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Straw bale: A waste from agriculture, a new construction material for sustainable buildings

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Abstract

Since the beginning of the 21st century, straw-bale buildings are reappearing in the world; however, their thermal performances were not thoroughly investigated up to now. The purpose of this study is to analyze thermal behavior and energy performance of a straw-bale building in Switzerland. Using Pleiades+Comfie Software, building designs have been studied to understand the best way to mitigate overheating risks due to the low heat capacity of straw. Thermal-dynamic results and Life Cycle Assessment conclude that straw bale buildings can be a sustainable alternative in the energy evolution of building construction, due to its low embodied energy and excellent thermal performance.

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1. Introduction

Following the oil crisis in 1973, European countries are engaged in a race toward energy independence. It is called "Energy Strategy 2050" in Switzerland; the objective is reducing the consumption of fossil fuels and replacing them gradually with renewable energies. This strategy affects the building sector enormously since it has the largest share of energy consumption. Recent technological advances have made the embodied energy in construction of buildings more visible and it has become comparable to the energy consumed during the operating life of buildings [1].

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It is around 10 years that the straw-bale buildings have reappeared in the European construction market. Often self-built, these buildings sometimes made only with straw bales and soil arouse interest for their energy and sustainability performance. In this context, the Municipality of Lausanne in Switzerland has decided to make an administrative straw-bale building in 2011 – that is to say without any structure but only straw – on the site of the service Parks and Areas of La Bourdonnette. An overall energy assessment of the construction was required to compare its consumption with the Swiss energy labels and the standard solutions. Straw is rarely used and data on that is quite scattered, which requires some effort for gathering information before modelling the building. This study will present thermal characteristics of straw as a construction material and uses them in the thermal model of the building, using Pleiades+Comfie Software. Results are used to assess the energy performance of the building ECO46 against some common Swiss administrative buildings. Through life cycle assessment (LCA), using SimaPro software, investigation was carried out to show the evolution of energy consumption from a building constructed in 1975 to the current construction and to evaluate the main environmental impacts of straw bale building.

2. The load bearing straw bale building ECO46

The idea of creating the straw building ECO46 was born thanks to the initiative of the "Strawd'laBalle" collective, to promote straw as an innovative building material [2]. Following the destruction of this "wild" building due to legal issues, the city of Lausanne requested a feasibility study about straw in 2009. Since the study promoted straw as a good solution, the municipality launched the construction of a straw bale building, functioning as a new administrative building for the service of Parks and Areas. According to the specifications, the building provides space for 7 workstations, 2 conference rooms (16 and 6 places), a little restaurant area and a kitchen. The main objective was to achieve the requirements of the Minergie-P-ECO® Swiss label. Following the preliminary study conducted by the Municipality of Lausanne [3], the choice of the technique Nebraska (load-bearing straw-bale building) was selected to achieve the label performances, because of the required thickness the straw wall (80 cm).

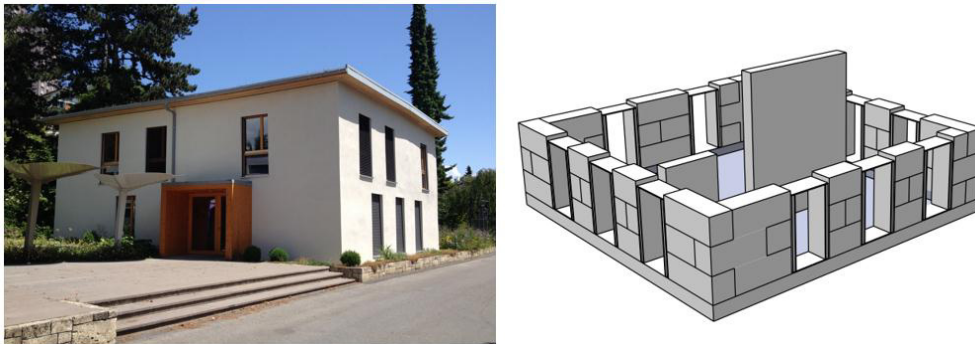


Fig. 1. (left) Picture of ECO46 – Lausanne, (right) Simulated building cross-section (ground floor)

The ECO46 building has been made mainly with ground/soil (central wall made with adobe, soil with a layer of ground, coating with lime and mud, vegetated roof), as well as wood from the forests surrounding Lausanne (intermediate floor, beams and structural) and finally with wheat straw (walls and roof insulation) in order to have the lowest environmental impact and to meet the requirements of Minergie-P-ECO® in terms of embodied energy. The heating system is based on a pellet stove of 6 kW and the transfer of heat through natural convection in the building and conduction in the inner walls. In a spirit of bio-climatism, the architects had planned vegetal occultation on the main facades but the idea has been replaced by automated external venetian blinds to meet the requirements of Minergie-P®. All the openings are made of triple glazing, the flat roof is provided with an extrusion called "Skylight" which supports 19 m² monocrystalline photovoltaic solar panels and has a north facing automatically opening at night during the summer, allowing natural ventilation through a chimney effect. The regulatory air renewal is ensured by a mechanical ventilation double flow required for obtaining the label. Lighting and electric devices have been designed to meet the requirements of Minergie-ECO®, mainly using low consumption bulbs and high performance kitchen devices. Finally, ECO46 building obtained Minergie-ECO® label which impose a tightness value of $Q_4 \leq 0,75 \text{ m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-2}$.

3. Controversy of straw thermal characteristics

3.1. Thermal conductivity and capacity of straw

It is not possible to set a unique value the thermal conductivity and heat capacity of straw, since many factors can affect its thermal properties, such as the type of straw employed, the water content, the density of the bale, the void between each bale, the density of the coating into the interstices, the orientation of fibers, the nature and thickness of the coatings. From the summary of the available values, it is possible to show that the range of straw thermal conductivity for any density and moisture content is contained in the interval given in Eq. 1 [4, 5]:

$$0,052 [\text{W.m}^{-1}.\text{K}^{-1}] \leq \lambda \leq 0,12 [\text{W.m}^{-1}.\text{K}^{-1}] \quad (1)$$

The straw heat capacity will be within the following range given in Eq. 2 [6, 7]:

$$1338 [\text{J.kg}^{-1}.\text{K}^{-1}] \leq C_p \leq 2000 [\text{J.kg}^{-1}.\text{K}^{-1}] \quad (2)$$

3.2. Thermal effusivity and diffusivity of straw

The thermal effusivity of a material characterizes its ability to exchange thermal energy with its environment [8]. Using the different intervals previously found in Eq. 1 and Eq. 2, we could give a range for straw bale effusivity given in Eq. 3.

$$417 [\text{J.K}^{-1}.\text{m}^{-2}.\text{s}^{-1/2}] \leq \text{Eff} \leq 775 [\text{J.K}^{-1}.\text{m}^{-2}.\text{s}^{-1/2}] \quad (3)$$

The thermal diffusivity characterizes the ability of a material to transmit a temperature signal from one point to another of this material [9]. The thermal diffusivity characterizes the thermal inertia of a material, that is to say its predisposition to keep its initial temperature a long time when a thermal disruption occurred. Data previously found in Eq. 1 and Eq. 2 allow us to determine also the interval for straw thermal diffusivity given in Eq. 4.

$$0,1 \times 10^{-6} [\text{m}^2.\text{s}^{-1}] \leq \text{Diff} \leq 3,6 \times 10^{-6} [\text{m}^2.\text{s}^{-1}] \quad (4)$$

The straw effusivity interval shows that its behaviour is quite similar to wood thermal behaviour (around $400 \text{ J.K}^{-1}.\text{m}^{-2}.\text{s}^{-1/2}$). Warming up building straw walls will be rapid and interior temperature should increase fast using heating system. However, the low diffusivity of the straw does not allow the wall to accumulate heat quickly. Therefore, the building could be subject to quick overheating if there are too intense solar gains in summer or renewal of hot air by opening the windows.

3.3. Determination of ECO46 straw conductivity and thermal capacity

As a set value was needed to complete a thermal-dynamic model of the straw bale building ECO46, a method has been developed to search the best value. As the wall was very thick and insulated, practical methods for determining U value of the wall like using a K-meter, have not produced satisfactory results. The only available and accurate result of “building use” was its yearly consumption of pellets. Considering the others parameters (design, behaviour and schedule) as proven using all the notes and surveys results produced on site, the decision was taken to create a dynamic thermal model with straw conductivity as the only variable parameter. First the thermal-dynamic model was created using all the on-site available weather data for 2013-2014, windows characteristics, internal devices, heating system regulation, clock and flow of the mechanical double-flow ventilation, electrical devices (lights and computers), hot water consumption and also human behaviour (schedule of each meeting and standard schedule for each employee). The only parameters studied were the conductivity and heat capacity of the straw in the intervals determined in the first part of the study. For each variation ($0.005 \text{ W.m}^{-1}.\text{K}^{-1}$ for conductivity and $100 \text{ J.kg}^{-1}.\text{K}^{-1}$ for heat capacity), model consumption results were compared with the real pellets consumption of 600 kg for 2013/2014 winter. Matrix of the model results shows that ECO46 straw conductivity gives the closest consumption results with the real ones for $0.08 \pm 0.005 \text{ W.m}^{-1}.\text{K}^{-1}$. Although changes in the heat capacity are not significant, because of the thickness and high insulation of the walls, the value $1.8 \pm 0.1 \text{ kJ.kg}^{-1}.\text{K}^{-1}$ gives also the best results comparing the simulation and the real data. Both of these values had been used for the rest of the study.

4. Energy performance of ECO46 straw bale building

Using the straw characteristics from the previous part, the calibration of thermal-dynamic model was performed against two sets of temperature data in winter and summer period of the 2013-2014 year using the ASHRAE 14-2002 comparison method. For each set of temperature, occupation, internal gains, shading devices, airflow of controlled ventilation, and air exchanger efficiency had been calibrated to get the most accurate model. The final model has respectively a NMBE (Normalized Mean Bias Error) of -0.01% and CV (RMSE) (Coefficient of Variation of the Root Mean Squared Error) of 3.79% for one set and -0.08% and 3.31% for the other set of temperature. These statistics are good compared with those estimated as valid in ASHRAE 14-2002 Guide that describes a good simulation below 10% for both criteria. To estimate the heating average energy consumed by ECO46, the calibrated model was subjected to the weather file proposed by the Meteonorm software for Lausanne, representing the average climatic conditions from 1996 to 2005. The results given by the model have a consumption of 3800 kWh of final energy, therefore, a consumption of $12,7 \text{ kWh.m}^{-2}.\text{an}^{-1}$ of final energy or of $8,9 \text{ kWh.m}^{-2}$ per year of primary energy as ECO46 has a surface area of 300 m^2 and the factor for wood primary/final energy is 0,7 in Switzerland in 2014. First, it is possible to compare this result to the value 111 kWh.m^{-2} per year of primary energy for existing administrative Swiss buildings [10]. The study shows that ECO46 consumes less than 10% energy consumed by standard office building. Electricity efficiency assessment of the building shows that the annual mechanical ventilation, Domestic Hot Water and lighting consumption (around 2080 kWh per year) is offset by 19 m^2 of the mono-crystalline solar panels. It can be concluded that, in terms of energy, the ECO46 energy performance for heating is excellent compared to most of the Swiss administrative buildings. Regarding thermal comfort, the Predicted Mean Vote (PMV) model was used to set the temperature of discomfort [11]. Three variable factors are considered in this study: air temperature; mean radiant temperature and relative humidity. The discomfort rate for a room is calculated as the ratio between the number of occupied hours out of the thermal comfort zone and the number of total hours of annual occupancy. In terms of overheating, occupied room presents a level of discomfort from 3.7 % (42 h) for the meeting room at east to 12.1% (246 h) for the office located at south. These results are slightly high for an administrative building but can be explained by the absence of air-conditioning system and the low inertia of straw bale buildings.

5. Thermal dynamic behavior of ECO46 straw bale building

5.1. Straw bale building inertia

As straw is a light material (250 kg.m^{-3} in the case of ECO46) compared to conventional structural material as concrete (about 2200 kg.m^{-3}) and most of straw bale buildings present some problems with overheating. In fact the issue of inertia is redundant in many cases in literature and seems to be confirmed by ECO46 results. As it was described previously, architects had taken in account this issue by adding a massive adobe wall in the middle of the building, a concrete slab and a layer of soil on the ground and the first floor. As there is no inertia effect from the wall, the only heat capacity of the building is coming from the interior mass. The results give a thermal capacity of $286 \text{ kJ.K}^{-1}.\text{m}^{-2}$ for the entire building, which may be compared to heat capacity classification of Switzerland [10]. We notice then that ECO46 can be categorized in buildings with medium inertia. The calculations give a thermal capacity of $205 \text{ kJ.K}^{-1}.\text{m}^{-2}$ in the absence of the wall; hence its category would be something between light and medium. This means that the adobe wall has a real effect on the building since it represents 28% of the total heat capacity of the building. It allows a lower heating consumption of the building in winter and lowers the inside temperature around $0,5^\circ\text{C}$ for high exterior temperatures thanks to its thermal inertia. The second valuable finding is about the clay wall coating; in the world of straw bale builders, there is lack of information about the added thermal capacity of the clay coating on walls. As the coating has a medium heat capacity (around $1500 \text{ J.kg}^{-1}.\text{K}^{-1}$), the impact of its thickness on temperatures in summer is near zero. However, increasing the thickness of the coating provides additional thermal resistance that results in a reduction for heating consumption. Therefore adding the clay coating reduces the heating demand, though not that effect on overheating. Meanwhile the coating guarantees a better sustainability of straw by protecting it from rodents and water projections.

5.2. Management of straw bale buildings overheating

The study has shown that straw bale buildings are very sensitive to solar gain and the effective management of blinds can bring a greater comfort to users. To meet the Minergie-P® label, architects provided automatic external blinds controlled by a clock to all windows. While users of the building well mastered heat solar gain as they had been aware of the building's sensitivity, a proper timing of blinds allows a significant comfort improvement in summer as the inside temperature can be lowered by 2°C without using air conditioning system. For example in summer, it is interesting to let all the blinds closed until a person opens it and to not have solar gains in empty rooms during the day. As the responsibility of managing these solar gains is up to users, the analysis of straw bale building shows also that the use of triple glazing is an interesting choice. In fact it permits to limit solar gains without users control due its low solar factor and reduce heating energy consumption because of their high thermal insulation.

6. Life Cycle assessment of straw bale Building

6.1 Evolution of buildings consumption sectors since 1975 until today

This section focuses on the evolution of total energy consumption of a building during its life from 1975 to today. The objective was to compare the importance of embodied energy with the energy consumed during the life and destruction of the building and compare straw bale building with standard solution. This Life Cycle Analysis (LCA) was conducted using SIMAPRO software that uses the database EcoInvent v2 and permits to calculate construction and destruction energy consumption. First of all, it is considered that resources are available in the environment. Only the necessary energy that has been expended to extract the raw material and transform it to create building materials is taken into account. The transport of materials to their site of production to the construction site is also taken into account. However the energy expended and the loss of material during the construction process is not taken into account. To trace this evolution, seven scenarios were modelled using the same ECO46 geometry and corresponding to key years of the building energy standards in Switzerland. Scenario 1 presents ECO46 building made only with 10 cm concrete for each side, with simple glazing, infiltration rate of 1 vol.h⁻¹ and old incandescent lamp. The scenario 2 presents the building with 5 cm of polystyrene insulation added with a conductivity of 0,04 W.m⁻¹.K⁻¹, double glazing and an infiltration rate of 0,8 vol.h⁻¹. Scenario 3 presents the building with 15 cm of insulation added, simple flow ventilation and infiltration rate of 0,4 vol.h⁻¹. Scenario 4 respects all requirements of actual SIA 380/1 (2009), using polystyrene insulation and double flow ventilation. Finally, scenario 5 presents ECO46 building with the same performance of ECO46 but constructed in concrete and 35 cm of polystyrene insulation meeting Minergie-P® requirements (triple glazing and energy saving bulb). Scenario 6 presents ECO46 building built with straw. A seventh variant is proposed with the incineration of waste at ECO46 end of life replacing conventional fuel consumption as the recycled straw is used in a district heating system. Each scenario has been modelled with Pleiades Software to determine the energy consumption for heating during the life of the building using the same Meteoronorm file for Swiss climate. The lighting, ventilation and hot water are taken into account in computing the electricity consumption. The lifespan of the building is 60 years.

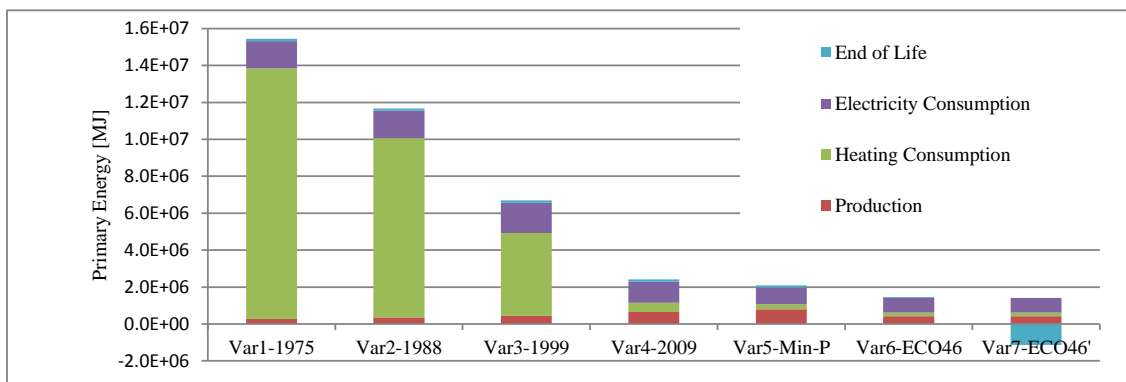


Fig. 2. Evolution of energy consumption depending on the date of construction of ECO46

Results of Fig. 2. show that in 1975 the heating sector was the leading energy consumption sector. The improvement of building envelope performance led to a drastic reduction in the consumption and has been replaced since 2009 by the electricity sector. The embodied energy becomes more and more important after 1999 due to the increasing use of insulation in buildings. The results show that only two sectors remain dominant with buildings constructed since 2009 and meeting Minergie P requirements: energy of construction and electrical power. If we consider that the electricity is now minimal with the latest performance of ventilation equipment and the use of energy-saving lamps, it seems that only the embodied energy of materials can be reduced in the energy balance of the building. Few materials can replace the homogeneity and performance of conventional materials such as concrete or plastic. In the case of ECO46, straw bales replace both structural and insulation part. The study shows that the use of straw reduces the impact of construction in the life cycle assessment of the building by nearly 50%.

Since the evolution of labels is towards including the embodied energy of buildings, it is reasonable to consider straw as an innovative material, which may find its place as a new building material. In the case of incinerating the straw at the end of its life cycle (Var7), then the total energy consumed becomes negligible compared to other scenarios as it is shown in Fig. 2, which present a total consumption of 250 GJ for the entire lifecycle of ECO46.

7. Conclusion

According to the results, the ECO46 building is well designed. The thermal mass of the central adobe wall enables to save more energy while reaching to a better thermal comfort with less variation in the indoor temperature. The thermal analysis showed that the possibility of natural night-time ventilation through the opening on the "skylight" gives to ECO46 the ability to offer a pleasant summer thermal comfort without using air conditioning. The proper ratio of openings, having triple glazing and the use of double flow ventilation allow ECO46 to count among the most energy efficient buildings in the category of administrative structures, with excellent comfort and indoor air quality. Finally, it is important to underline that all users seem satisfied with the use of the building.

The straw constructions are not more expensive than those made with traditional materials and their prices could lower in the coming years with the increasing number of professionals in this field. In addition, straw-bale construction is simple which permits self-construction. The assessment of ECO46 confirms that this type of construction has characteristics very similar to the standard low energy consumption constructions, though it requires special attention to cope with overheating during summer. It must be remembered that the straw is a waste product of agriculture that is often buried or burned by farmers. The use of straw seems an appropriate response against the depletion of finite resources. The straw is therefore an interesting alternative comparing to commonly used construction materials such as wood or masonry.

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References

- [1] SIA 2032, L'énergie grise des Bâtiments, 2010
- [2] Collectif Straw d'la balle: La maison de paille de Lausanne, Edition de la Lanteur, 2013
- [3] ATBA, La construction en botte de paille, Étude de faisabilité, Lausanne, mars 2009
- [4] <http://www.legifrance.gouv.fr>
- [5] A. De Bouter, B. King: Concevoir des Bâtiments en bottes de paille, p. 229, Eyrolles, 2009
- [6] <http://www.compaillons.eu>
- [7] C. Atkinson: Energy Assessment of a Straw Bale Building, 2008
- [8] http://en.wikipedia.org/wiki/Thermal_effusivity
- [9] http://en.wikipedia.org/wiki/Thermal_diffusivity
- [10] SIA 380/1, L'énergie dans le bâtiment, 2009
- [11] Dear, R.J., and G.S. Brager "Towards an adaptive model of thermal comfort "ASHRAE, 1998