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Physical-thermal straw properties advantages in the design of a sustainable panel-type construction system to be used as an architectural dividing element

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Abstract. The walls in architecture determine the energy behavior of a home, the physical and thermal properties of the building elements are capable of controlling the energy transfer of to the interior, avoiding dependence on artificial cooling systems, which increase energy consumption. The research takes advantage of the physical-thermal attributes of straw, considering its use as a material, presenting sustainable constructive solutions for the walls configuration in rural houses with a warm tropical climate. The proposed design starts from identifying the properties of materials with a low carbon footprint such as straw, wood, cardboard, which are viable due to their low weight and easy obtaining. The result is the modular design of the EcoStraw panel that consists of a compressed straw matrix, embedded in a module whose function is to isolate the heat conduction between the interior and exterior, a modular and wooden support structure with the aim of giving structural stability in the stack and a cardboard laminate lining that acts as an interior closing surface. The constructive solution can be industrialized, economical and with a low impact on the environment.

1. Introduction

A large percentage of total carbon dioxide (CO_2) emissions worldwide comes from the construction industry, associated transportation, and dependence on cooling and / or heating equipment [1]. This has generated the idea of implementing environmentally friendly materials and thus mitigate the carbon footprint that conventional materials such as metal, synthetic, and ceramic produce in their elaboration and residual stage after being demolished [2,3]. Natural organic products are of great potential to mitigate these problems, recognizing straw as one of the most valuable for its easy obtaining due to high agricultural activity locally and globally. In addition, to be an element that has the ability to absorb CO_2 during its growth as well; 10 kg of wheat straw absorbs 14 kg of carbon dioxide, which they retain throughout their lifetime [3].

The low environmental impact of straw as well as the high agricultural activity worldwide (wheat, rice, barley, etc.), it generates a large amount of waste, considering it as a suitable by-product for the field of construction, because the background makes evidence isolation and structural application showing thermal and acoustic characteristics [4]. Due to the fact that antecedents show Table 1, that the straw physical properties confer structural and thermal insulation advantages due to its low conductivity, surpassing traditional and non-traditional materials [5]. This research focuses on identifying these attributes, especially the physical-thermal ones of the material, to later implement them in the design of a sustainable panel-type construction system as an architectural dividing element. Taking into account studies that highlight the design of insulated products to optimize thermal efficiency, thus ensuring the internal comfort of the space.

This research aims to analyze the way in which the physical-thermal properties of straw have been used in traditional construction systems such as Nebraska and Greb, until reaching prefabricated panels of the same material, carrying out the compilation of basic aspects such as their constructive characteristics and a breakdown of materials that complement it, ending with a proposal for a panel-type modular design as a dividing element for architectural projects optimizing thermal comfort, the execution time of the work, the space for installation, and maintenance of internal networks, in addition to minimizing the square meters that the construction methods mentioned occupy.

Table 1. Physical-thermal properties of materials.

Material	Density (Kg/m^3)	Conductivity λ (W/mK)
Compressed soil wall [6]	1.400	0.600
Compressed soil block [6]	1.700	0.810
Adobe [6]	1.200	0.460
Straw bales [7]	60.00	0.067
Mass concrete with aggregates [8]	2.400	1.630
Solid brick wall [8]	1.800	0.870

2. Methodology

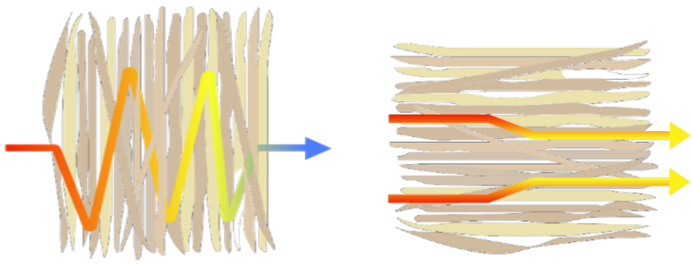
The present work consists of three main phases: the first involves a study of the current state of the art corresponding to the recognition of the physical properties of straw and the straw panel construction technique, in order to obtain a better understanding of it. The physical properties and mechanical resistance of the straw are two variables that were crossed to identify the viability of the designs investigated and prepared by different companies interested in this field, in order to compare them and thus be able to identify their strengths and weaknesses to finally present the development of a modular design that takes into account the shortcomings that appear in the previous models, creating a series of fundamental criteria which guide the design process, highlighting thermal insulation as a bioclimatic benefit in the configuration of homes for the rural area with a warm tropical climate.

2.1. Straw physical-thermal properties

Regarding the thermal behavior of straw, previous research results show that adding passive thermal insulation strategies from the design process in architecture is an effective method to generate sustainable responses in low-cost and thermally efficient products. Understanding thermal conductivity as the physical property that describes the ability of a material to transfer heat by conduction, that is, by direct contact and without exchange of matter. Thermal conductivity has the function of transmitting heat uniformly through the material. Chemically, a molecule has specific kinetic energy and when it collides with another, the one that is hottest will transfer heat to the coldest, the effect that results from all the constant collisions between a molecule with a higher temperature to a lower one will be heat conduction [9]. Accordingly, straw offers the ability to be an effective thermal insulator by its nature, due to the blades or fibers present in it, given its porosity at the compaction time. It is important not only the position of the bales but also the blades direction in the straw bale, positioning the previous ones perpendicular to the heat flow and thus maximizing the trajectory, contrary to what happens when they are located in the parallel, as shown in Figure 1 where the Figure 1(a) show the perpendicular direction to the thermal flow and the Figure 1(b) show the parallel direction to the thermal flow, since the above favors the passage of heat through the interior tubular cavities [1].

2.2. Traditional construction techniques in straw

The standardization of this method was based on the “Norma Técnica Colombiana” NTC-ISO 20481:2008 [10], which is the reference method for the determination of caffeine by high performance liquid chromatography (HPLC), in which the aspects to take into account for the determination of caffeine by this technique are shown.



(a) (b)

Figure 1. Direction of the blades in the straw bales. (a) perpendicular direction to the thermal flow; (b) Parallel direction to the thermal flow.

2.2.1. Nebraska. The Nebraska system uses self-supporting straw bales as a construction system, it is versatile in terms of firmness and resistance to be used in the field, as long as it is taken into account certain characteristics such as humidity, compression and shape. In addition, this straw bale has the function of receiving the loads derived from the roofs without the use or support of a construction system, locating the straw bales by rows and in the form of blocks, joining with stakes, and compressing the straw walls previously to the roof installation [1].

2.2.2. Greb. The Greb technique combines several components: straw bales are used as filler material in a wooden load bearing structure reinforced with metal ties between each layer of straw bales. These are processed between the wooden posts. Finally, a light mortar is applied between the wooden structure against the straw bales [11].

2.3. Modular techniques
The following techniques present basic and essential characteristics of the designs developed by each company mentioned below in order to make a comparison of necessary aspects for the panel EcoStraw model development.

2.3.1. ModCell®. ModCell® panels are built and tailored to each individual project they are used on. However, the standard module is three bales wide, enclosed by a laminated wooden frame box, with an overall size of 3 m width by 3.2 m height, weighing 1.7ton. Transport affects size, where width is the most critical dimension. Several tests have been conducted on ModCell® panels, mainly through the ongoing research program in conjunction with the University of Bath. The U value or thermal transmittance of a ModCell® wall ranges from 0.11 W/m^2·K - 0.19 W/m^2·K, depending on the type of panel chosen [12].

2.3.2. Ecococon. The size of the panels varies between 0.4 m – 1.2 m in width and 0.4 m - 3 m in height. However, they can be designed and adjusted to each specific project, but they are often rectangular in shape. Cutouts, such as doors and windows, are not built into the module; instead, they are built around their planned position. An Ecococon wall has a U value of approximately 0.11 W/m^2·K. The panels are plastered on the inside, while the outside is wrapped in an airtight vapor-permeable layer. This layer should be covered with wood fiber boards, at least 60 mm thick [12].

2.3.3. Isopaille. IsoPaille designs its straw modules for each specific project. However, the limit is a maximum weight of three tons per panel, and the measurements must not exceed 10 m width and 3.6 m height. The U value for the wall panels is 0.11 W/m^2·K. A wooden I-beam is constructed vertically on each side of the straw bale, with horizontal tacks at the bottom and top, holding the I-beams together, creating a frame [12].

2.4. Design process of the EcoStraw panel as an architectural dividing element
The EcoStraw panel model considered the following criteria for the design elaboration in order to have a specific guide of needs and priorities to address as shown in Table 2.

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Table 2. Design criteria in the straw panel prototype.

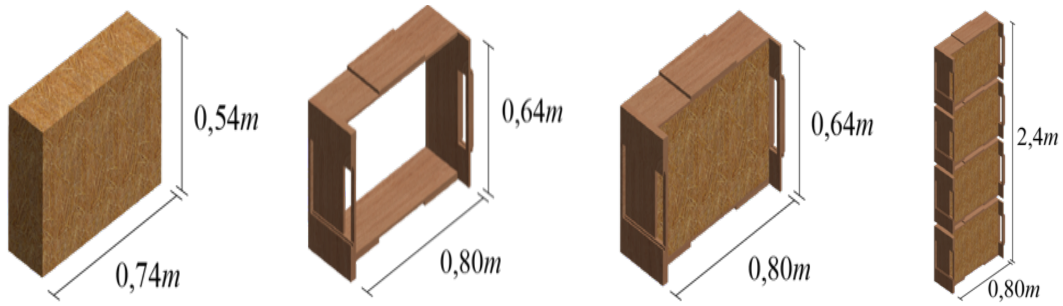
No.	Features
1.	Thermal resistance
2.	Integrated structural system in modules
3.	Modular panels
4.	Flexible installation in situ
5.	Flexible shape and size
6.	Contribution to the circular economy
7.	Ventilated chamber for internal installations
8.	Easy transport of the prototype

The data referenced in Table 3 where the density and thermal conductivity of straw bales are mentioned, that is, the projected dimensions in the design proposal, consider at the moment of compression of the straw a density of approximately 60 kg/m^3 and related to the thermal conductivity of 0.067 W/mK. fulfilling with the previous requirement to achieve the necessary thermal resistance, in a volume of de 0.74 m x 0.20 m x 0.54 m, taking into account that a wooden structure will be made that will form the final module, as shown in Figure 2. The module has an air chamber as a support for internal networks located between the straw bale and the final cardboard lining, helping to further delay the thermal transmission of the panel.

Additionally, the panel measurements regarding its height may change in terms of the arrangement of modules, suggesting four modules to complete a standard panel height of 2.4 m in this situation, as shown in Figure 2, where the Figure 2(a) show the compression of straw, the Figure 2(b) show the wood structure, Figure 2(c) show the final module and the Figure 2(d) show the standard panel height.

Table 3. EcoStraw panel module components and physical-thermal characteristics.

Material	Width (m)	Conductivity λ (W/mK)
Straw bale [7]	0.200	0.067
Air chamber / installations [9]	0.097	0.026
cardboard [13]	0.003	0.065



(a) (b) (c) (d)

Figure 2. EcoStraw panel components in the design process. (a) compression of straw; (b) wood structure; (c) final module; (d) standard panel height.

2.5. Thermal analysis of the EcoStraw panel

The heat transfer diagram in the proposed module is analyzed from the section represented in Figure 3 which is made up of three moments that relate the design dimensions (width) since the thickness in each layer of the panel proposed versus the material properties in which this compound has a direct impact on the thermal resistance and therefore on the decrease in temperature, going from 36 °C outside to the average comfort temperature of de 23 °C inside. By altering the dimensions (width) and by including an air chamber within the section of the module, a set of variables is achieved from the architectural design that allow delaying heat transfer by conduction.

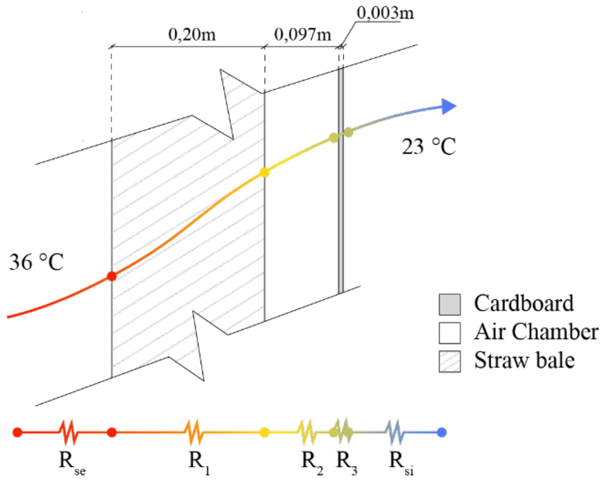


Figure 3. Heat transfer diagram in the section of a EcoStraw panel module.

To determine the incidence of the architectural design from the thermal transmittance or U value, we started by analyzing and identifying the materials thermal properties and the environment near the panel, followed by the calculation that expresses the Equation (1).

$$U = \frac{1}{R_t}. \tag{1}$$

Where, U is the thermal transmittance. R_t is the total thermal resistance of the panel, which is calculated by expressing the Equation (2):

$$R_t = R_{se} + R_1 + R_2 + R_3 + R_{si}. \tag{2}$$

Rse and Rsi are the surface thermal resistances for indoor air 0.04 $m^2 \cdot K/W$ and outdoor 0.13 $m^2 \cdot K/W$ [13]. R 1, R2 and R3 refer to the straw bale individual resistance, air chamber and cardboard materials respectively, which are found as a result of Equation (3).

$$R = \frac{e}{\lambda}. \tag{3}$$

Where, R is the thermal resistance of each material; e is the material thickness (m) and λ is thermal conductivity according to the material (W/K·m) take the values from Table 3. Substituting the values in order of Equation (3), Equation (2), and Equation (1), we obtain as a result the Value $U = 0.0608\ W/m^2 \cdot K$.

3. Results

The results obtained in the equations are reflected in the design of the constructive solution based on the EcoStraw panel prototype allowing the U values of the proposed solution to be compared against the others previously analyzed, showing that a panel composed of the air chamber and the coating they insulate even more than just straw as the panel matrix as shown in Table 4.

On the other hand, the EcoStraw panel design shows great versatility in terms of its easy installation and use of space, due to the fact that its panel-type wooden structure as well as the other modular techniques mentioned make it more stable and with the possibility of reducing its dimensions, as shown in Figure 4 compared to traditional Nebraska and Greb systems [12], which use formatted bales of straw 2400 mm x 1200 mm x 700 mm while this proposal only reaches 800 mm x 300 mm x 2400 mm, thus maximizing the useful area in the configuration of architectural spaces by up to 75%, preserving and optimizing the thermal insulation characteristics.

During the development of the EcoStraw panel design, it was concluded that the best way to modulate this piece was through inserts so that its installation is easier, solving the current problems of some modular techniques and it is possible to propose a room in cases of emergency, disarm / arm or having walls according to bioclimatic needs.

Table 4. Comparison of U values of construction and / or insulating systems in straw.

Material	U ($W/m^2 \cdot K$)
ModCell®	0.1900
Ecococon	0.1100
Isopaille	0.1100
EcoStraw panel	0.0608

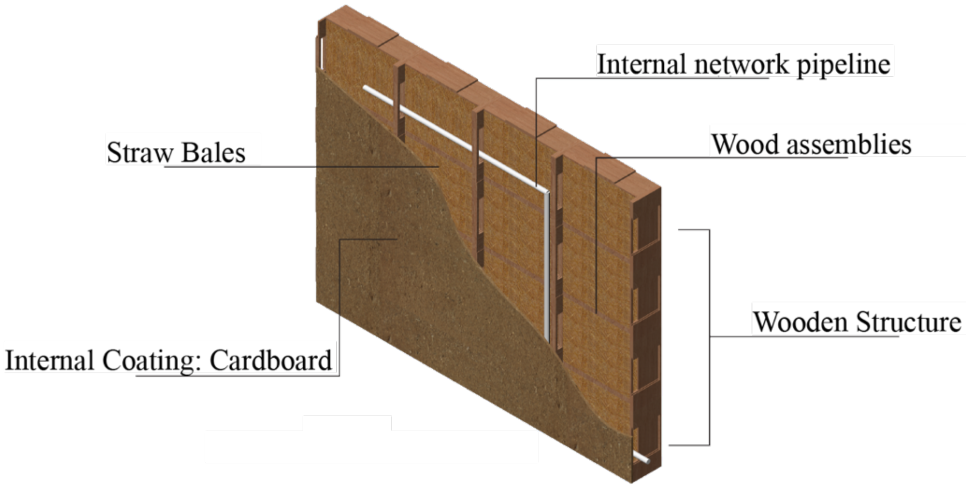


Figure 4. Composition of an architectural dividing wall from the EcoStraw panel.

4. Conclusions

The EcoStraw panel proposed development integrates different disciplines in order to conceive a comprehensive idea of an architectural and sustainable constructive solution from the physical-thermal analysis of the materials to reaching decision-making in terms of design. The previous analysis and the proposed design conclude that the EcoStraw panel is less conductive of heat since the coefficient of thermal conductivity of the straw embedded in the wood panels is better. On the other hand, the EcoStraw panel solves disadvantages presented by traditional Nebraska and Greb construction systems and certain existing modular techniques, by ruling out the need to drill straw bales to carry out the installation and maintenance of internal networks, due to its ventilated air camera, also showing minimum values in its U value, as shown in Table 4, based on the proposed design. It should be noted that this element contributes to diversify and expand application opportunities to continue studying this rarely used material and to recognize the constructive options that it offers in housing projects based on sustainable principles as it is a reusable agricultural product, with low environmental impact and easy obtaining much of our Colombian territory and the world. Finally, the implemented methodology constitutes a starting point for design and innovation processes in the sustainable construction industry, legitimizing the social, cultural, economic, and thermal comfort value of construction with vernacular materials.

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