration on indoor CO_2 levels was also evaluated. The results obtained from the simulations showed that indoor CO_2 levels were always lower in the hemp concrete buildings compared to the building made of clay bricks. However, in hemp concrete buildings with high air infiltration rates, the effect of the CO_2 absorption by the hemp concrete wall might be negligible. The energy required for the mechanical ventilation to maintain the CO_2 levels under the 1200 ppm threshold was estimated to be 0.28, 0.02 and 0.01 kWh/(m^2 yr), for the clay brick with low infiltration, hemp concrete houses with low and high air infiltration, respectively. Therefore, the operation of hemp concrete buildings with CO_2-based demand-controlled ventilation may have a slightly lower energy consumption as well as environmental impact than the equivalent clay brick buildings.

1. Introduction

The revised Energy Performance of building directive (EPBD) is reinforcing the need to reduce the energy consumption of buildings with the vision of a decarbonized building stock by 2050. Achieving zero emissions from the existing building stock will require not only increasing energy efficiency and generating 100 % renewable energy, but also reducing the emissions associated with the manufacture of the construction materials, the so-called embodied carbon emissions. Therefore, the construction sector plays a critical role in fighting climate change and a significant shift is required towards the use of more eco-friendly and sustainable materials to meet the European climate-neutral targets. In this context, hemp concrete has been recently adopted as an innovative solution by the building industry to reduce emissions, as this material stores more than 90 % of the carbon dioxide (CO_2) emitted during its production (Jami et al., 2019). Part of this storage occurs during its service life leading to a decrease of indoor CO_2 levels. Given this feature, the use of this material in buildings with CO_2-based demand-controlled ventilation might lead to lower ventilation requirements and a potential reduction of the energy consumption of the building.

Several studies have been conducted to characterize the CO_2 sequestration potential of hemp concrete (Arehart et al., 2020; Jami et al., 2016), most of them being focused on the assessment of its carbon footprint through Life Cycle Assessment (Pretot et al., 2014). However, the influence of CO_2 storage capacity of hemp concrete on the energy consumption of a building made with this material has not been explored so far. Thus, the aim of this research was to

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develop an energy model including CO_2 absorption by hemp concrete to estimate the energy savings achievable in a hemp concrete residential building with CO_2-based demand-controlled ventilation and compare them with the energy consumption of the same building made of clay bricks.

2. Methodology

In this study, dynamic thermal simulations were used to evaluate the performance of hemp-based constructions. The thermal transmittance of a hemp concrete wall was calculated based on the data provided by the manufacturer, and experimental measurements were conducted to estimate CO_2 absorption rate of a hemp concrete wall. Then, these experimental data were included in a building energy model created using EnergyPlus to estimate the energy consumption of a hemp concrete building with CO_2-based demand-controlled ventilation. The same model was used to estimate the energy consumption of an identical house made of clay bricks for comparison.

2.1 Modeling

2.1.1 Reference Building

The case study building is representative of typical new single-family houses in the South Tyrol region (northern Italy). This building was chosen as a result of the analysis of a building stock in a valley in South Tyrol obtained from the TABULA project[1] and the guidelines and database of the local energy certification agency called Agenzia per l'Energia Alto Adige-CasaClima.

The case-study building was modeled and simulated with EnergyPlus 9.3.0 (US Department of Energy's (DOE), USA). Each simulation was performed over an entire reference year using an hourly timestep. For the simulations, the city of Bolzano (capital of South Tyrol) was selected and the corresponding weather file was taken from the energy plus weather platform (https://energyplus.net/weather).

[1] https://episcope.eu/iee-project/tabula/

2.1.2 Geometry And Construction Type

The geometry of a building has a major impact on the efficiency of the building. In particular, the volume-to-surface ratio determines the relative heat loss on the thermal envelope. In order to partially reduce the heat losses, the building was assumed to be a semi-detached house, as illustrated in Fig. 1. The opaque components of the building are listed in Table 2. These elements were taken from a freely available catalogue (dataholz.eu) which is a catalogue of wood and wood-based materials, building materials, components and component connections for timber construction covering thermal, acoustic, fire and ecological performance levels, released by accredited testing institutes or accepted research institutions.

The case-study building consists of 9 thermal zones: one living room, two bathrooms, three bedrooms and one studio. The building has a net floor area of 124 m^2 and a floor-to-ceiling height of 2.7 m. The east façade was assumed to be adjacent to another similar building (adiabatic).

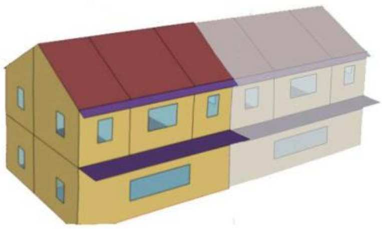


Fig. 1 – Reference case-study building

For the external walls, two typologies were simulated:

- A supporting structure of wood, filled with clay bricks and an external insulation (see Table 1)
- A supporting structure of wood, filled with hemp bricks (see Table 2).

2.1.3 Internal Gains, Heating And Ventilation

The internal gains, heating and ventilation systems were modeled as in previous work (Babich et al., 2020). The key points are as follows:

Schedules for occupancy, lighting and electric equipment set according to the 2014 Building America House Simulation Protocol (Wilson et al., 2014) were applied, as this protocol considers disaggregated schedules for living room and bedrooms, as well as for weekdays and weekends.

Table 1 – Brick wall stratigraphy

n.	Material	S [m]	λ [W/(m K)]	P [kg/m³]	c [J/(kg K)]
1	External Plaster	0.015	0.7	1400	1000
2	Insulation	0.16	0.04	18	1450
3	Clay Brick	0.3	0.22	930	1450
4	Interior Plaster	0.015	0.7	1400	1000

Total thickness = 0.49 m
U-value = 0.18 W/(m² K)

The total number of occupants in the house was assumed as being equal to four. Based on typical metabolic heat generation for domestic activities (ASHRAE, 2009), the heat gains related to the occupancy were assumed to be 126 W for a standing relaxed person and 72 W for seated person.
The amount of carbon dioxide generated by a person depends on their activity level. In this model, the activity for the occupants of the living room was assumed to be equal to 1 met (i.e., seated quiet person) and 0.7 met for people occupying the bedroom (i.e., sleeping person). Based on these activity levels, the rate of CO_2 generation was calculated according to Eq. 2 (ASHRAE, 2009):

$$G_{CO_2} = G_{O_2} * RQ = \frac{0.00276 * A_D * M}{(0.23 * RQ + 0.77)} * RQ \qquad (1)$$

Where G_{CO_2} is a CO_2 generation rate per person (L/s); A_D is the Dubois area (m²); RQ is the respiratory quotient (-); and M is the metabolic rate (met).
The heating setpoint was set to 20 °C during the day and a constant setback of 18 °C during the night. The heating system was modeled as an ideal system with infinite heating capacity that supplied conditioned air to the zone, meeting all the load requirement and consuming no energy.
To guarantee acceptable indoor air quality, pollutants must remain below a certain threshold. In this study, only CO_2 was considered and a CO_2 threshold value of 1200 ppm was selected for the activation of the mechanical ventilation based on category 2 (i.e., normal level of expectation, which is the suggested level for residential buildings) of the standard EN 16798-1:2019.
The reference building was intended to represent a typical new residential building of the South Tyrol region. According to the local legislation, air tightness of n_{50} = 1.5 h^{-1} was selected to meet the requirements of CasaClima A and B standard. Additionally, a value of n_{50} = 3 h^{-1} was also simulated to investigate the relevance of the air tightness on the CO_2 absorption capacity of hemp concrete walls.

2.1.4 Carbon Dioxide Sequestration

To model contaminant levels in EnergyPlus, the ZoneAirContaminantBalance object is commonly used. It can be used also to model CO_2 levels, although carbon dioxide is not considered an indoor contaminant. In this object, the outdoor CO_2 concentration was assumed to be equal to 400 ppm. The carbon dioxide sequestration capability of hemp concrete was modeled using a ZoneContaminantSourceAndSink:Carbondioxide object. This object allows the input of carbon dioxide sources or sinks in a zone. To model the hemp concrete walls as a sink, a value of -1 for the design carbon generation rate (m³/s) was set for each room. The design value is modified by the schedule, which was defined based on the experimental measurements conducted in the hemp concrete prototype house.

2.2 Thermal Transmittance Calculation

The thermal transmittance (U value) defines the ability of an element of structure to transmit heat under steady-state conditions (Willoughby, 2002). It is a measure of the quantity of heat that will flow through a given element subjected to a temperature difference on its external surfaces. The measurement of transmittance allows an estimate of the thermal conduction characteristics of vertical and horizontal opaque closures, which are necessary for calculating the heating requirements of buildings and, consequently, energy demands.
The composition of the hemp concrete façade investigated in this work is presented in Table 2. The wall was composed of an external plaster, two rows of hemp bricks of 24 cm each and an internal plaster.

Hemp bricks were composed of a mixture of hemp shives and a lime binder.

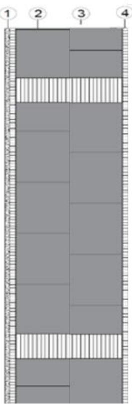
The thermal transmittance of a wall was estimated according to the standard UNI EN ISO 6946:2008 based on the thermal transmittance of the different elements of the wall provided by the manufacturer. Knowing the thickness (s_i) and the conductivity (λ_i) of each layer, it is possible to calculate its thermal resistance and then the thermal transmittance (see Eq. 1) of the wall.

$$U = \frac{1}{R} = \frac{1}{R_{si}+\frac{s_i}{\lambda_i}+\frac{s_n}{\lambda_n}+\frac{1}{C}+R_{se}} \qquad (2)$$

Where R_{si} is the internal surface resistance, R_{se} is the external surface resistance and R the total thermal resistance of the wall.

Table 2 – Stratigraphy of the analysed wall

n.	Material	S [m]	λ [W/(m K)]	ϱ [kg/m3]	C [J/(kg K)]
1	External Plaster	0.020	0.7	1400	1000
2	Hemp brick	0.24	0.07	330	1700
3	Hemp brick	0.24	0.07	330	1700
4	Plaster	0.020	0.7	1400	1000
	Total thickness = 0.40 m U-value = 0.18 W/(m^2 K)				



2.3 CO_2 Monitoring

To estimate the CO_2 absorption rate of hemp concrete, CO_2 levels were monitored in a prototype house (see Fig. 2). The interior of the prototype house consisted of a wooden floor and ceiling and hemp concrete walls, whereas the façade was made of wood. In this house, two CO_2 sensors (K30, CO_2 meter, USA) were installed one inside and another outside the house to continuously monitor CO_2 levels from July to October 2021.

Outdoor air is an additional source of CO_2, therefore, the outdoor air supply entering the prototype house should be considered in order to estimate the CO_2 absorption rate of hemp concrete. A blower door test was conducted to determine the number of air exchanges per hour in the prototype house.

Fig. 2 - Prototype house made of hemp concrete and wood

3. Results And Discussion

3.1 Thermal Transmittance

The thermal transmittance calculated according to UNI EN ISO 6946:2008 was equal to 0.18 W/(m^2 K). This value is lower than the required thermal transmittance by the National standard (Ministero Dello Sviluppo Economico, 2015), which is set at 0.26 W/(m^2 K) for new buildings in climate zone E, indicating that hemp concrete has high insulation properties.

The same thermal transmittance value was obtained for the modeled clay brick wall, thus the energy consumption related to the heating requirements is expected to be similar in both buildings. However, it is important to mention that the hemp brick wall does not have any thermal insulation layer and hence a lower variety of raw materials is needed for its manufacture. In the case of clay bricks, an insulation layer is required to meet the national standards for new buildings in terms of thermal transmittance. Therefore, besides the energy consumption and CO_2 emissions associated with the manufacturing process of the bricks, an additional amount of resources is needed for the manufacture of the insulation layer, which may potentially increase the environmental impact of the building construction.

3.2 CO_2 Absorption Rate

To estimate the CO_2 absorption rate, the CO_2 levels measured inside the prototype house were analyzed and the air exchange rate of house was determined. The air exchange rate (n_{50}) per hour in the prototype house determined by the blower door test under a pressure difference of 50 Pa was found to be 7.22 h^{-1}. However, it is important to mention that this value represents the number of air exchanges at a pressure difference of 50 Pa when, at ambient pressure levels, this difference is approximately between 1 and 4 Pa. Therefore, the air exchange rate at 1 Pa was estimated from the air exchange rate at 50 Pa to be equal to 0.57 h^{-1} using the equations proposed in ASHRAE Handbook of Fundamentals.

The CO_2 levels inside the prototype house were analyzed and a repetitive daily pattern was identified over the different weeks of the monitoring campaign as illustrated in Fig. 3. During the morning, the indoor CO_2 concentration was closer to the ambient levels (~400 ppm) and slightly higher (500-750 ppm) when occupants were inside the house. Every evening, when the occupants were gone and the house was closed, CO_2 levels sharply decreased down to 50-100 ppm. As can be seen in the figure, the upper part of the CO_2 concentration curve is linear, but the lower part has the shape of an exponential function indicating that steady-state concentration was reached overnight.

During the monitoring campaign, the different linear intervals (from 400 to 50-100 ppm) of the CO_2 level decreases were analyzed and an average CO_2 concentration variation of -103.2 ppm/h was estimated. This concentration variation was the result of two processes: i) addition of CO_2 coming from the outdoor air due the infiltration in the building and ii) CO_2 absorption by hemp concrete.

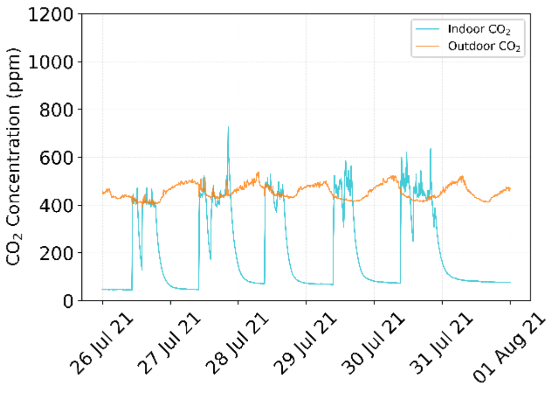


Fig. 3 - CO_2 levels measured inside and outside the prototype

Thus, considering an outdoor CO_2 level of ~400 ppm, an air exchange per hour at 1 Pa of 0.57 h^{-1}, and assuming steady-state conditions in a ventilated space with a uniform CO_2 concentration the average CO_2 absorption rate of hemp concrete was estimated to be equal to 331.2 ppm/h.

3.3 Indoor CO_2 Levels

The simulation was run for the three investigated house configurations. The CO_2 concentrations obtained over a day in the living room are presented in Fig. 4. As it was the most crowded room, the living room was selected to illustrate the effect of hemp concrete walls on indoor CO_2 concentrations. Due to the CO_2 sequestration capability of hemp concrete, the CO_2 levels in the houses made with this material were always lower than in the brick house. Comparing the two hemp concrete houses, the CO_2 trends are very similar, most of the time the levels being slightly lower in the house with a lower infiltration rate. Interestingly, between 8 pm and 3 am, the CO_2 levels were lower in the hemp concrete house with n50 = 3 h^{-1} than in the one with n_{50} = 1.5 h^{-1}. This fact might be explained by the higher infiltration rate, which allowed a faster air renewal and thus contributed to the dilution of the indoor CO_2 concentrations.

According to the results obtained, hemp concrete walls might influence indoor CO_2 levels, however, the impact of this absorptive property on the indoor CO_2 levels strongly depends on the air infiltration rate. In buildings with infiltration rates higher than 3 h^{-1}, the CO_2 sequestrated by the hemp wall might be negligible, as the rate of air renewal is much higher than the absorption rate and thus the indoor CO_2 is evacuated before it can be absorbed by the wall.

3.4 Energy consumption

The energy consumption was estimated for the three house configurations investigated. The main sources of energy consumption were the district heating and the mechanical ventilation. As expected, the energy consumption associated with the heating is very similar for the hemp concrete and the clay brick buildings with a low infiltration rate (see

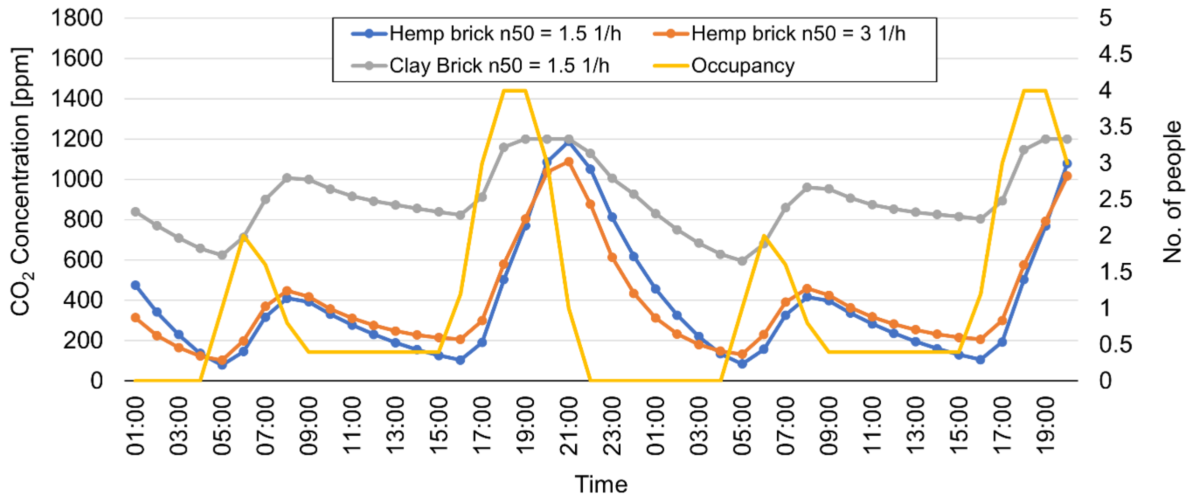


Fig. 4 - CO_2 concentration in the living room of the three investigated configurations

Table 3), as these walls have similar thermal properties. In the case of the hemp concrete building with higher infiltration rate, the energy consumption significantly increased due to the heat losses resulting from the faster air renewal. On the other hand, the energy required to run the mechanical ventilation and maintain the CO_2 levels under the 1200 ppm threshold was estimated to be 0.28, 0.02 and 0.01 kWh/(m^2 yr), for the clay brick and the hemp concrete houses with low and high air infiltration, respectively. In this case, as clay bricks are not able to sequestrate CO_2, a great difference was observed between the house made of this material and the ones made of hemp concrete, regardless of the air infiltration. However, even if the difference is remarkable, the absolute value is relatively small and might not have a significant impact on the overall energy consumption of the building.

Nonetheless, the energy consumption should be evaluated in context. An increase in the energy consumption also means an increment in greenhouse emissions. To uniformly express the climate impact of different greenhouse gases, the CO_2 equivalent unit is commonly used.

In Italy, the CO_2 emission factors used to convert from energy data to CO_2 equivalents are defined and regularly updated by the Italian National Energy Efficiency Agency ENEA (Agenzia Nazionale Efficienza Energetica). These factors depend on the primary source used to generate electricity and the generation efficiency.

Table 3 - Final energy and mechanical ventilation needed for three different configurations

	Thermal Energy Demand [kWh/(m^2 yr)]	**Energy Needs for Mechanical Ventilation [kWh/(m^2 yr)]**
Hemp brick $n_{50} = 1.5\ h^{-1}$	29.55	0.02
Clay brick $n_{50} = 1.5\ h^{-1}$	31.25	0.28
Hemp brick $n_{50} = 3\ h^{-1}$	46.75	0.01

In Bolzano, there is a district heating plant that provides heating from waste incineration. For this type of energy generation, the CO_2 emission factor is 0.17 $kg_{CO2,equi}/kWh_{fin}$. Conversely, the mechanical ventilation requires electrical energy and the CO_2 emission factor for this conversion is equal to 0.46 $kg_{CO2,equi}/kWh_{fin}$ (Istituto Superiore per la Protezione e la Ricerca Ambientale, 2021). Based on these factors, the associated greenhouse emissions were calculated in CO_2 equivalents. As shown in Fig. 5, the emissions produced by the hemp concrete house with lower air infiltration are 8 % and 58 % lower than the ones associated with the clay brick house and the hemp concrete house with higher air infiltration, respectively. These results indicate that the operation of hemp concrete buildings with CO_2-based demand-controlled ventilation may have a slightly smaller environmental impact than its clay brick counterparts.

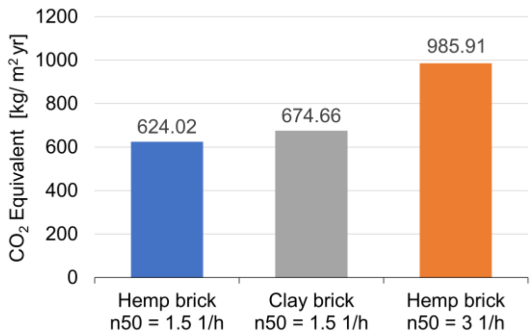


Fig. 5 - CO_2 equivalent emissions for the three different house configurations

4. Conclusion

The research presented in this paper aimed to develop an energy model including the CO_2 absorption by hemp concrete to estimate the potential energy savings achievable in a hemp concrete residential building with CO_2-based demand controlled ventilation and compare them with the energy consumption of the same building made of clay bricks. The key findings are:

- Indoor CO_2 levels in hemp concrete buildings are lower than in clay brick buildings due to the CO_2 sequestration capability of hemp concrete.
- In hemp concrete buildings with high air infiltration rates, the effect of the CO_2 absorption by the hemp concrete wall may be negligible.
- Regardless of the air infiltration, there is a significant difference in the electrical energy required to run the mechanical ventilation and maintain the CO_2 levels under the 1200 ppm threshold between hemp concrete and clay brick houses.
- The operation of hemp concrete buildings with CO_2-based demand-controlled ventilation may have a slightly lower environmental impact than the equivalent clay brick buildings.

4.1 Limitations And Future Work

Estimation of CO_2 absorption rate strongly depends on the temperature, the relative humidity and composition of the hemp concrete. In this study, only one type of hemp concrete was investigated, thus the results obtained can only be considered for hemp concretes with comparable composition. Moreover, CO_2 measurements in the prototype house were conducted from July to October. The data collected during those months were averaged to estimate an average CO_2 absorption rate. However, this time interval does not represent the full year and seasonal variability (i.e., low temperatures during winter) could potentially affect the CO_2 absorption rate. Therefore, the CO_2 absorption rate averaged over the entire year might be slightly different from the estimated value. More studies in which CO_2 is monitored over a longer period including all seasons of the year are needed in order to accurately determine the CO_2 absorption rate of hemp concrete.

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Nomenclature

Symbols

s	Thickness (m)
λ	Thermal Conductivity (W/(m K))
ρ	Density (kg/m^3)
C	Specific heat (J/(kg K))
U	Thermal transmittance (W/(m^2 K))
Ug	Thermal transmittance of glass (W/(m^2 K))
Uf	Thermal transmittance of window frame (W/(m^2 K))

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