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Comparative evaluation of the physical, mechanical and thermal properties of traditional H10 and H15 red clay blocks manufactured by the ceramic industry from San José de Cúcuta, Colombia

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Abstract. The traditional blocks of baked clay represent 15% of the total production of the ceramics cluster in the Norte de Santander region, with a product typology whose dimensions, shape, weight and price are the most demanded of the market. Its positioning becomes a molding element of the materiality of the architectural covering in the metropolitan area of San José de Cúcuta. This research focuses on the study of two of the most economical and used products in building materials constructions in the city: the blocks manufactured by extruded H-10 of 6 rectangular cavities with market dimensions L: 300 mm, W: 100 mm, H: 200 mm and H-15 of 9 rectangular cavities of size L: 300 mm, W: 150 mm, H: 200 mm and seeks to report its physical-mechanical characteristics to compare the impact of the variables in the units thermal behavior in the enclosure system. This work is carried out by applying 2 methods: in the first phase tests are carried out at the laboratory level using the Norma Técnica Colombiana 4017 and the Norma Técnica Colombiana 4205 to determine the qualitative properties of the building units in each format, and a simulation of temperature distribution and heat flux by finite element method in software ANSYS R16 evaluating the incidence of variables in the heat transfer in a traditional masonry system, evaluating the thermal performance in extreme temperature conditions of 33 °C typical of the region. The results show a difference of 0.709 °C between the thermal behavior between the formats, with a reduction of final thermal energy by the approximate increase of 50 mm in the thickness, this variant presents an opportunity of development to minimize the impacts of the loads of temperature in the envelope, favorable for warm tropical climates.

1. Introduction

Clay is a native raw material from the department of Norte de Santander (Colombia), with excellent properties for the production of ceramics. These characteristics articulate an industrial cluster that shapes part of the economy in the region [1], and whose derivatives build in large measure the material identity of the municipality of San José de Cúcuta. The present investigation focused on the study of two types of cooked ceramic block manufactured by extrusion with horizontal perforation: the block in H-10 format with dimensions: length: 300 mm, width:100 mm and height: 200 mm of 6 rectangular cavities (Figure 1) and its counterpart in the H-15 format of length:300 mm, width:150 mm and height:200 mm with 9 rectangular cavities (Figure 2).



Considering the block as the most demanded product of the market with 15% of the total production of the region [1] and usually used in low cost constructions, this work evaluated the qualitative properties of each constructive unit applying the NTC 4017 and verifying the fulfillment of the NTC 4205. The results of the initial method were applied finite element method (FEM) in a computer assisted engineering (CAE) procedure through computer assisted design (CAD) models of simple masonry systems stacked with mortar board, generally used in external enclosures, without coating and exposed directly to environmental conditions of temperature, humidity, solar radiation and winds, therefore, the simulation was made from values of the warm tropical climate proper of San José de Cúcuta city (Colombia). According to the literature review [4-6] the purpose of this methodology is to report the mechanical physical characterization and the thermal performance of the two types of product under specific parameters.

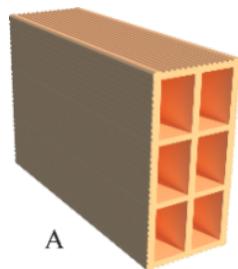


Figure 1. Block in H-10 format.

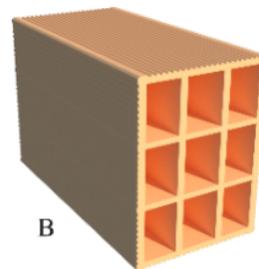


Figure 2. Block in H-15 format.

2. Initial Procedure

2.1. Methodology NTC 4017

The tests were carried out in the “Centro de Investigación de Materiales Cerámicos (CIMAC)” of the Universidad Francisco de Paula Santander, and consisted on determining the physical and mechanical characteristics from the parameters of the NTC 4017 [7], taking an initial sample of 10 units of block masonry H-10 and 10 type H-15, randomly selecting each specimen from a standard batch manufactured in the region, where each sample was subsequently divided into groups of 5 units to perform evaluations of determination of geometric characteristics of masonry units (DMU), mechanical resistance to compression in Masonry units (RCU), water adsorption in Masonry units (AAU) and efflorescence in Masonry units (EFU), the results were compared with NTC 4205 [8]. In the DMU to identify the dimensions and morphology of each product, it was established L: length, W: width and H: height, and the thicknesses of P and T to observe the variables between the units and to establish average dimensions. Likewise, RCU tests were carried out on the edge of the specimens, where the load is submitted to the masonry system, through the established method for horizontal drilling units (NTC 4017) [7]. The AAU tests were carried out by means of the immersion method during 24 h, establishing the: W_s : dry mass of the specimen before immersion (g) and W_{ss} : mass submerged in water of the saturated specimen after immersion (g), see Equation (1).

$$\% \text{ absorption} = \frac{100 \times (W_{ss} - W_s)}{W_s} \quad (1)$$

With a contribution to the uncertainty in the method of 6% and 94% of the sample. Finally, qualitative EFU determination tests were performed by internal method, with environmental conditions of 20.1 °C and 64.0% RH for block H-10, and 19.7 °C and 64.1% RH for block H- 15.

2.2. Results method NTC 4017

Figure 3 reports the results of DMU, which showed some variations in the length of the specimens with an average L: 298.81 mm for the block of 6 cavities, and L average: 289.45 mm for the product of 9

cavities, in relation to the width no greater discrepancy was reported between the samples with average W:146.09 mm for H-10 and W average: 99.99 mm in H-15 formats, in the case of the height it was evident a deviation of 0.58% in the H-10 dimensions with H:201.16 mm in the average and -2.15% in the H-15 format with H:195.71 mm in average.

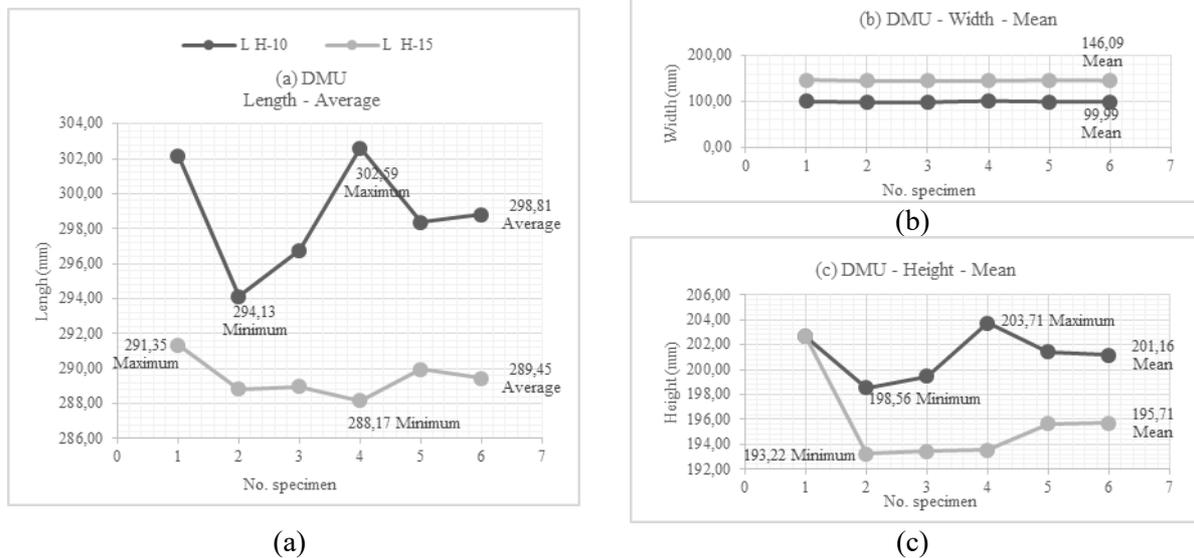


Figure 3. DMU Results, (a) length, (b) width and (c) height.

In NTC 4205 a minimum wall thickness of 16 mm to 10 mm is dictated in structural and non-structural masonry equally, therefore, for this case only product H-15 acts in accordance with the norm for non-structural system. Regarding the partitions, a minimum regulatory thickness of 10 mm structural and 6 mm non-structural is established, in the results this criterion is met in both formats for non-structural masonry (Table 1), where P: Thickness of the walls and T: Thickness of the partitions.

Table 1. DMU Results.

DMU Type	Crude specimen area with perforated walls (m ²)	Area of specimen perforations (cm ²)	Net area of the specimen with perforated walls (cm ²)	P Minimum thickness of the walls (mm)	T Minimum thickness of the partitions (mm)	
					Length (mm)	Width (mm)
H-10	201.16	21.00	180.16	09.85	55.19	09.35
H-15	285.95	20.26	265.69	10.29	52.37	07.79

In NTC 4205, the minimum values of RCU range between structural 30 and 50 kgf/cm² non-structural, in the sample the product H-10 approaches, but does not fulfill with the minimum parameters, and in the case of H-15 fulfills with the parameters of the standard only for the structural system (Table 2).

Table 2. RCU Results.

RCU Type	length (mm)	width (mm)	high (mm)	net area (cm ²)	Burst load per compression (kgf)	Compression resistance (kgf/cm ²)	Uncertainty (μ)
H-10	298.81	99.99	201.16	298.81	8726.00	29.24	± 5.50 kg/cm ²
H-15	289.45	146.10	194.47	422.88	18493.00	43.78	± 8.37 kg/cm ²

In the AAU, maximum values of 13% and 13.5% are established for indoor and outdoor use respectively (NTC 4205), in both cases the values are well below the percentage, this result represents an advantage, determining that lower values of AAU indicate lower open porosity, which translates into a lower capacity of the product to absorb water from the environment, as a criterion for products of excellent quality, a characteristic that in turn is favorable for reducing thermal conductivity (Table 3).

Table 3. AAU Results.

AAU Type	Dry mass of the average specimen (g)	Mass average specimen moisture (g)	Water absorption (%)	Uncertainty (μ)
H-10	4409.40	4692.66	6.44	$\pm 1.46\%$
H-15	5705.28	6006.30	5.28	$\pm 0.48\%$

In relation to the qualitative determination of EFU for block H-10 in general the sample did not report efflorescence on the edge, however, for block H-15 the sample presented a percentage of 5 to 25% slightly effloresced on the edge.

In general, the deviations in the samples are related to the production process, specifically to the characteristics of the raw material [9], the extrusion mold and the cutting process, parameters directly related to a correct calculation of contractions in drying processes and cooking [2,10].

3. Final procedure

3.1. Finite element method methodology

Applying the results of the initial procedure, the finite element method is used to determine the thermal behavior of sample H-10 and H-15, using CAE in software ANSYS R16 through CAD in software SolidWorks 2017 in parasolid extension, with standard masonry system models, the configuration used can be seen in Figure 4.

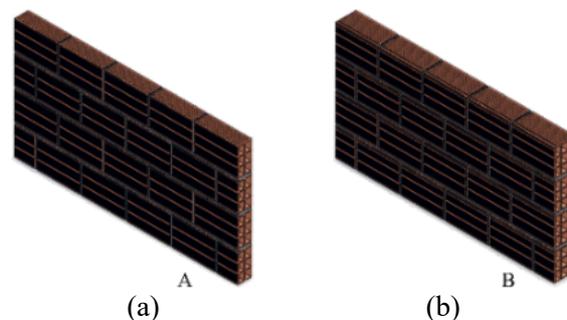


Figure 4. CAD in SolidWorks 2017 (a) H10 block and (b) H15 block.

3.1.1. Data. The data used for thermal conductivity for standard clay block and cement mortar [3] are: $k_{\text{Block}} = 0.391 \text{ W/m} \cdot ^\circ\text{C}$ and $k_{\text{Mortar}} = 0.88 \text{ W/m} \cdot ^\circ\text{C}$.

The data on local environmental conditions are taken from Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM) [11] for the month of July in the city of San José de Cúcuta, Colombia with: average maximum temperature = $33 \text{ }^\circ\text{C}$, average maximum solar radiation = 695.4 W.h/m^2 , $Q_{\text{Solar}} = 695.4 \text{ W/m}^2$, Wind speed average = 5.5 m/s and $\Delta t = 12:00 \text{ hours to } 13:00 \text{ hours} = 1 \text{ hour}$.

In relation to the calculated data, the coefficient of heat transfer by convection is the value that depends on the wind speed and the conditions of temperature and pressure, see Equation (2), where h = convection heat transfer coefficient, Nu = number of Nusselt, k = thermal conductivity of the air and L_c = assumed characteristic length of 30 cm .

$$h = \frac{Nu * k}{Lc} \quad (2)$$

The Nusselt number is a dimensionless value that describes the increase in the transfer of heat over a surface. For rectangular cross section and cross flow, see Equation (3), where Re = Reynolds number and Pr = Number of Prandtl.

$$Nu = 0,102Re^{0,675} * Pr^{1/3} \quad (3)$$

The Reynolds number is a dimensionless value that describes the behavior of the air flow on the surface of the block, see Equation (4), where ρ : density of the air, V : wind speed, μ : dynamic air viscosity.

$$Re = \frac{\rho * V * Lc}{\mu} \quad (4)$$

The properties of air at a temperature of 33 °C are taken from [12] and are: $\rho = 1.1526 \text{ kg/m}^3$, $k = 0.026102 \text{ W/m} \cdot \text{°C}$, $\mu = 0.000018858 \text{ kg/m} \cdot \text{s}$ and $Pr = 0.72736$.

By replacing the values in order of Equation (4), Equation (3) and Equation (2), a convection heat transfer coefficient of $h = 19.035 \text{ W/m}^2 \cdot \text{°C}$ is obtained as a result, to be applied to the outer section of the geometry, where the wind speed has an effect. For surfaces that are not enclosed as internal air chambers, a natural convection heat transfers of $h = 5 \text{ W/m}^2 \cdot \text{°C}$ is assumed [12].

3.1.2. CAE procedure. Each simulation was solved in 7 steps, defining: a) as System 01-A for H-10 format, and b) as System 02-A for Format H-15.

- 1) Analysis System Type: The schematic of the project formed by analysis system of the steady state thermal type was made, where the geometries were worked independently, assigning the same material of block and mortar.
- 2) Engineering Data: The supplied properties are entered into the ANSYS R16 database using the engineering data source and are related to all the analysis system.
- 3) Geometry: The import of the pieces was done in the design modeler and the geometry of the surface was optimized with face and edge correction.
- 4) Model: From this step we worked on the mechanical interface of ANSYS R16. Performing the assignment of cement material, block or mortar, and configuring the mesh to use the physical preference type CFD and the fluent solver.
- 5) Setup: in relation to the conditions to which all the pieces on the front face are exposed, the external conditions of wind and direct solar radiation, as well as natural convection on the rear face of the wall were applied, the values used are related below:
 - A: Convection ($5 \text{ W/m}^2 \cdot \text{°C}$)
 - B: Heat flow (695.4 W/m^2)
 - C: Convection ($19.035 \text{ W/m}^2 \cdot \text{°C}$)
- 6) Solution: For the analysis of the configurations, the two most relevant solutions are applied: Temperature distribution (Figure 5) and Total heat flow (Figure 6).

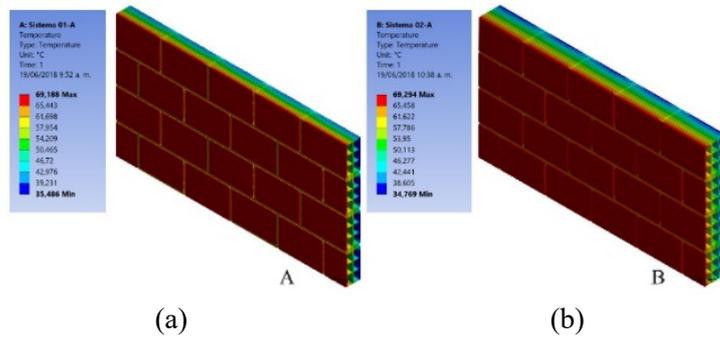


Figure 5. Temperature distribution isometry (a) H10 block and (b) H15 block.

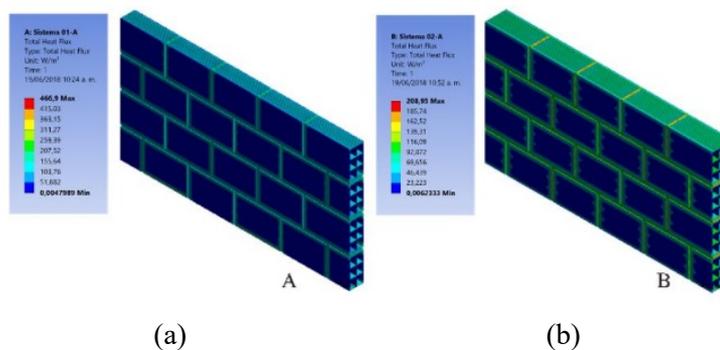


Figure 6. Heat flow isometry (a) H10 block and (b) H15 block..

3.2. Results

The results obtained show a temperature distribution profile for the H-10 block of 69.168 °C on average for the initial value of the exterior face and a final interior temperature of 35.667 °C average in the masonry system, with a loss of driving temperature of 33.501 °C in relation to a profile 99.99 mm wide that has solid (clay) and air phases in 6 rectangular cavities, reflecting 2.66 °C above the ambient temperature 33 °C (Figure 8). Regarding the thermal flow, a greater concentration of heat is evidenced on the partitions in relation to the walls of the block, reporting an average value of 4669.9 W/m² for partitions and an average value of 0.0047989 W/m² in walls, the results are shown in Figure 8.

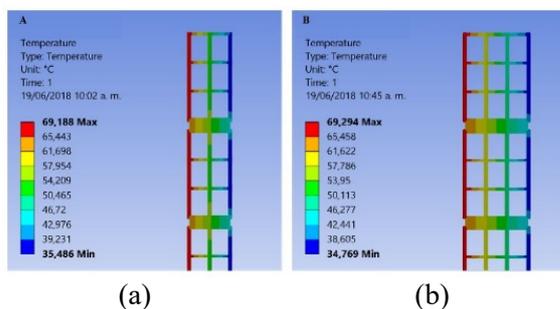


Figure 7. Temperature distribution profile (a) H10 block and (b) H15 block.

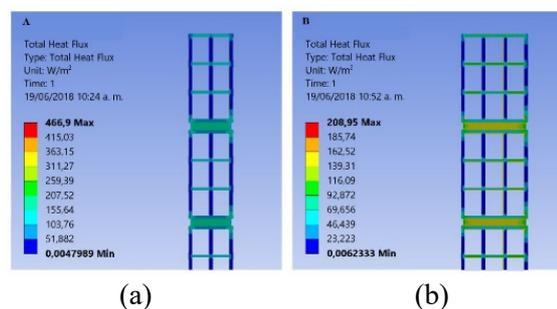


Figure 8. Heat flow profile (a) H10 block and (b) H15 block.

Table 4. Temperature distribution results.

Name	Average external temperature (°C)	Average internal temperature (°C)
System 01-A	69.168	35.667
System 02-A	69.287	34.958

Table 5. Heat flow results.

Name	Average heat flow in partitions (W/m ²)	Average heat flow in walls (W/m ²)
System 01-A	4669.9	0.0047989
System 02-A	208.95	0.0062333

In the case of block H-15 with a width of 146.10 mm, an initial value of 69.287 °C is reported for the exterior surface and an interior final temperature of 34.958 °C average in relation to the temperature distribution (Figure 7, Table 4), with a loss thermal of 34.329 °C by conduction considering a width value 46.11 mm greater than the H-10 format, as well as, 9 rectangular cavities, these characteristics establish a temperature of 1.958 °C on the environmental conditions of 33 °C. In the case of temperature concentration by heat flow (Figure 8, Table 5), similar characteristics are evidenced in both formats, with a concentration on the partitions of 208.95 W/m² on average, greater than that of the walls with 0.0062333 W/m² in average.

In the previous literature the physical, mechanical properties [2] and thermal conductivity [3] of the H-10 type product have been reported, as a contribution, this research presents for the first time the results of the physical-mechanical and thermal behavior for a product H-15, and a comparative evaluation of the variables between both construction pieces, considering an approximate increase of 50 mm in thickness and a difference of 6 cavities in Block H-10 to 9 cavities in Block h-15 at temperatures of 33 °C, in the results of thermal behavior it is possible to observe a decrease in the temperature transferred in Blocks H-15 due to the influence exerted by the 3 additional cavities where the thermal conductivity decreases by the increase of the air chambers, and the increase of the heat flow path through a greater mass due to the increase in thickness, where, in a standard H-10 block, the path consists of three solid phases (ceramic) and two gaseous (air) and 100 mm of partition wall extension as a thermal bridge, and Block H-15 of four solid phases and three gaseous phases (air) 150 mm of partition wall, showing that the increase in gas phases by presenting less conductivity ($k = 0.026102 \text{ W/m} \cdot \text{°C}$) favor the decrease in the final temperature transferred. These results are presented as a basis for the academic-scientific and technological development of new products with thermal insulating properties.

4. Conclusions

The characterization of DMU present a certain fluctuation with respect to the measure offered in the market, finding that for block H-10 a dimension L is determined: 298.81 mm, W: 99.99 mm, H:201 mm on average, and a L:289.45 mm, W:146.10 mm, H:194.47 mm on average for H-15 format; in relation to the thickness of partitions and walls it is reported that the dimensions in general comply with the NTC 4205 non-structural masonry. In values relative to RCU it is identified that only product H-15 complies with the regulations for structural system; On the other hand, the results of AAU show that the products manufactured in the region fulfill with quality standards for structural masonry and no structure for exterior and interior use. In the results by FEM method, a model of thermal behavior and distribution of heat fluxes was obtained under simulated conditions of warm tropical climate, specific for the city of San José de Cúcuta of 33 °C of temperature, wind speed of 5.5m/s and a solar radiation of 695.4 Wh/m², reporting 35.667 °C on average temperature on the interior surface of System 01-A with block H-10 and a temperature value of 34.958 °C on the final surface of system 02-A with block H-15; in the case of heat flow concentrations, greater accumulated heat was observed in partitions as direct thermal bridges, than on the walls of the blocks for both cases.

Regarding the comparative results, considering a variant of 46.11 mm in dimension A, in this study a difference of 0.709 °C was obtained between two types of product with similar morphologies, showing a reduction in final thermal energy, this variant presents an opportunity development to minimize the impacts of temperature loads in the envelope, which is favorable for warm tropical climates, however, it is necessary to consider that the results can be optimized when working on other factors such as thermal bridges in the partitions or the ceramic units' material composition as a contribution to the technological development of products with thermal efficiency properties that can positively impact sustainability challenges in the construction sector in Colombia.

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