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Comparative analysis of thermal and mechanical properties of straw and compressed earth blocks versus traditional masonry products

Análisis comparativo de las propiedades térmicas y mecánicas de bloques de paja y tierra compactada versus sistemas constructivos de mampostería tradicional

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Abstract

Straw is a material with benefits of resistance to humidity, thermal and acoustic insulation. Therefore, this paper studies thermal and mechanical properties of a constructive solution manufactured with straw and compressed earth, in order to compare it with traditional systems. The methodology is applied research and was developed in 3 phases: characterization of thermal and mechanical properties of the material, analysis of the temperature behaviour of 4 product types through simulations in ANSYS and development at 1:1 scale of 4 block types. The results obtained are contrasted with literature of traditional systems. The results show improvements in thermal performance of the composite material of straw and compressed earth, compared to products made of clay, concrete, adobe, among others. Nevertheless, the characterization of mechanical strength is inferior to traditional products. Notwithstanding, the material meets minimum non-structural standards. Finally, temperature behaviour of perforated block typologies reduces interior surfaces 7.31 °C, compared to solid typologies. The feasibility of implementing new construction solutions is based the recognition of the properties of the material and its benefits for architecture.

Keywords: Thermal insulation, block, energy efficiency, straw, constructive solutions.

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Resumen

La paja es un material para la construcción milenario con beneficios de aislamiento térmico, acústico y resistencia a la humedad. Sin embargo, requiere complementarse con otros materiales y/o sistemas estructurales para ser autoportante. Partiendo de las ventajas anteriores, este trabajo estudia las propiedades térmicas y mecánicas de una solución constructiva para un sistema alternativo de paja y tierra compactada, con el fin de compararlo con sistemas tradicionales. La metodología es investigación aplicada, la cual se desarrolló en 3 fases: caracterización de las propiedades térmicas y mecánicas del material, diseño y desarrollo a escala 1:1 de 4 tipologías de bloque y, análisis del comportamiento de la temperatura según los diseños a través de simulaciones en ANSYS. Además, el estudio comparativo de los sistemas tradicionales se desarrolla a lo largo de la investigación, de tal manera que los resultados obtenidos se contrastan con la literatura. Los resultados demuestran las ventajas de soluciones constructivas compuestas de paja y tierra compactada gracias a las mejoras del rendimiento térmico. La caracterización de propiedades térmicas del material de estudio resalta la baja conductividad en comparación con productos de arcilla, hormigón, adobe, entre otros. Sin embargo, la caracterización de resistencia mecánica es inferior a los productos tradicionales. No obstante, la muestra cumple los estándares mínimos no estructurales para vivienda rural. Por último, el comportamiento de temperatura de las tipologías de bloques con perforaciones reduce hasta 7.31°C las superficies interiores, comparados con las tipologías de bloque macizo. La viabilidad de implementar nuevas soluciones constructivas se sustenta en el reconocimiento de las propiedades del material y sus bondades para la arquitectura.

Palabras clave: Aislamiento Térmico, Bloque, Eficiencia Energética, Paja, Soluciones Constructivas.

Introduction

Rural housing in Latin America is a social and economic question that involves the development of the countries from the peasant communities. In countries such as Mexico, there is a policy to incorporate the rural population through the special concurrent program for sustainable rural development [1]. On the other hand, in Argentina, they have developed a sustainable prototype for rural housing in order to respond to the needs of the rural environment, such as social, economic, cultural and environmental aspects [2].

In this context as well, rural housing in Colombia is also a focus of study not only from architectural perspective, but also reflections about planning of rural habitat. In the first place, efforts have focused on the study of rural dwelling basic considerations in terms of function, materials, using of resources, population identity in order to offer sustainable guidelines that guarantee the improvement of the quality of life of peasants. Consequently, several models of rural social housing emerge in Colombia based on solving problems such as overcrowding, poor materials, inaccessible resources, lack of basic service coverage, among others [3]-[7].

Along that order of ideas, the need for rural housing demands new architectural and constructive solutions, and also materials and products accessible to the different communities in rural areas. One of the products that is most in line with the expectations of the problem raised above is the compressed earth block, due to the environmental and economic advantages in the manufacturing processes and the accessibility to the raw material [8]-[10].

The main properties studied in compressed earth blocks research are thermal, acoustic, fire resistance and all those related to the safety and comfort of the end user [11]. Furthermore, another main focus of study is the resistance to compression because their function in the conformation of masonry walls. The main resistance tests they perform are splitting tensile strength, elastic modulus and fracture energy [8].

The development of earth blocks has evolved the field of materials research due to innovation in the use of agro and non-agro industrial waste. The literature records that the standards and methods for testing blocks vary according to the type of waste used because factors such as fiber size and soil composition affect [11]. Teixeira et al. [10] also support that the size of material particles used for compressed earth blocks influences the porosity, water absorption, durability and thermal behavior.

The optimization of the distribution of particles of the material (soil) is a strategy to improve the properties of construction units. The foregoing means that, in the case of unifying the size of smaller particles, the results improve aspects such as mechanical resistance through the reduction of porosity, nevertheless, the thermal transmittance will increase. For this reason, the relationship between mechanical and thermal properties must be taken into account [10].

The success of the compressed earth blocks lies in the soil stabilizer, because it guarantees the mechanical properties of the product. Glass waste is a viable alternative that improves mechanical resistance with only 4% additive in the base mixture. Even, low percentages of glass residue results great mechanical behavior with less porosity [12].

On the other hand, the presence of fly ash in compressed earth blocks improves compressive strength of the products between 6 and 61% compared to the blocks that only use cement stabilizer, notwithstanding, fly ash does not work without cement. Therefore, authors concludes that the optimal formulations of compressed earth blocks with fly ash and cement are 10%-3%, 20%-5% and 30%-10%, respectively [9].

In the same vein, Sore et al. [13] have developed polymers with local materials which work as binders for the manufacture of blocks with compacted earth in Burkina Faso. The benefits are not only environmental due to the reduction of CO2 emissions, but also related to physical and thermal properties. First of all, the geopolymer improves the cohesion of the particles by about 15%, compared to the blocks that do not have the binder. In addition, the compressive strength improves between 10% and 15%. Secondly, thermal properties of the blocks with compressed earth are not affected by the geopolymer while the blocks stabilized with cement do register negative alterations [13].

It is necessary to improve the quality of compacted earth blocks to implement them in buildings [10]. Due to, compressed earth blocks are a solution for the construction of low-cost housing [14].

In this context, straw is a controversial material in the construction industry with thermal, environmental and economic potentials. The advantage of thermal insulation is the main incentive of multiple investigations. The low conductivity of the material [15]- [17] favours the temperature behaviour of construction systems that incorporate this material [15], [16], [18].

In spite of, straw is affordable because it is the waste of rice, wheat, rye and barley industries and promotes reuse and circular economy [15], [17], [19]. It is a material that cannot be analysed individually in the construction field because it requires other elements or materials to form composite construction systems, such as sandwich panels, straw bales confined in wooden frames or products with the help of binder materials [15].

Nevertheless, its affordability and flexibility to adapt to new self-constructing solutions makes it an economical option in terms of material costs, labour and execution time [15], [17], [19], [20].

According to the literature, compressed earth blocks are an environmental necessity with potential applications in construction, mainly in rural areas, where the raw material is accessible and alternative, such as earth and straw. For this reason, the object of this paper is to analyse thermal and mechanical properties of a constructive system manufactured with straw and compressed earth as a binder material to compare it with traditional masonry systems through the characterization of raw material, analysis of heat transfer and the manufacture of the product on a 1:1 scale.

Materials and methods

The methodology is applied research. The development phases are 3: Characterization of thermal and mechanical properties of the mixture composed with straw and compressed earth, analysis of the temperature behaviour of 4 block types through simulations in ANSYS and finally, development at 1:1 scale of block types with a mixture of straw and compressed earth.

Characterization of thermal and mechanical properties of the material

The characterization of thermal and mechanical properties requires the samples elaboration with the material, straw and compressed earth. For this reason, 6 samples were made with 60% straw and 40% compressed earth, of which 3 samples were used for thermal characterization and 3 samples for mechanical characterization. Finally, it was necessary to polish the surfaces of the samples manufactured with a number 400 sandpaper to match them and remove roughness that could imply possible damage to the sensor of the measurement equipment. Table I records the dimensions of the samples required for the performance of each test.

Table I. Dimensions of the specimens for laboratory testing

	Thermal properties		Mechanical properties					
	Height (mm)	Standard deviation (mm)	Length (cm)	Diameter (cm)	Pi	Weight (gr)	Área (mm²)	Weight (gr/cm³)
M1	19.06	0.37	88	44	3.1416	171.6	1520.53	14.11
M2	19.35	0.45	93.2	44.1		183.6	1527.45	14.22
M3	19.84	2.14	91.7	43.5		180.7	1486.17	14.42

The characterization of thermal properties determines thermal conductivity, thermal dysfusivity and specific heat. It was developed under the transient plane source method (TPS) regulated by ISO 22007-2 [21]. The equipment used is Hot Disk thermal constant analyzer, model TPS 500 S from Thermtest - Thermal conductivity instruments in a working range of 0.03 to 100 W/mK in thermal conductivity. Figure 1 shows the equipment used (a) and the sample tested (b).

In addition to that, parameters of the test are type of sensor, method, applied power, measurement time and temperature. The type of sensor is a Kapton 5501 device with a radius of 6.403 mm. The conditions of the selected method were established for porous materials with power of 0.34W, for 40 seconds (time) in a range of 3-200, under a temperature of 24°C, with a variation of 0.5°C. Nevertheless, some adjustments were made to minimize the alerts.

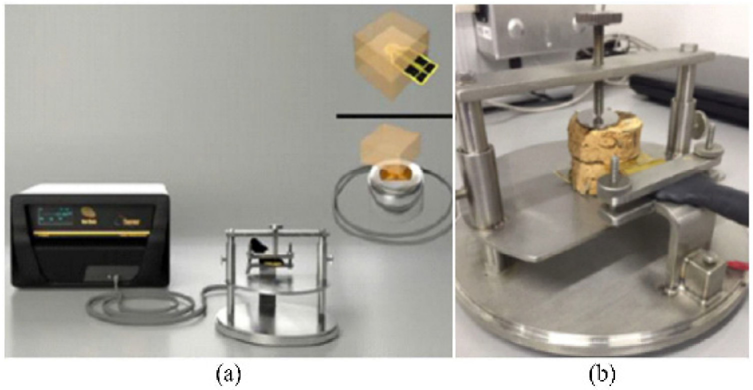

Figure 1. Thermal constant analyzer equipment: Hot Disk TPS 500 S (a). Measurement of the thermal properties of material (b).

On the other hand, the characterization of mechanical properties determines the resistance to compression of products regulated by ICONTEC 673 Standard for cylindrical specimens [22]. According to the regulations, the method establishes that the determination of compressive resistance is obtained from the application of axial compression loads on cylinders, such as the samples described in Table 1, at a speed framed in a pre-established range until the sample fail [22]. Next, Figure 2 compiles the photographic record of the samples made for the thermal characterization (a), (b), (c) and the effect of the samples during the mechanical resistance test (d), (e), (f).

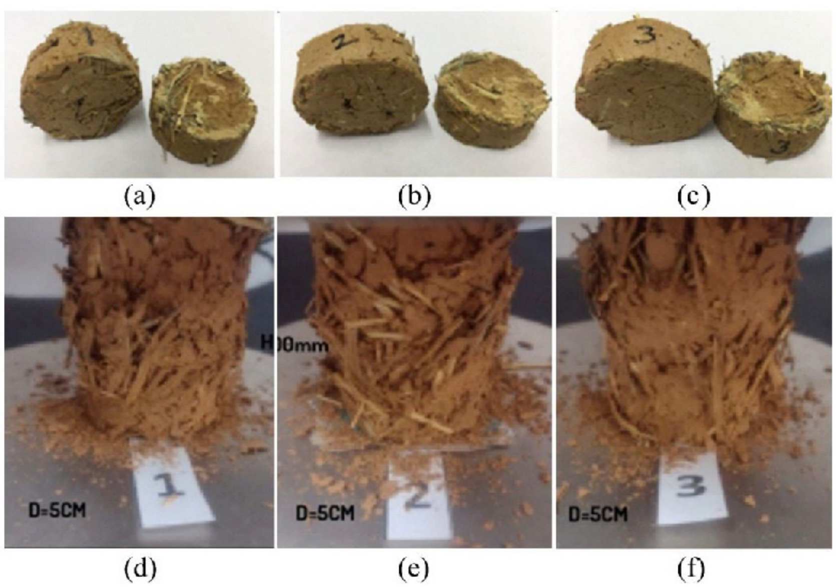

Figure 2. Straw and compressed earth samples subjected to thermal conductivity, thermal diffusivity and specific heat measurement test (a), (b), (c) and samples during the compressive strength test (d), (e), (f).

Analysis of the temperature behavior of blocks manufactured with straw and compressed earth

The analysis of temperature behaviour of blocks manufactured with straw and compressed earth (S-CEB) begins with design of 4 types of block. Table II records the dimensions of length, width, height, and cylindrical perforations.

Table II. Dimensions of Straw and Compressed Earth Blocks typologies (S-CEB)

S-CEB	Length (cm)	Width (cm)	Height (cm)	Perforation (Diameter)
S-CEB 1	25	20	25	5
S-CEB 2	25	25	10	5
S-CEB 3	25	20	10	Not applicable
S-CEB 4	25	12	10	Not applicable

Subsequently, 3D models of S-CEB typologies are exported in the Initial Graphics Exchange Specification (IGS) format to enter them in ANSYS and perform the simulations under the finite element method (FEM) [23].

Taking into account that simulations are configured with climate data from a specific environment, the selected information corresponds to the city of Cucuta, Norte de Santander, Colombia. The weather data in the month of September in the schedule between 12:00 and 13:00 are the average maximum temperature (33 °C), average maximum solar radiation (796.8W/m^2) and average maximum speed (4m/s) [24]. In addition, the thermal conductivity data of the initial characterization of the material was also considered.

It is important to consider during the temperature analysis that the simulation was performed from an experimental thermal conductivity obtained from a laboratory test as described in section 2.1. Characterization of thermal and mechanical properties of the material, which was taken as a constant in the software parameters. In this vein, In this the material will assume a homogeneous behavior due to the conductivity constant obtained experimentally in the laboratory of a sample made of a composite material.

Scale development of straw and compressed earth blocks typologies

The development of S-CEB typologies at 1:1 scale used easily accessible materials such as earth and straw. Therefore, the land used was obtained from the topsoil (-10cm). The preparation consisted mainly of cleaning contaminants such as garbage, vegetation or rocks. Subsequently, the agglutination test was carried out to verify compaction, which consists of exposing samples of compressed material to a free fall of 1.75m.

On the other hand, straw is a fibrous material with a morphological structure of particular sizes between 40cm and 50cm in length in natural state. Therefore, the preparation of the straw initially required fibre cuts between 20cm and 25cm to facilitate handling and compaction. Nonetheless, an additional fibre cut between 5cm and 10cm was necessary, which presented better handling and compaction. Figure 3 shows raw material for the elaboration of S-CEB in its different states according to the preparation, as well as, Larbi et al. [12] suggests that the manufacturing processes of compacted earth blocks should consider aspects such as the size and distribution of the granulometry of the particles.

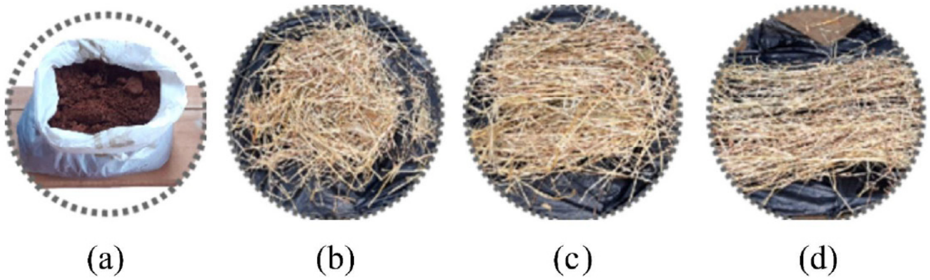

Figure 3. Raw material of S-CEB: Earth (a), Straw with fibers of 5 and 10cm (b), Straw with fibers of 20 and 25cm (c), Natural straw (d)

In addition to raw material preparation, manual manufacture of S-CEB considered variables during the elaboration of the blocks. Table III compiles the composition of mixtures, the preparation time in the compaction of the material in the molds, the time required to remove the formwork and the drying time in sun hours.

Table III. Manufacturing variables of Straw and Compressed Earth Blocks typologies (S-CEB)

S-CEB	Mixture	Preparation time	Formwork removal	Drying time
S-CEB 1	50% Straw and 50%Compressed Earth	2 Hours	2 days	18 hours of sun
S-CEB 2	60% Straw and 40%Compressed Earth	1 Hour	1½ days	18 hours of sun
S-CEB 3	60% Straw and 40%Compressed Earth	30 minutes	5 minutes	12 hours of sun
S-CEB 4	60% Straw and 40%Compressed Earth	30 minutes	5 minutes	12 hours of sun

Results and discussion

The results of this paper not only expose material characterization, the analysis of S-CEB temperature behaviour and development of blocks at 1:1 scale, but also, it discusses the comparative study of the physical and mechanical properties between products manufactured with straw and compressed earth and products of traditional systems.

Characterization of thermal and mechanical properties of the material

The characterization of thermal and mechanical properties of the samples manufactured with 60% straw and 40% compressed earth is recorded in Table IV. Thermal conductivity is 0.793 W/mK, thermal diffusivity is 0.610 mm²/s, the specific heat is 1,306 MJ/m³K, maximum stress is 2,067 KN and 1,267 MPa and cohesion is 0.637 MPa.

Table IV. Thermal and mechanical properties of the material: Straw and compressed earth

	Thermal properties			Mechanical properties		
	Thermal conductivity (W/mK)	Thermal diffusivity (mm²/s)	Specific heat (MJ/m³K)	Maximum effort (KN)	Maximum effort (MPa)	Cohesion (Mpa)
M1	0.7788	0.6556	1.1880	2.56	1.35	0.68
M2	0.7685	0.6064	1.2670	1.98	1.33	0.67
M3	0.8303	0.5670	1.4640	1.66	1.12	0.56
Average	0.793	0.610	1.306	2.067	1.267	0.637

According to literature, straw as an individual material presents low conductivities between 0.0487 W/mK and 0.0517 W/mK [16] or between 0.038 Wm-1K-1 and 0.08 Wm-1K-1 [15]. Nevertheless, the samples increase their conductive value because the formulated mixture requires for a binder material that allows compaction of the straw in order to create a block-type product.

S-CEB temperature behavior analysis

The simulation of temperature distribution is a great tool to estimate and analyse temperature behaviour of a product. In this case, the analysis focuses on the study of the behaviour of the material composed of 60% straw and 40% compressed earth in different types of products, which has an average conductivity of 0.793 W/mK.

Table V complements Figure 4 and Figure 5 and records the values of temperature behaviour and also heat fluxes S-CEB typologies. According to the results of Table V, exterior surface temperature increases 2.13 °C in typologies with perforations, S-CEB 1 and S-CEB 2, compared to S-CEB 4. Nonetheless, temperature behavior of interior surface is inversely proportional to the exterior.

Table V. Thermal and heat fluxes behavior of S-CEB typologies

S-CEB	Maximum temperature (°C)	Minimum temperature (°C)	Maximum heat flux (W/m^2)	Minimum heat flux (W/m^2)
S-CEB 1	73.85	49.43	191.06	0.308
S-CEB 2	73.85	49.49	191.56	8.676
S-CEB 3	73.39	50.86	89.294	89.294
S-CEB 4	71.72	56.74	118.69	118.69

Due to S-CEB 1 and S-CEB 2 considerably reduce interior temperatures between 7.25 °C and 7.31 °C compared to S-CEB 4 which presents the highest values. To a lesser extent, S-CEB 3 decreases 5.88 °C. On the other hand, Table 5 indicates that the difference between outside and inside temperature is 24 °C in typologies with perforations, S-CEB 1 S-CEB 2, while S-CEB 3 differs 22 °C and S-CEB 4 differs 15 °C. Figure 4 illustrates the temperature behaviour (°C) according to the distribution from the outside to the inside of S-CEB typologies.

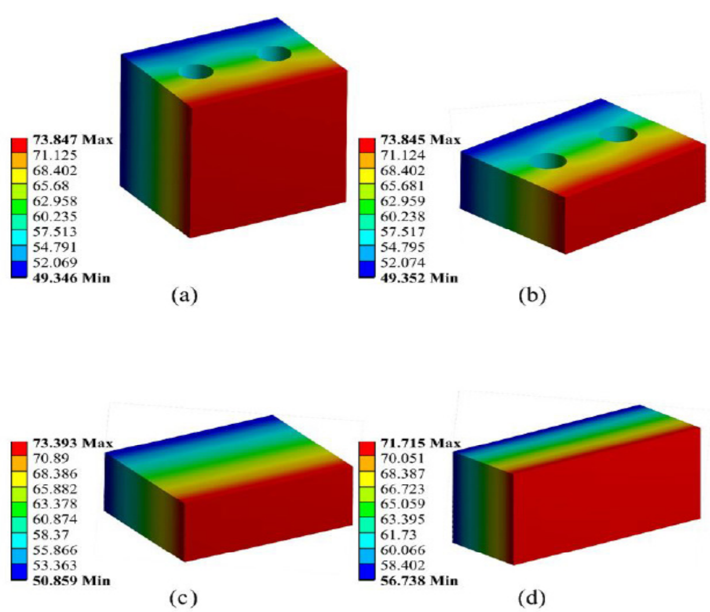

Figure 4. Temperature (°C) behaviour of S-CEB typologies: S-CEB 1 (a), S-CEB 2 (b), S-CEB 3 (c) and S-CEB 4 (d)

In addition, Figure 5 illustrates the heat fluxes (w2) according to the distribution from the outside to the inside of S-CEB typologies and Table 5 indicates that typologies with perforations, S-CEB 1 and S-CEB 2, vary heat fluxes throughout the product between 95% and 99%. While solid typologies, S-CEB 3 and S-CEB 4, do not dissipate energy throughout the product and concentrate it uniformly. Which is an approach that coincides with investigations that demonstrate influence of product design on energy behaviour [23], [25]- [27].

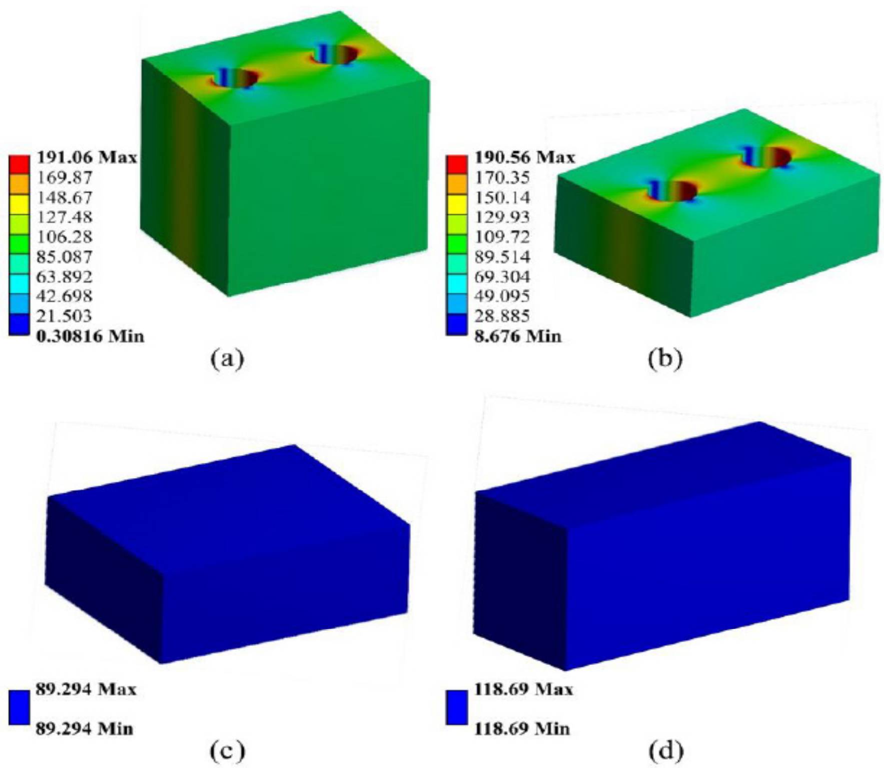

Figure 5. Heat flux (w2) behaviour of S-CEB typologies: S-CEB 1 (a), S-CEB 2 (b), S-CEB 3 (c) and S-CEB 4 (d)

The advantages coincide that dissipation of energy concentration is a result of the implementation of dissipative geometry strategies [23], ventilated air chambers [18], [27], treatment of mortar joints [28] and shadow generation [29]. For example, Eco Straw Model (ESM) incorporates straw in a constructive system with a ventilated air chamber that favours the temperature of the interior surface 1.49 °C and 6.6° C the exterior surface [18].

Scale development of S-CEB typologies

The development of S-CEB typologies begins with the preparation of raw materials, the design and manufacture of the mold and the manufacture of blocks types mentioned in Table 2. Taking into account that straw and earth required specific preparations mentioned in methodology section, the results of 1:1 scale development are collected from the mold design process, as shown in Figure 6.

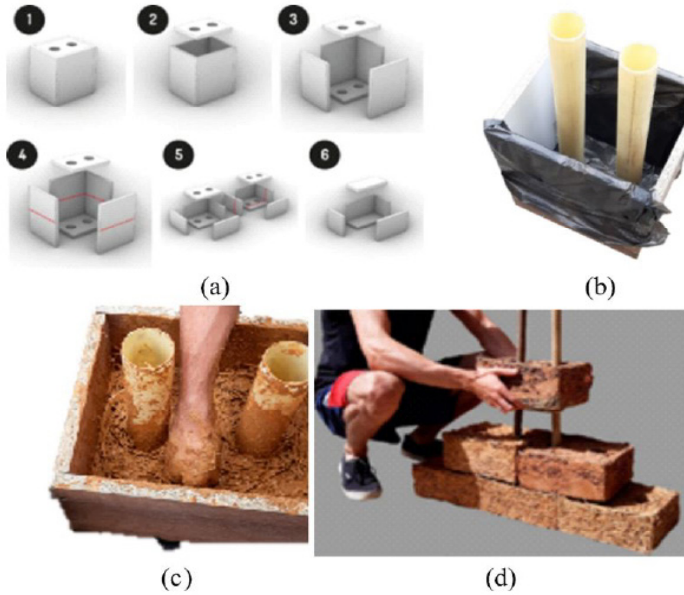

Figure 6. 3D exploded model of the mold (a). Mold (b). Manufacturing of S-CEB (c). Assembly of the constructive system made with S-CEB (d).

The geometry of the mold design is cubic. It also considers lengths proportional of straw bale and existing formats of traditional construction products. The materials used were triplex wood (1.5 cm thick) and PVC pipes (5 cm in diameter). The mold structure corresponds to lower face where the lateral faces and the PVC pipes are stabilized to generate the perforations. Figure 5 records the filling of the material into the mold to compact it from the top face. The manufacture of S-CEB typologies used straw fibres of 5cm and 10cm, which were mixed with earth to start the composition and compaction of the material. The filling of the mold is defined according to the height of the designed block. Once finished, the formwork removal process continues according to the variables in Table 3 and the results of the S-CEB typologies observed in Figure 7 are obtained. It is important to reiterate that the manufacturing process is handmade in order to demonstrate the feasibility of prototypes manufacturing. As well as, Teixeira et al. [10], these blocks do not have industrialized production, therefore, the determination of the Resistance may present failures or possible errors.

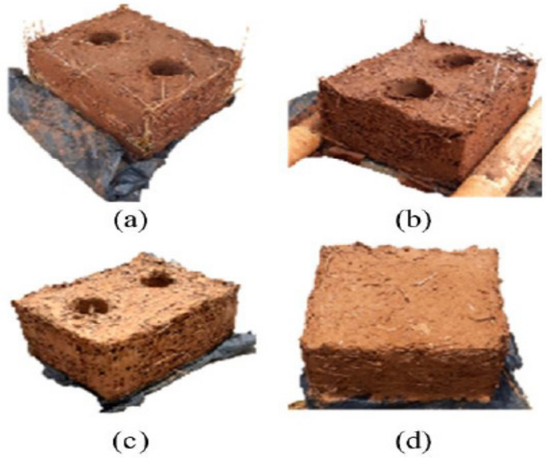

Figure 7. S-CEB results according to the manufacturing variables: S-CEB 1 (a), S-CEB 2 (b), S-CEB 3 (c) y S-CEB 4 (d)

Comparative analysis of thermal and mechanical properties of S-CEB versus traditional systems

The comparative study of S-CEB versus traditional construction products is a broad overview of the advantages and disadvantages of current and alternative construction solutions.

First, formal characteristics of dimensions, recorded in Table 6, indicate that the yield per square meter is not favorable for S-CEB because 40 pieces are required, while products such as block H10, block H12 and concrete block they only require 13 or 16 pieces. Nevertheless, the advantage of S-CEB over this limitation is that as it is a hand-made product, the manufacturer can increase the height to increase performance per meter square and therefore reduce the number of parts.

Fortunately, thermal properties of S-CEB are considerable advantages over materials such as clay and concrete. Table VI registers a low conductivity of the study material and only competes with solid brick, which also has disadvantages in performance per square meter. On the other hand, the most competitive products are H10 block, H12 block and concrete block, but their thermal properties are questionable, because they increase their ability to conduct heat between 233% and 266% compared to S-CEB.

Table VI. Comparison of thermal and mechanical properties between S-CEB and traditional systems

Product	Format Dimensions (cm) Height	Width	Length	Mechanical properties Weight Kg	Compressive strength Kg/cm²	MPa	Thermal properties Conductivity W/mK	Density Kg/m³
S-CEB	10	20	25	5	13.5	1.33	0.7925	500
H10 block [16]	20	10	30	4.2	32.83	3.22	1.85	168
Solid brick [16]	6	10	20	4	214.22	21.01	0.87	1800
Concrete block [16]	19	12	39	10	58.2	5.74	2.08	1460
H12 block [16]	20	12	30	4.2	32.83	3.22	1.85	168
Solid Concrete block [16]	20	12	30	6	58.2	5.74	2.08	1460

Conclusions

The housing deficits of rural social housing in Colombia demand the development of friendly products with the environment and the community, in order to optimize the quality of life of the rural population in the different regions of Latin America.

The field of study of compressed earth blocks is booming thanks to the industrialization of manufacturing processes to improve the physical and mechanical properties of construction units. Moreover, innovation in the search for new additives to optimize traditional mixtures generates other value chains for organic and non-organic industrial waste to transform them into new raw material.

S-CEB typologies are a constructive solution for masonry with advantages in thermal properties. Thermal conductivity (0.79 W/mK) is one of the lowest, compared to the other construction methods. The variation of minimum temperatures of interior surfaces is between 5.88 °C and 7.31 °C and the variation of maximum temperatures of exterior surfaces is between 1.67 °C and 2.13 °C.

In addition, it promotes the use of reusable materials such as waste from the rice, rye, barley and wheat industries. Its accessibility and flexibility of handling does not require transportation methods and qualified labor. In fact, it reduces production times and avoids the greatest amount of polluting effects such as Co2 and waste materials.

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