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Utilization of agro-industrial waste to improve thermal behavior of products made of fired clay for traditional masonry

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Abstract. The reutilization of agro-industrial waste in the manufacture of fired clay products is a sustainable strategy that aims at the circular economy. The most known waste in Norte de Santander, Colombia, are coffee husk and rice husk. For this reason, this research studies the thermal impact of their insulating properties in traditional masonry products made of fired clay to be considered as insulating additives. The methodology involves the simulation of heat transfer and heat flux of the multiperforated brick and H10 block manufactured in mixtures of 100% clay and 95% clay and 5% additive to wastes in North Santander, Colombia, in the software ANSYS under the finite element method in extreme conditions of San José de Cúcuta. The results demonstrate that the residues of rice husk and coffee husk act as insulating technological nutrients with a reduction of temperatures of the interior surfaces of the products between 0.22 °C and 0.88 °C, respectively. The reutilization of residual raw materials from alternate construction industries is a sustainable consideration to evaluate new possibilities for the manufacture of products with less embedded energy and, therefore, with a lower carbon footprint than traditional fired clay products.

1. Introduction

The reuse of agro-industrial waste in the industry of fired clay construction products has established new guidelines for the responsible consumption of waste. In Norte de Santander, Colombia, the residues from the rice and coffee industries stand out: rice husk and coffee husk, respectively, which are potential alternatives as additives to improve thermal properties of the products.

The annual rice production was about 3.000.000 tons during 2016, with the participation of 6.2% of Norte de Santander, Colombia [1]. The residues of rice husk represent 20% of the Colombian production [2]. According to the above, the volume of this residue is considerable and therefore, its properties should be examined for future applications.

On the other hand, the panorama of coffee production is lower than rice production. Nevertheless, in 2014, almost 800.000 tons of dry parchment coffee were registered throughout the national territory. According to the census of agro-industrial crops, 13.2% of the production of these crops corresponds to coffee, with the participation of 2.2% from Norte de Santander [3]. Like rice, coffee production generates different types of residues, such as coffee pulp, coffee mucilage, husk, stems and damaged coffee beans that can be used in other industries [4]. In the case of coffee husk, it represents 4.2% of the weight of fresh coffee fruit [5].

The above data is the reason why the reutilization of rice husk and coffee husk is a sustainable strategy in the manufacture of fired clay products for construction. The main advantages are the reduction of energy transfer in envelopes that consider these residues due to their low thermal conductivity [6-11], reduction of the carbon footprint [11] and pollution of water sources, because of waste as rice husk and coffee husk are difficult to decompose and hence, they are not suitable for human and animal consumption. For this reason, industries prefer to use them as biomass or throw them in rivers [12,13].

Then, this paper introduces the analysis of heat transfer and heat flux of individual mixtures of clay fired with 5% coffee husk and 5% rice husk applied in the multi-perforated brick (MB) and the H10 block (B-H10). In order to assess the impact of thermal behavior of the agro-industrial waste in traditional products of Norte de Santander for masonry.

2. Methodology

The methodology is divided into 2 main phases: Identification of raw material and typology of product for masonry and analysis of heat transfer and heat flux simulations.

The first stage identifies and describes the physical, chemical and thermal properties of rice husk and coffee husk as additives in clay mixtures. In addition, typology of products selects MB and B-H10 as the most commercialized traditional masonry products in the ceramic industry of Norte de Santander, Colombia. The product model is made by drawing in 2 dimensions (2D) and in 3 dimensions (3D) in the AutoCAD software, taking into account the measurements defined in the product catalogue of Induarcilla [14].

Second, analysis of heat transfer and heat flux simulations consists of assessment of temperature distribution and energy concentration values along the surfaces of MB and B-H10 in the ANSYS software through the finite element method (FEM).

The data supplied for the simulation are 3D modeling of the products in initial graphics exchange specification (IGES) format, conductivity of the materials, weather conditions of the environment and flux applied on the surfaces of the products. Next, Table 1 describes the name, composition and conductivity of the mixture applied to 3D modeling of MB, B-H10 and mortar joints in the simulation.

The data provided for the weather conditions are from the city of San José de Cúcuta located in Norte de Santander, Colombia. The month selected was September because its solar incidence is the highest in the year (796.8 Whm^2) and therefore, the average maximum temperatures is 33 °C, mainly from 12:00 to 13:00 hours and the average wind speed is 4 m/s [16].

Table 1. Composition and conductivity of the mixtures.

Name	Composition	Conductivity (Wm°C)
M C	100% Clay	0.407 [11]
M CRH-5	95% clay and 5% rice husk	0.388 [11]
M CCH-5	95% clay and 5% coffee husk	0.325 [11]
Mortar	-	0.880 [15]

The types of flux that intervene in the mechanisms of heat transfer are expressed in Table 2 and vary according to the exposure of the surface which is applied. Heat transfer by radiation and heat transfer coefficient by convection act on the outer surfaces, meanwhile the natural convection flow acts in the inner surfaces.

Table 2. Flux applied on the surfaces of the products.

Flux type	Value
Heat transfer by radiation	796.8 Whm^2
Heat transfer coefficient by convection	25.903 Wm² °C
Natural convection of interior surfaces	5 Wm² °C

3. Results and discussion

3.1. Identification of raw materials and typologies of products

The identification of the properties of rice husk and coffee husk is essential to relate all the benefits obtained from the implementation of residues in the manufacturing processes of products in fired clay for masonry. Typologies of products describes MB and B-H10 because they are leading masonry products in the Norte de Santander, Colombia, market [25].

3.1.1. Raw materials. Figure 1 shows rice husk (a) and coffee husk (b) in their natural state, before any grinding or sieving preparation.


(a) (b)

Figure 1. Agro-industrial waste as technological nutrients: Rice husk (a) and coffee husk (b).

The main chemical components of rice husk are 15.56% of silicon in the inorganic phase [7,11], which means complex material biodegradation, not for suitable food. This first aspect classifies rice husk as an alternative for the generation of new materials for construction [17]. In addition, its low conductivity is ideal for the design of insulating envelopes (0.0036 Wm°C) [18].

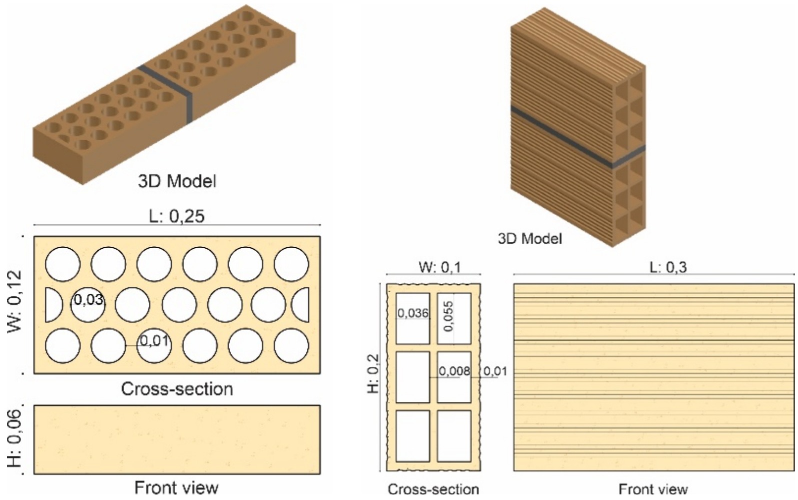
Rice husk is resistant to fire [6,19]. Nevertheless, the material undergoes calcination processes after 1000 °C, since it presents 84% loss on ignition (LOI) in its chemical composition [7,11]. In the case of the production of bricks and blocks with rice husk as an additive, this property generates pores in the fired clay mixture and therefore, the alteration of the physical-mechanical properties of the final product [8]. For this reason, it is common that the preparation of raw materials uses sieves to obtain granulometries of small particles for the manufacture of new construction elements [8,20].

A the same as rice husk, coffee husk is an organic material with high percentage of LOI (98.24%) [10]. Although it is a potential material for combustion [4,12,13], it is also optimal for construction because of its difficult decomposition and thermal and acoustic insulating properties [10,11,21]. Due to the wavelength, coffee husk is able to absorb high frequencies [21].

Definitely, the calcination of the material in bricks and blocks firing processes implies alterations in the mechanical resistance to compression, water absorptive capacity and heat resistance [10,11], [22]. Notwithstanding thermal benefits, the addition of coffee husk reduces 40% compressive strength according to the percentage of the additive in the mixture [22], which is an aspect that must be examined due to the requirements established by NTC 4205 [23].

Furthermore, chemical composition of coffee husk presents low concentrations of sulfur, which means probability of surfaces affectation of the products in fired clay due to the evaporation of sulfates from both clay and the coffee husk [24]. Fortunately, the values of this element are minimal and risks by efflorescence also [10, 11].

3.1.2. Typologies of products. Figure 2 illustrates 3D model and 2D drawing dimensions of length, width, height, partition thickness and perforation size of MB and B-H10. MB is a brick with smooth surfaces and vertical cylindrical perforations (18 units) in a format of width (W) 120 mm, length (L) 250 mm and height (H) 60 mm [23]. The average width of the partitions is 10 mm, the diameter of the perforations is 30 mm [14] and the perforated area is 42.41% of the entire cross section. On the other hand, B-H10 is a building element with scratched surfaces, the horizontal perforations are rectangular prisms (6 units) orthogonally aligned in a format of W=100 mm, L=300 mm and H=200 mm [23]. The average width of interior partitions is 8mm and exterior walls is 10 mm [14]. On the contrary of MB, the perforated area of B-H10 is 59.4%.



(a) (b)

Figure 2. Dimensions of MB (a) and B-H10 (b): Measurements of L, W, H, width of partitions (P) and perforations.

3.2. *Analysis of heat transfer and heat flux simulations*

The heat transfer simulation estimates the distribution of temperatures and heat fluxes LM and B-H10 in Table 1 registered mixtures. Assuming that the thermal conductivity of the mixtures with 5% agro-industrial waste are less than M C, which works as a comparative standard.

The values recorded in Table 3 M CRH-5 reduces 0.2 °C and 0.33 °C the temperature of the interior surface in B-H10 and MB, respectively. Meanwhile, products made in M CCH-5 reach a decrease of 0.88 °C in MB and 0.84 °C in B-H10.

Table 3. Values of heat transfer and heat fluxes of MB and B-H10 in M C, M CRH-5 and M CCH-5.

Type of product	Mixture	Temperature distribution °C		Heat flux W/m^2	
		External surface	Inner surface	Maximum	Minimum
MB	M C	75.93	42.46	216.15	0.15
	M CRH-5	76.02	42.13	217.77	0.09
	M CCH-5	62.26	41.58	217.36	6.41
B-H10	M C	77.70	37.12	346.80	0.11
	M CRH-5	77.74	36.92	336.83	0.02
	M CCH-5	77.88	36.28	304.97	0.13

The implementation of 5% of coffee husk in a fired clay mixture means the improvement of the thermal properties between 2.07% and 2.26% while the benefit of the rice husk is only 0.54% and 0.77% in B-H10 and MB, respectively. At first sight, the improvement in the thermal performance of products with nutrient technologies appears to be minimal.

The advantages not only transform the products properties, but also contribute to the reduction of the carbon footprint in the production processes, the prolongation of the useful life cycle of an agro-industrial waste and the reduction of the contamination of water sources [11,12].

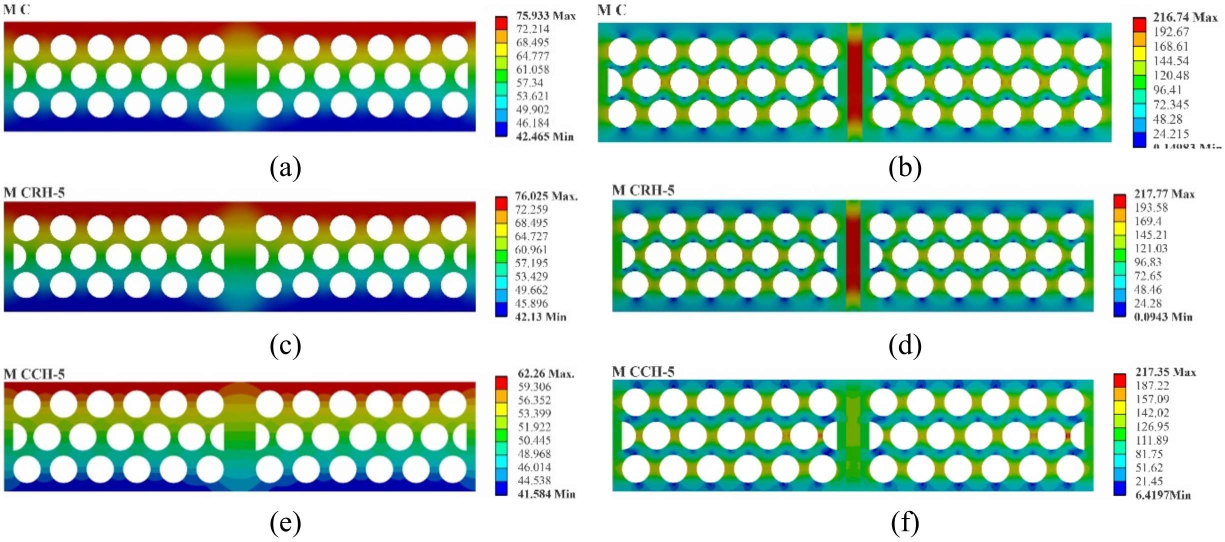
Second, Table 3, Figure 3 and Figure 4 prove that not only the conductivity of materials but also, the shape of the product and facades also influences the thermal behavior [22,26,27]. Because the record of interior surface temperature of B-H10 varies between 5.21 °C and 5.34 °C less than interior surface temperature of MB. On the contrary, exterior surface temperature of B-H10 exceed between 1.71 °C and 15.62 °C at MB. To sum up, the comparison of temperature distribution profiles positions B-H10 with better thermal performance on the internal surface compared to MB in M C, M CRH-5 and M CCH-5.

In addition to analysis of temperature distribution, this paper assesses heat flux of MB in M C, M CRH-5 and M CCH-5, show in Figure 3 and Figure 4. The main thermal bridge is concentrated in the mortar joints (between 142.02 Wm^2 and 271.1 Wm^2) and the partitions adjacent to the mortar joints (between 67.87 Wm^2 and 77.15 Wm^2 in B-H10 and between 96.83Wm^2 and 126.95Wm^2 in MB).

On the other hand, Figure 3 shows areas where the energy concentration decreases associated with the interior and exterior surfaces of MB and the longitudinal stripes between the rows of cylindrical perforations (66.68 Wm^2 and 121.03 Wm^2). Similarly, B-H10 areas with lower energy concentration are also interior and exterior surfaces of the product and its vertical partitions (between 0.018 Wm^2 and 0.13 Wm^2).

Furthermore, B-H10 perforated area exceeds 17% the perforated area of MB, notwithstanding, MB has more perforations than B-H10. This fact interferes during heat transfer because of perforations, as air chambers, exchange energy by convection. As it is shown in studies of product characterization in fired clay with additives of technological nutrients, most known as agro-industrial waste, the main effect on heat flux patterns is due to the geometry of the cavities that conform the product design, but the variation in temperatures due to the formulation of the mixtures is less disruptive [28-30].

The above is shown in Figure 3 and Figure 4, the design of perforations plays a fundamental role because it defines the energy concentration according to the variation of raw material conductivities between MC, M CRH-5 and M CCH-5 is minimal compared to the difference between in heat concentration values according to the shape of the product, for this reason the temperature difference between MB and B-H10 reaches 5 °C.

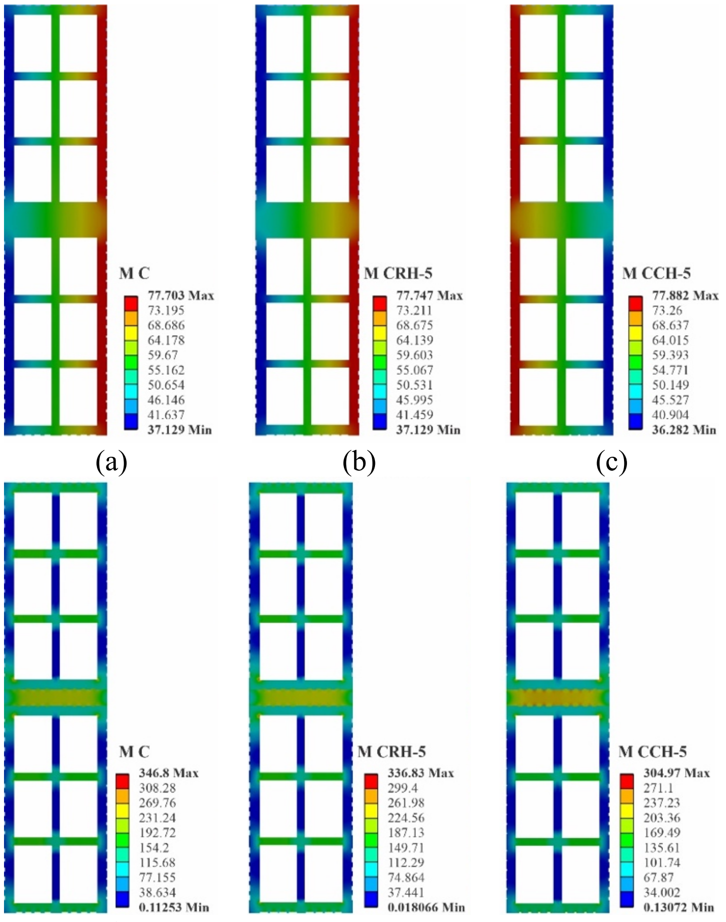


(a) (b)

(c) (d)

(e) (f)

Figure 3. Simulation of MB heat transfer. Temperature distribution profiles (°C) of M C (a) M CCH-5 (c) M CCH-5 (e) and heat fluxes (W/m^2) in M C (b), M CRH-5 (d) and M CCH-5 (f).



(a) (b) (c)

(d) (e) (e)

Figure 4. Simulation of B-H10 heat transfer. Temperature distribution profiles (°C) of M C (a) M CCH-5 (b) M CCH-5 (d) and heat fluxes (W/m^2) in M C (d), M CRH-5 (e) and M CCH-5 (f).

4. Conclusions

Finally, the reuse of rice husk and coffee husk as an additive for products manufactured in fired clay is a sustainable strategy that not only improves thermal performance of the products, but also reduces pollution and lengthens the useful life cycle of these agro-industrial residues.

The analysis of heat transfer and heat fluxes demonstrates the improvement in the temperature distribution in the products with rice husks and coffee beans. Thermal benefit of coffee husk addition varies between 2.07% and 2.26%, while thermal benefit of rice husk addition varies between 0.54% and 0.77%. On the other hand, pattern energy concentration is similar in each type of product due to energy behaves according to the shape and concentration values vary conductivity but does not alter the pattern of heat flux.

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