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Thermal and mechanical properties laboratory evaluation of hollow brick made of fired clay and rice husk additive

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Abstract. Hollow bricks in fired clay for masonry are important in design and construction of buildings. Their thermal and mechanical properties must be considered because of the impact they have on energy consumption. The objective of this research is to evaluate thermal and mechanical properties of a new hollow brick, called Eco Design, made of fired clay and rice husk additive, in order to identify the benefits of its use in the construction of masonry walls in regions with a tropical climate. The methodology develops simulation of thermal properties of brick, manufacturing at the laboratory level and characterization of mechanical properties of finished product. Thermal validation simulates the behavior of heat transfer and fluxes of Eco Design in mixtures of 100% fired clay, 95% -5%, 85% -15% and 70% -30% fired clay with rice husk, respectively. Eco Design samples are manufactured by extrusion and fired at 1000 °C. The characterization of mechanical properties of samples manufactured consists of determining dimensions, water absorptive capacity, linear shrinkage, mass losses and mechanical resistance to compression according to Colombian normative. The results indicate that Eco Design brick has a thermal benefit of 6.9 °C in 95% -5% mixture, as the percentage of rice husk increases, benefit increases 0.75 °C additional. Furthermore, the implementation of rice husk additive improves 7.15% mechanical resistance to compression and increases 18.3% water absorption capacity. Finally, the assessment of thermal and mechanical properties of Eco Design is a reference to promote innovation in ceramic industry in Norte de Santander and Colombia.

1. Introduction

The shape of the ceramic products affects their thermal behavior and does not depend exclusively on the composition of the material and its conductivity or specific heat [1,2]. Energy efficiency of building varies considerably according to the geometry of the surfaces, volumetry and conductivity of the envelope [1-5]. These factors intervene in the impact of the solar incidence on the exterior surfaces through the transfer of thermal energy inside the buildings. The shape of the product ceramic used in exterior walls is crucial for the facade thermal behavior, since the modification of the interior holes and the intersection of the mortar joint can improve the performance achieving a reduction of the inner temperature between 0.62 °C and 1.23 °C [1]. In the same way, the variation in the design of the holes in the ceramic blocks contributes to the decrease of 1.55 °C [6]. In the ceramic industry of Norte de Santander, its products for masonry, roofs and floors stand out, which blocks, bricks, tiles, tablets, among others, have been standardized. The multi-perforated brick (MB) is a practical and aesthetic product for masonry, in addition, apart from fulfilling its enclosure function, it does not require cladding [2,7]. According to the Norma Técnica Colombiana (NTC) 4205 [8], MB is classified in the group of construction units with vertical perforation for exterior walls with circular holes uniformly distributed over the rectangular format that contains them and mortar joints exposed to solar incidence [8]. Likewise, the conductivity of the materials used in façade enclosure products also plays an important role in the design of thermal insulating envelopes. The incorporation of agro-industrial residues as technological nutrients in the ceramic mass for the manufacture of bricks points to the reduction of the clay mixtures conductivity of the Norte de Santander region [5]. For example, rice husk (RH) is a local alternative due to its chemical, structural and morphological characteristics. The rice husk is an amorphous material, its morphological structure is laminar type fibrous [5]. However, the inorganic phase of the chemical composition presents high concentrations of silicon, which slow down its biodegradation and allows this residue to be a potential additive for the generation of new materials for construction [5,9-10]. Furthermore, RH insulating properties are associated with the high percentage of losses on ignition of the chemical composition, due to the fact that it calcines at high temperatures during brick firing. However, the pores formation in the firing process of the bricks alters the resistance of the product [5]. This way, the purpose of this paper is to evaluate the thermal, physical and mechanical properties of a new type of hollow brick made of fired clay with addition of rice husk for masonry walls in tropical climates at the laboratory level.

2. Methodology

The methodology consists of two main stages: thermal validation and characterization of Eco Design on a laboratory scale. In order to obtain the design and manufacture of hollow brick and the characterization of thermal, physical and mechanical properties of Eco Design.

2.1. Thermal validation

Eco Design is the name of the new propose of hollow brick to assess. Eco is the abbreviation of ecological, thanks to thermal properties of the design is attributed this term. Thermal validation was performed using heat transfer and heat flow simulations in ANSYS R16 software. Simulations require material conductivity previous data and specific environmental conditions to build virtually the most extreme scenario that products could be subjected to. As well, the thermal behavior of MB was validated to compare the influence of design on the energy performance of a product.

2.1.1. Conductivity of materials. Table 1 contains the formulation and conductivity of mixtures to simulate Eco Design. The first mixture is composed of clay in its totality, while the following mixtures add 5%, 15% and 30% of technological nutrient. The simulation model also includes conductivity of mortar for the joints. The conductivity of clay mixtures with different concentrations of rice husk were obtained from the relationship between the conductivity of clay fired at 1000 °C [5] and conductivity of rice husk (0.0036 Wm °C) [9].

Table 1. Formulation and mixtures conductivity.

Mixture	Composition	Conductivity
M C	100% Clay	0.407 Wm °C [5]
M CRH-5	95% Clay and 5% Rice husk	0.388 Wm °C
M CRH -15	85% Clay and 15% Rice husk	0.351 Wm °C
M CRH -30	70% Clay and 30% Rice husk	0.295 Wm °C
Mortar	-	0.88 *Wm °C* [12]

2.1.2. Climatic condition of environment. As already mentioned, the climatic conditions of the environment establish of the specific scenario where the products behavior to be simulated is to be evaluated. For this reason, San José de Cúcuta city in Colombia was selected in its most extreme climatic conditions. According to the "Instituto de Hidrología, Meteorologia y Estudios Ambientales

(IDEAM)", the month of September between 12:00 and 13:00 is the highest value of solar incidence (796.8 W.hm²), temperature (33 °C) and speed of the wind (4 m/s) [11].

2.1.3. Radiation and convection heat transfer fluxes. The fluxes applied in the simulation to Eco Design are 3. The first fluxe is the solar incidence (796.8 Wm² °C). The second and third fluxes correspond to heat transfer coefficient by convection applied to the exterior surfaces and ventilated air chamber perforations (25.903 Wm² °C) and to the internal surfaces of the product (5 Wm² °C). The heat transfer coefficient (Equation (1)) by convection is determined by the relationship between the Nusselt number (Nu) for air conductivity (k) and the assumed characteristic length (Lc), which correspond to the height of the brick (6cm) [13]. The equation to calculate the coefficient of convective heat transfer (h) is Equation (1).

$$h = \frac{Nu*k}{Lc}. \quad (1)$$

2.2. Characterization of eco design at laboratory scale

The manufacture of the product on a laboratory scale is divided into 5 stages: selection of mixtures to manufactured Eco Design, preparation of the mixture, extrusion, drying and firing. The mixtures selected for the manufacture of Eco Design are M C and M CRH -5 with the lowest additive concentration. Due to, RH calcination in the brick firing processes can affect the physical and mechanical properties of the finished product [14]. The preparation of mixture varies according to the raw material, in this case study, 2 materials are manipulated, clay and rice husk, which clay is the main material and RH is the technological nutrient. The clay used for the manufacture of these prototypes was subjected to drying, crushing and grinding. Rice husk was subjected to a prior processing, 80 mesh sieving. Due to the scale of the ceramic product is smaller than the actual product. Once these processes were finished, the quantities required for manufacturing were weighed and kneaded. Two extrusion sessions were carried out in the laboratory of the "Centro de Investigación de Materiales Cerámicos (CIMAC)", Universidad Francisco de Paula Santander, Colombia, in M C and M CRH-5, Figure 1. The first drying stage consisted of resting the specimens for 24 hours at room temperature and later, in a drying oven at 100 °C -110 °C for another 24-hours period. Finally, the samples were fired at 1000 °C in 24 hours. The characterization of physical and mechanical properties of prototypes manufactured at 1:75 scale of Eco Design in MC and M-CRH were determined through laboratory tests required by the Colombian Technical Standard NTC 4017 [15]. The tests are linear contraction, mass losses, mechanical resistance to compression, water absorption and dimensions [15].

3. Results and discussion

This section presents the results obtained on the evaluation of the formal, thermal, physical and mechanical characteristics of Eco Design. In addition, each subsection describes its contribution in the process of developing a new hollow brick for masonry to relate aspects of design, thermal efficiency, and physical and mechanical properties of the product and materials. In order to evaluate the advantages and disadvantages in masonry product innovation from the element shape.

3.1. Product design

Eco Design proposal modifies the distribution and shape of the internal holes generating an air chamber ventilated to the outside, Figure 2. The geometry of the internal holes are regular rectangles configured so that the path from the outer surface to the inner one is longer. The air chamber is made up of 4 rectangles that generate vertical channels for air circulation and extend 15 mm at each end to generate flanges that protect the mortar joints from solar incidence [16]. Furthermore, the outer surface of the product has a relief that adapts to generate the perforations of the ventilated chamber and also, to generate its own shadows [2]. Figure 2 shows Eco Design prototypes manufactured in fired clay with 5% of RH additive on a laboratory scale.

Figure 1. Eco Design laboratory scale extrusion.

Figure 2. Eco Design prototypes manufactured in M CRH-5 at laboratory scale.

3.2. Characterization of thermal properties of eco design
Heat transfer records temperature values from the outer surface to the inner surface of the brick. On the other hand, heat fluxes record the concentration of energy according to the element shape. Thermal validation performs Eco Design heat transfer and heat flux simulations in M C, M CRH-5, M CRH -15 and M CRH -30 (Table 2).

Table 2. Values of temperature distribution and heat fluxes of MB in M C and M CRH-5 and Eco Design in M C, M CRH-5, M CRH-15 and M CRH-30.

Model	Mixture	Temperature distribution (ºC)		Heat fluxes (W/m²)		
		Exterior	Interior	Mortar joint	Outer surface	Holes
MB	M C	75.93	42.04	216.74	48.280	168.610
	M CRH-5	76.02	42.13	217.77	48.467	169.400
Eco Design	M C	72.77	35.13	295.57	665.020	0.00430
	M CRH-5	72.97	35.01	287.71	646.990	0.09480
	M CRH-15	73.39	34.76	271.08	609.930	0.00757
	M CRH-30	74.08	34.38	243.63	548.150	0.00840

3.2.1. Comparative thermal analysis between multi perforated brick and eco design. The analysis of the thermal validation results begins with the comparison of Eco Design and MB in M C and M CRH-5. Figure 3 shows temperatures of the whole section of bricks from exterior surface until interior surfaces, MB (Figure 3(a)) and Eco Design (Figure 3(b)) in M C. Figure 3 also shows heat fluxes of MB (Figure 3(c)) and Eco Design (Figure 3(d)) in M C. The thermal benefit is evidenced in the behavior of eco design in M C (Figure 3(b)), since the temperature reduction of the interior surface reaches 6.91 °C. The exterior surfaces of Eco Design are heated 3.16 °C less than the exterior surface of MB (Figure 3(a)), due to the ventilated air chamber, insulation or protection of the mortar joint and holes distribution [1].Table 2 registers values of temperature distribution of exterior and interior surfaces and heat fluxes of mortar joint, outer surface and holes of MB in M C and M CRH-5 and Eco Design in M C, M CRH-5, M CRH-15 and M CRH-30. Table 2 indicates that the presence of rice husk only reduces 0.12 °C more than the reference model, that is, the variation is minimal when adding technological nutrients in the mixture composition as the design did, as supported by [1,2].

3.2.2. Comparative energy fluxes analysis between multi perforated brick and eco design. Heat fluxes represent the way in which energy is distributed. In this way, it is possible to identify which points concentrate the highest and the lowest concentration of heat. At first glance, the energy concentration values indicate that the new proposal duplicates the heat in Table 2. However, it is observed that MB (Figure 3(a)) presents high energy concentrations along the surface, while in Eco Design (Figure 3(d)) only concentrates the energy in the air chamber and dissipates in low concentrations immediately in the interior holes, canceling the transfer of energy to the interior in its totality [1-3]. The energy benefit of Eco Design (Figure 3(d)) versus MB (Figure 3(c)) is concluded from the difference in the energy concentrations located in the mortar joints (thermal bridge), the air chamber and the internal holes. At first glance, a large concentration of energy is observed in the MB mortar joints, however, the values of the Eco Design mortar joints raise the accumulated energy between 70W/m^2 and 80W/m^2 (Table 2). On the other hand, the outer surfaces of Eco Design concentrate their maximum values at certain points of the air chambers, exceeding the energy concentration of the outer surface of MB by around 600W/m^2 (Table 2). However, energy flux in these areas is minimal, therefore it does not affect the energy conduction of Eco Design. Contrary to heat fluxes of the interior holes, the energy in the Eco Design perforations is practically zero since it does not reach even 1W/m^2, unlike MB that reaches up to 170W/m^2 throughout the volume surface [1-3].

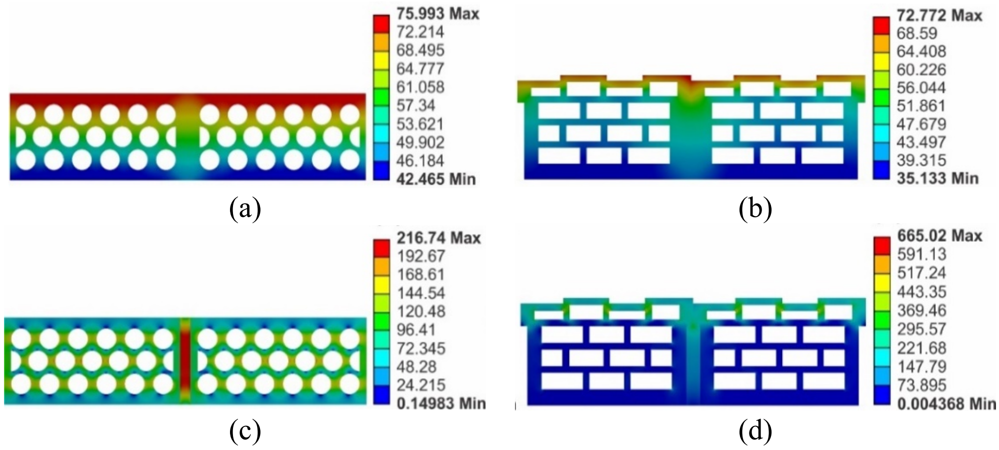

Figure 3. Thermal profiles of MB and Eco Design in M C: temperatures distribution of MB (a), Eco Design (b) and heat fluxes of MB (c), Eco Design (d).

3.2.3. Thermal analysis of rice husk in eco design. The analysis of the thermal benefit in Eco Design with the rice husk implementation in larger proportions. According to Table 2, an increase in temperatures is observed on the outer surface as the percentage of rice husk increases, between 0.2 °C and 1.31 °C. Whereas, the inner surface experiences a reduction between 0.12 °C and 0.75 °C as the percentage of the technological nutrient in the mixture increases. Unlike the temperature distribution, heat fluxes increase in the interior holes and decrease in the exterior surfaces. Similarly, the decrease in the exterior surfaces varies between 18.03 W/m2 and 116.87 W/m2 with the increase in the concentration of the rice husk and the increase in the concentration of heat fluxes to the interior does not exceed 0.09 W/m2. For this reason, increasing the concentration of energy inside does not imply an increase in internal temperatures.

3.3. Characterization of physical and mechanical properties of eco design

Characterization of physical and mechanical properties of Eco Design encompasses determination of dimensions (length, width, height and areas) (Figure 4(a)), linear shrinkage, mass losses, water absorption by boiling and compressive strength (Figure 4(b)) in M C and M CRH-5, registered in Table 3. The net area of the extrusion section of the samples in M C is 63.3% and 36.7% holes. Whereas, the samples in M CRH-5 reduce the net area to 59.3% and increase the hole area to 40.7% (Table 3). Eco Design dimensions handle an average of 4.8% difference between dimensions in M C and M CRH-5. This behavior is associated with the fired linear shrinkage values, since the length measurements vary between 5.6% and 3.97% mixtures in the width of the samples. Taking into account the results of Table 3, the samples in M CRH-5 are smaller because the contraction triples. This behavior implies a greater probability of fissure and crack pathologies [14].

The water absorption increases 18.3% and the mechanical resistance to compression is optimized 7.15% in the samples of M CRH-5, compared to M C (Table 3). The results obtained produced interesting data on the rice husk behavior in relation to the properties of water absorption and resistance to compression and the relationship with the fired linear shrinkage, because the literature supports a detriment in these characteristics [2,14]. Despite optimizing the performance of Eco Design in M CRHA-5, the samples do not meet the minimum standards established for vertical drilling non-structural masonry units established by NTC 4205 [8]. Figure 4 shows the results obtained from the compressive strength test. Finally, Eco Design samples in M C fulfill the maximum water absorption percentages for interior and exterior [10]. Whereas, Eco Design samples in M CRH-5 only satisfy with regulations for interiors, but Eco Design is a product designed for facades and therefore requires implantation in areas exposed to solar incidence to mitigate heat, if not, it would not meet its thermal insulation target.

Table 3. Physical and mechanical properties of Eco Design in M C and M CRH-5.

	Test	M C	M CRH-5
Dimensions	Length (mm)	44.57	42.05
	Width (mm)	27.14	26.06
	Thickness / Height (mm)	12.37	15.00
	Total area (cm^2)	12.10	10.94
	Hole area (cm^2)	4.44	4.46
	Net area (cm^2)	7.66	6.48
Linear shrinkage (%)	Drying	6.714	6.213
	Firing	0.576	1.539
Mass losses (%)	Drying	18.743	5.514
	Firing	22.504	9.127
Water absorption by boiling (%)		11.60	14.20
Compressive strength (Kgf/cm²)		12.59	13.56

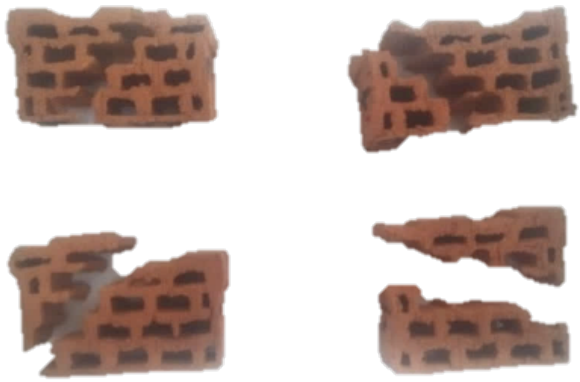

Figure 4. Samples after compression resistance test.

4. Conclusions

The proposed design reduces the temperature until 7.66ºC, which it is equivalent to a reduction in the conductivity of 0.295 Wm°C and generate thermal insulation, as long as factors such as ventilated air chamber, insulation or protection of the mortar joint and distribution of the holes are taken into account. While the addition of technological nutrients in the composition of the mixture only improves up to 1.31 °C. Likewise, the variation in percentages of technological nutrient implies an increase in the absorption of water and the mechanical resistance to compression of the constructive unit. The formal characteristics of Eco Design influence the dissipation of energy, from the ventilated air chamber, the modification of the holes and the protection of the thermal bridge. In contrast, MB's exposed and direct thermal bridge concentrates energy (unidirectional) and regular holes allow almost direct passage of heat from the outer surface to the interior. Eco Design is a product with extraordinary thermal potentials, however, it must consider adjustments in favor of technological properties such as linear shrinkage, water absorption, compressive resistance, among others, to compete in the clay industry market in Norte Santander, Colombia.

References

[1] Colmenares-Uribe A P Sánchez-Molina J, Díaz-Fuentes C X 2019 *J. Phys. Conf. Ser.* **1386** 012130:1
[2] Colmenares-Uribe A P Sánchez-Molina J, Díaz-Fuentes C X 2018 *Diseño de Prototipos de Producto Ceramico para Mamposteria con Propiedades Esteticas y de Aislamiento Térmico* (Colombia: Colciencias, Universidad Francisco de Paula Santander)
[3] Navarro J, Niño M 2014 *Diseño de Una Solucion Constructiva Ceramica, Que Rreduzca la Radiación Solar Directa Sobre Fachadas: Caso Cúcuta* (Colombia: Cúcuta: Universidad Francisco de Paula Santander)
[4] Narváez-Ortega M S Sánchez-Molina J, Díaz-Fuentes C X 2019 *J. Phys. Conf. Ser.* **1388** 012007:1
[5] Sanchez-Molina J Corpas F, Alvarez-Rozo D 2018 *Aplicaciones de Los Nutrientes Tecnologicos en la Industria Ceramica del Area Metropolitana de Cucuta* (Colombia: Ecoe Ediciones Ltda)
[6] Narváez-Ortega M S Sánchez-Molina J, Díaz-Fuentes C X 2019 *J. Phys. Conf. Ser.* **1386** 012084:1
[7] Sánchez-Molina J Gonzalez-Mendoza J A, Avendano-Castro W 2019 *El Clúster Cerámico. Apuesta de Desarrollo Socioeconómico de Norte de Santander* (Colombia: Ecoe Ediciones Ltda)
[8] Instituto Colombiano de Normas Técnicas y Certificación (ICONTEC) 2018 *Unidades de Mampostería de Arcilla Cocida. Ladrillos y Bloques Cerámicos NTC 4205* (Colombia: Instituto Colombiano de Normas Técnicas y Certificación)
[9] Cadena G, Bula A 2002 *Revista Cientifica Ingenieria & Desarrollo* **12(12)** 1
[10] Sierra J, Vergara C 2009 *Alternativas de Aprovechamiento de la Cascarilla de Arroz en Colombia* (Colombia: Universidad de Sucre)
[11] Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM) 2010 *Atlas Interactivo Climatológico, de Radiación Solar y de Viento de Colombia* (Colombia: Instituto de Hidrología, Meteorología y Estudios Ambientales)
[12] Centro de Investigación en Salud Integral y Bienestar Socio-económico (CISBE) 2007 *Thermal Properties of Building Structures Guide A: Environmental Design* (Colombia: Centro de Investigación en Salud Integral y Bienestar Socio-económico) Chapter 3
[13] Cengel Y A 2007 *Transferencia de Calor y Masa, un Enfoque Práctico* (México: McGraw-Hill Interamericana)
[14] Görhan G, Simsek O 2013 *Construction and Building Materials* **40** 390
[15] Instituto Colombiano de Normas Técnicas y Certificación (ICONTEC) 2018 *Métodos Para Muestreo y Ensayos de Unidades de Mampostería y Otros Productos de Arcilla, NTC 4017* (Colombia: Instituto Colombiano de Normas Técnicas y Certificación)
[16] Sánchez-Zuñiga J Sánchez-Molina J, Díaz-Fuentes C X 2019 *Diseño de un Producto Cerámico para la Construcción y su Configuración Constructiva Bajo Principios de la Arquitectura Bioclimática y Sostenible* (Colombia: Colciencias, Universidad Francisco de Paula Santander)