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Characterization of the physical-mechanical and thermal behavior of a clay building unit designed with thermo-insulating attributes and a coffee cisco organic additive

To cite this article: M S Narváez-Ortega *et al* 2019 *J. Phys.: Conf. Ser.* **1386** 012084

Characterization of the physical-mechanical and thermal behavior of a clay building unit designed with thermo-insulating attributes and a coffee cisco organic additive

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Abstract: This research is articulated from the clay framework as material wealth of the region of Norte de Santander, Colombia, and seeks to structure attributes of passive thermal cooling in a ceramic piece for low cost masonry type block cooked with physical, mechanical and thermals feasible characteristics for warm tropical weather conditions of 33 °C on average. This work is based on previous studies that explores the partitions structure morphology in Blocks H10 establishing a model of 6 horizontal cavities for low thermal conductivity and having oblique geometry partitions to interrupt heat conduction by direct thermal bridge inside of the constructive unit called Form-C, which is taken as the object of analysis, adding 5% organic coffee cisco additive in the 95% clay mixture to increase the porosity with a proportion that does not affect the deterioration of the mechanical properties and allow to optimize the thermal insulation capacity regarding to a traditional product. Methodologies: in the first phase, prototypes of Block H10 with Form-A are manufactured by extrusion at the laboratory level as a comparative witness of the properties of a standard piece and Form-C as a piece with thermo-insulating strategies to execute physical-ceramic, geometric evaluations of mechanical resistance and water absorption applying the Norma Técnica Colombiana 4017 for masonry units. In the second stage, simulations of temperature distribution and heat flow are prepared by finite element method in ANSYS R16 software to determine the incidence of the variables in the mixture on heat transfer. The results obtained from thermal simulations show an energy decrease of 1.5 °C on average in relation to Form-A. In conclusion, the use of agro industrial scraps and the implementation of passive design techniques in the ceramic piece generate added value in a product that can be industrialized with improvements in technological properties from a thermal efficiency perspective in construction ceramics.

1. Introduction

The ceramic industry of the Norte de Santander, Colombia, it is immersed in a mineral context rich in clay deposits with physical-chemical properties of excellent quality for the manufacture of a wide variety of products for construction [1], constituting one of the most representative sectors of the economy; the derivatives of this industrial process shape the materiality of the buildings and, therefore, their components define to a large extent the thermal behavior of the local architectural covering.

From this perspective, in recent years this market niche has dabbled in the incorporation of thermal efficiency strategies from the axis of sustainability and innovation through the design of ceramic

products and materials with thermo-insulating attributes. In response, as an object of development this research takes the cooked block H-10 as one of the products with the best thermal opportunities when presenting a low conductivity (k Block 0.37 W/m °C at a temperature of 35 °C) in relation to other types of red clay products [2] and proposes a comparative study of a standard H-10 cooked block prototype and a product prototype with morphological attributes of passive cooling called Form-C (Figure 1); in relation to the design, this study is structured as an extension of a previous research process [3,4] in which results of temperature reduction of up to 0.981 °C were obtained with Form-C achieving an average temperature in the final surface of 34.505 °C when implementing an oblique partition morphology that interrupts the thermal bridge of the internal cells of the building without modifying the traditional material composition of 100% red clay (Figure 1).

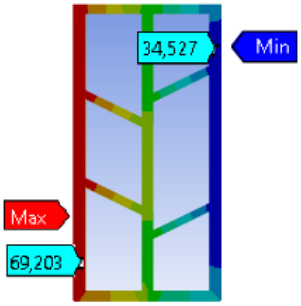

Figure 1. Form-C, temperature distribution.

Based on theoretical and practical background that show that the addition of coffee processing remainders in clay mixtures is a mechanism to generate pores by combustion at the time of cooking that improve the thermal properties of the material, and preserve the mechanical properties of a traditional mixture [5-9]. In this research a 5% concentration of coffee cisco is added as a substitute in the ceramic paste as an organic additive called M-CCC, to characterize its physical, mechanical and thermal performance implementing comparative methods to characterize the efficiency potential of the synergy of passive techniques in a new industrializable part that can contribute to the technological development of a ceramic material, applicable to warm tropical climates, an important approach, representing 80% of the climatic conditions in Colombia [10]; the implemented method allows to evaluate and report the behavior of new materials for the manufacturing of construction products as a contribution to the academic-scientific and industrial community, the results can strengthen the ceramic sector innovation processes.

2. Methodology

The purpose of this paper is to report the physical-mechanical and thermal characterization of the products named B-1 and B-2: B-1 as a witness of a traditional constructive unit of material composition 100% red clay and B-2 an innovative product Form-C with composition 95% red clay and 5% coffee cisco as a technological nutrient. The study is carried out using 2 methods: in the first phase, NTC 4017 [10] is applied in the in the laboratory of the Centro de Investigación en Materiales Cerámicos (CIMAC), Mexico, to determine the qualitative properties in a comparative analysis of ceramic physical analysis by extruded for masonry units (CPAE), determination of geometric characteristics of masonry units (DGCU), water adsorption in masonry units (WAU) and mechanical resistance to compression in masonry units (MRCU) between the two products. Subsequently, in the second phase, a finite element method (FEM) finite element method is used to analyze the thermal performance of the B-1 and B-2 parts in a comparative manner through profiles of temperature distribution and heat flow under specific parameters of San José de Cúcuta, Colombia as a case of application in warm tropical climate.

2.1. Method NTC 4017

2.1.1. Materials. In the development of this study, the NTC 4017 [10] was implemented to determine the physical-mechanical behavior by manufacturing prototypes at 1: 6 scale of parts B-1 and B-2 (Table 1), using two metal nozzles to be adapted to the extruder of the laboratory CIMAC of the Universidad Francisco de Paula Santander, San José deCúcuta , Colombia, where:

Table 1. Prototypes description.

B-1	Shape	Mouthpiece -1 (H10 traditional block type)
	Mixture	Mixture M-C (100% red clay)
B-2	Shape	Mouthpiece -2 (H10 proposed block type with Form-C)
	Mixture	Mixture M-CCD (95% red clay and 5% coffee cisco)

Two types of clay paste were used: the first mixture was called MC with a composition of 100% red clay from the municipality of Zulia, Norte de Santander, Colombia and it was prepared through a grinding and milling process (Figure 2 and Figure 3), and M-CCC as a mixture of 95% red clay and a concentration of 5% coffee cisco harvested from a traditional crop of the region, the coffee cisco was ground in a hammer mill and sieved in an 80-gauge mesh.

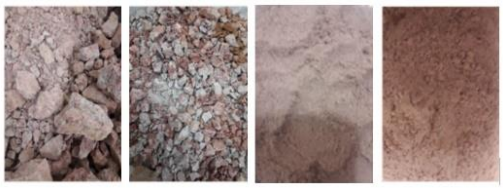

Figure 2. Preparation of clay; M-C (100% clay).

Figure 3. Preparation of coffee cisco; M-CCD (95% red clay and 5% coffee cisco).

2.1.2. Process. The manufacturing process required (8) steps: starting with the (1) preparation of the pastes where the mixture was made and (2) kneading the raw materials until completing a homogeneous texture.

For the elaboration of the analyzes, 30 specimens of each type B-1 and B-2 were manufactured, in a process of (3) extrusion, (4) cutting at approximately 80 mm (considering the linear shrinkage and loss of mass) and the (5) molding each piece (Figure 4). From this phase, 9 specimens are randomly selected to record length (mm) and mass (g) dimensions using a caliper and a scale of 1.500 g, under conditions of: wet, dry and cooked for analysis of CPAE.

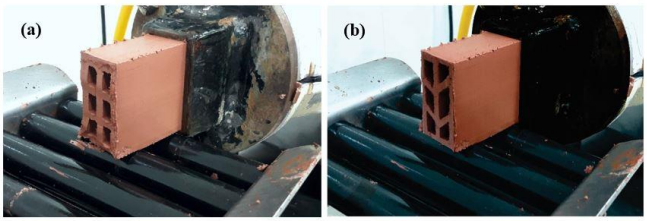

Figure 4. (a) B-1 and (b) B-2 extrusion.

In the last stage of manufacture, a process of (6) natural drying at room temperature for 24 hours is carried out, to later dispose the prototypes in a furnace of (7) artificial drying at 110 °C of temperature for 24 hours in a laboratory dryer; and finally, the (8) baking process at a 1000 °C of temperature for 48 hours is carried out.

2.1.3. Analysis. For the DGCU analysis, the medication of (9) cooked specimens of each form B-1 and B-2 is recorded, registering L: length, W: width, H: height, thickness of walls, thickness of partitions in (mm) and areas of the gaps (mm2) with a caliper to determine the average dimensions. In the determination of WAU, a 24-hour immersion method in water at a temperature of 30 °C is used for (9) specimens of each format without loose particles or cracks and are arranged on a metal mesh that allows the circulation of water all over the pieces' sides; its weight is recorded in a balance of 1.500 g, the calculation of absorption is made by the following Equation (1):

$$\%\ \text{Absorption} = \frac{100 \times (\text{Wss} - \text{Ws})}{\text{Ws}} \tag{1}$$

Ws: dry mass of the specimen before immersion (g) Wss: mass submerged in water of the saturated specimen after immersion in cold water (g).

The MRCU analyzes (Figure 5) are carried out by submitting 4 pieces of form B-1 and B-2 to loads in the same direction and position as they occupy in a masonry building system, applying a uniform loading speed of 0.8 mm/min, calculating the resistance with the following expression (Equation 2):

$$\text{Compressive strength C} = \frac{\text{W}}{\text{A}} \tag{2}$$

C: specimen resistance to compression (kgf/cm^2) W: maximum breaking load (kgf) A: average of the gross areas of the upper and lower surfaces of the specimen in cm^2

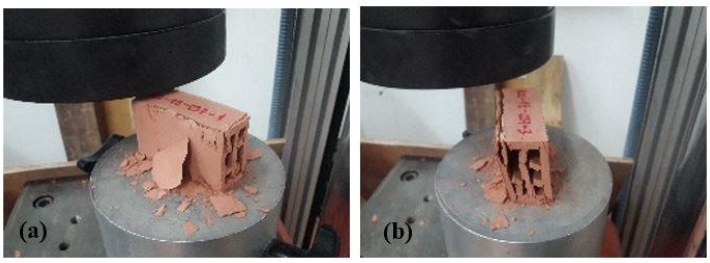

Figure 5. Analysis of MRCU of (a) B-1 and (b) B-2.

3. Results

Table 2. reports the physical-mechanical characterization of prototypes B-1 and B-2, the CPAE results show a reduction in drying shrinkage by the presence of 5% coffee cisco in the mixture with a higher percentage of water absorption and a mass loss difference of 4.67% between samples **(**Figure 6). In the MRCU analyzes a significant reduction of resistance in Sample B-2 is evident due to an increase in the porosity of the piece by the combustion of the compound Organic coffee cisco in cooking and the influence of the morphological modification of the septum

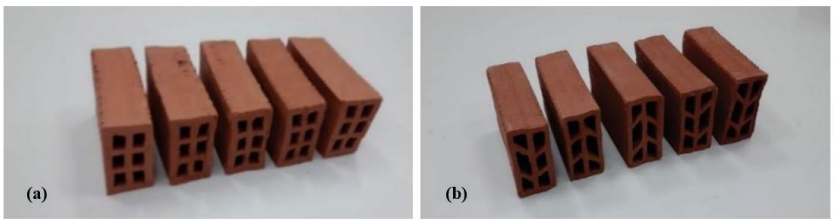

Figure 6. Prototypes (a) B-1 and (b) B-2.

Table 2. Results physical-mechanical characterization of constructive unit M-C and M-CCD.

Average results		M-C	M-CCD
CPAE Analysis	Contractionn (%)	01.24	00.97
	Lost mass (%)	05.30	09.97
	Water adsorption (%)	11.50	16.23
DGCU Analysis	L (mm)	68.34	72.62
	W (mm)	25.52	21.50
	H (mm)	45.28	44.76
	Wall (mm)	04.38	03.57
	Partition wall (mm)	03.87	03.54
	Area of gaps (mm^2)	44.18	43.47
WAU Analysis	Water absorption percentage (%)	75.17	79.65
MRCU Analysis	Compressive strength (kgf/cm^2)	08.51	03.53

3.1. FEM Method

3.1.1. Materials. Computer-assisted engineering (CAE) is used in software ANSYS R16 through computer assisted design (CAD) in software Solidworks 2017 in Parasolid extension, with models of the constructive units in B-1 and B-2. With the objective of characterizing thermal behavior through comparative analysis in distribution results of pieces' temperature and heat flow.

3.1.2. CAD Procedure. The data used for thermal conductivity for M-C and M-CCD [6], and the local environmental data are taken from Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM) [11] in September, San José de Cúcuta, Colombia. There, kclay: 0.407 W/ m °C, kcoffee cisco: 0.335 W/ m °C, average maximum temperature: 33 °C [9], average maximum solar radiation: 796.8 W h/m^2, $QSolar$: 796.8 W/m^2, average wind speed: 4 m/s, Δt: 1 hour, k: 0.407 W/ m °C.

In relation to the calculated data, the coefficient of heat transfer (Equation (3)) by convection is the value that depends on the wind speed and the temperature conditions and the pressure in which it is:

$$h = \frac{\mathrm{Nu} * \mathrm{k}}{\mathrm{Lc}} \tag{3}$$

h: Convection heat transfer coefficient. Nu: number of Nusselt. k: air thermal conductivity. Lc: assumed characteristic length of 20 cm.

The Nusselt number (Equation (4)) is a dimensionless value that describes the increase in heat transfer over a surface. For rectangular cross section and cross flow, it is:

$$Nu = 0{,}102\, Re^{0.675} * Pr^{1/3} \tag{4}$$

Re: Reynolds number. Pr: number of Prandtl. The Reynolds number (Equation (5)) is a dimensionless value that describes the behavior of the air flow on the block surface

$$Re = \frac{\rho * V * Lc}{\mu} \tag{5}$$

ρ: Density of the air. V: Wind speed. μ: Dynamic air viscosity. As follow, the properties of air for a temperature of 33 °C [12] are described. ρ: 1.1526 Kg/m^3; k: 0.026102 $W/m\,°C$; μ: 0.000018858 $Kg/m\,s$; Pr: 0.72736.

Replacing the values in order of the Equation (5), Equation (4) and Equation (3), we obtain as a result a heat transfer coefficient by convection of h= 17.5154 $W/m^2\,°C$ that will be applied to the section

outside of geometry, where the wind speed has an effect. For surfaces that are not enclosed as internal air chambers, a natural convection heat transfer coefficient of $h = 5\ W/m^2\ °C$ is assumed [12].

3.1.3. CAE procedure. Each simulation was solved in 7 steps (Figure 7).

Figure 7. CAE procedure, simulation (A): Block H-10 with the traditional form and 100% clay as material; simulation (B): Block H-10 with form 2 and clay with 5% coffee cisco as material.

The conditions to which blocks H10 are subjected are shown in Figure 8. On the front face, the external condition of the wind and solar radiation is applied, and on the rear face, the internal condition of natural convection is applied. Where: A: Convection 1 (5 $W/m^2\ °C$), B: Heat flow (796.8 W/m^2), C: Convection 2 (17.5154 $W/m^2\ °C$).

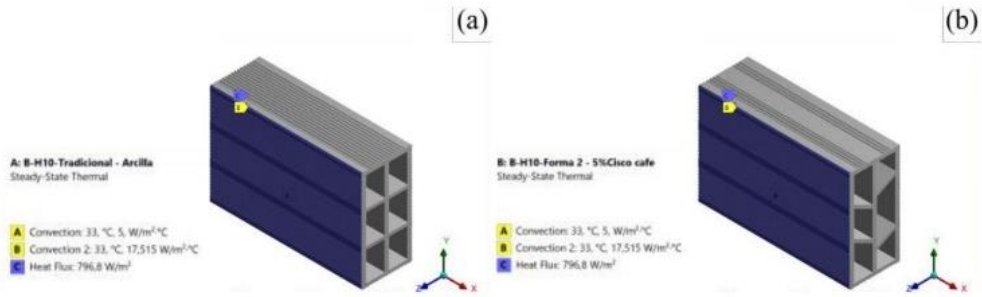

Figure 8. Conditions applied to the model, (A) simulation A, (B) simulation B.

Figure 9 and Figure 10 report the thermal characterization of the pieces, whose results show a greater average heat flow over the partitions of the M-C sample with 187.69 W / m2 in relation to 134.4 W / m2 of M-CCC (Table 3 and Table 4), it being possible to deduce a heat loss of 77,964 ° C in Form-A and 78,170 ° C in the Form-C sample, evidencing in comparative results that the presence of 5% coffee cisco in the mixture and the modification of the morphology of the cells allows to reduce the thermal conductivity of the ceramic product, a positive result to decrease the temperature transferred by ceramic envelopes for masonry with block type H10, reducing the temperature inside the buildings, with an opportunity in the decrease of energy consumption by active air conditioning in warm tropical climate zones.

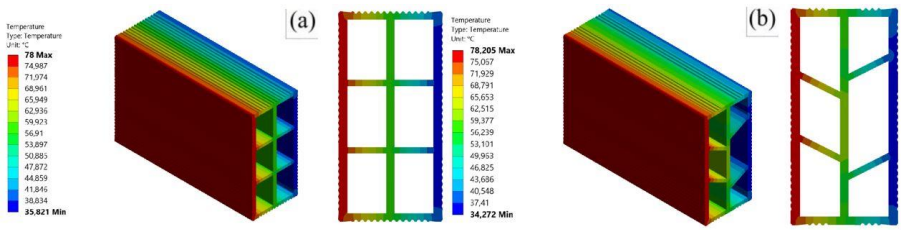

Figure 9. Temperature distribution.

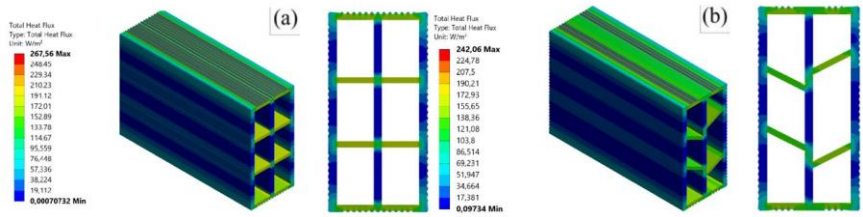

Figure 10. Heat flow

Table 3. Thermal characterization results by temperature distribution of constructive unit M-C and M-CCD.

Product	Maximum Temperature Initial surface (°C)	Minimum Temperature Final Surface (°C)
Form A	78.000	35.821
Form C	78.205	34.272

Table 4. Thermal characterization results of heat flow of constructive unit M-C and M-CCD.

Product	Heat flow (w/m^2)		
	Maximum	Minimum	Average
Forma A	267.560	29.930	187.690
Forma C	242.060	15.502	134.400

4. Conclusions

The results of the physical-mechanical properties characterization show in CPAE analysis a lower contraction in the samples with M-CCC in a percentage of 0.96% with a greater mass loss close to 10% and water adsorption of 16.23% associated with the porosity resulting from the calcination of the coffee cisco additive, this is reflected in the analysis of WAU in cooked condition where the sample MC presents 75.17% and M-CCC a 79.65%, in relation to MRCU, the M-CCC with form B-2 shows a decrease in compressive strength in relation to the traditional MC sample with B-1 form close to 41%; Regarding the thermal behavior, it is possible to achieve a reduction of 1,549 °C in average of a piece B-2 with Form-C in relation to a piece with standard characteristics B-1 type traditional block H-10, verifying that the application of technological nutrients and the innovation in the shape of the partitions allow adding value to a piece of construction for a warm tropical climate; the results of the research allow us to verify that adding heat insulating passive strategies from the design process is an effective method to generate sustainable responses in low cost products from an axis of thermal efficiency. The methodology implemented establishes a starting point for the design and innovation processes in the ceramics industry, where it is possible to characterize the designs by applying technical analyzes at a laboratory scale within previous innovation processes to industrial development.

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