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Improvements in the thermal behavior in the manufacture of the H10 block using coffee husks as an alternative industrial additive

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Abstract. Industrial organic waste reuse in product manufacturing processes is a strategy that strengthens the circular economy. Thanks to materials science, the coffee husk is considered a sustainable alternative that promotes industrial processes optimization in the ceramic industry and contributes to the energy efficiency of buildings. This paper summarizes the behavior of H10 blocks on a laboratory scale in 2 mixtures of clay and coffee husk fired in 3 different temperatures: 900 °C, 1000 °C, and 1100 °C, at the "Centro de Investigación en Materiales Cerámicos, Universidad Francisco de Paula Santander", Colombia; and evaluates the relationship of physical and mechanical properties with thermal behavior by heat transfer and heat fluxes, simulated in the analysis system software through the finite element method. The results support the improvement of thermal insulation capacity. Due to this, coffee husk combustion generates internal air chambers that increase the porosity of the product. In spite of, physical and mechanical properties contrast thermal benefits with increasing water absorption percentages and thus decreasing the compressive strength of samples. In conclusion, new materials development is a technological advance that expands possibilities to create new solutions for buildings and even improves standardized designs in the ceramic industry.

1. Introduction
Circular economy is a strategy focused on the waste reuse generated in industrial processes in order to reduce the environmental impact of pollution. This initiative promotes the study of waste potentials to be implemented in new production processes in order to optimize them and extend life cycle of these resources [1]. From this situation, new materials and products can be obtained to improve people quality of life from reduction of energy consumption, thermal insulation, among others [1,2].

A particular case is coffee industry which generates around 7 by-products, among them is coffee husk, obtained in the threshing process [3]. Thanks to its combustible properties, its main application in Colombia is limited to be a source of energy for furnaces [3,4]; nevertheless, there are studies that demonstrate coffee husk and derivatives scope in the manufacture of building products. Among the main advantages of this additive, highlights thermal insulation capacity of the resulting from porosity and water absorption increase of the product [5-9]; nonetheless, coffee husk incidence in ceramic industry may affect the mechanical resistance to compression, bending and tension [1,5,7].

In this sense, this study analyses the scope and possible benefits that could be obtained through coffee husk implementation in the manufacture of H10 block of San José de Cúcuta metropolitan area, Colombia. The research process is shown below, from characterization of chemical, structural and morphological components of clay and the coffee husk, through characterization of technological and thermal properties that validate new product performance with coffee husk. Likewise, H10 block is validated in 100% clay to compare the results and conclude the study contributions.

2. Methodology

Coffee husk implementation, as an alternative of industrial additive, in the manufacture of the H10 block at laboratory scale was developed at the "Centro de Investigación en Materiales Cerámicos (CIMAC), Universidad Francisco de Paula Santander", Colombia. Before starting H10 block manufacture, raw material characterization was carried out through X-ray diffraction (XRD), X-ray fluorescence (XRF) and scanning electron microscopes (SEM). For the blocks manufacture, two mixtures were formulated with different concentrations of coffee husk. The particle size of the coffee husk is 177 µm (80 mesh), approximately. The formulation of ceramic pastes to be used in the present study is in the Table 1.

Table 1. Formulation of ceramic pastes of H10 block manufacturing.

Name	Composition
M C	100% clay
M CCH-5	95% clay and 5% coffee husk
M CCH-10	90% clay and 10% coffee husk

Following ceramic pastes preparation, manufacturing was carried out at the laboratory level in the CIMAC. The processes executed in this part were: extrusion, drying and firing. The samples were kept in a rest period of 24 hours after being extruded. Following 24 hours, samples were subjected to a drying oven at 110 °C to culminate with firing at 900 °C, 1000 °C and 1100 °C. Each of the samples cooked at different temperatures was exposed to tests of linear shrinkage, water absorption and compressive strength under the guidelines of the Colombian technical standard NTC 4017 [9] in the CIMAC laboratory. Each of fired samples at different temperatures was exposed to tests of linear shrinkage, water absorption and compressive strength under the guidelines of Colombian technical standard NTC 4017 [10] in the CIMAC laboratory.

Finally, thermal properties characterization of H10 blocks with coffee husk was performed through simulations of distribution of temperatures and heat fluxes in the analysis systems (ANSYS) software. This exercise conditions were established (Table 2), according to the conductivity of the materials [1] and environmental conditions of San José de Cúcuta, Colombia, in the month of highest solar incidence, September [11].

Table 2. Data provided for thermal properties characterization of H10 block.

Material conductivity	Environmental conditions (San José de Cúcuta, Colombia)
k M C = 0.691W/m•°C	Maximum average temperature: 33 °C
k M CCH 5% = 0.347 W/m•°C	Average maximum solar radiation: 796800 W•h/m^2
	Time: 12:00-13:00 hours = 1 hour
	Qsolar: 796.800 W/m^2
	Average wind speed: 4 m/s

3. Results and discussion

3.1. Structural, chemical and morphological composition of clay and coffee husk

The characterization of the raw material presents the relationship between structural, chemical and morphological components of clay and coffee husk. Besides, it is a basis for the physical, mechanical and thermal properties of H10 block.

Quantitative analysis of clay structural composition enhances quartz in the crystalline phase and muscovite and kaolinite, as show the Table 3. Anatase and microcline are present in small concentrations. Chemical composition records presence of high content of silicon, iron, magnesium and calcium. The percentage of losses on ignition (LOI) is low (6.280%), which could be assumed that there is a proportional relationship with the absorptive capacity of the fired material [1]. Finally, morphological characterization not only allows to see the particle size (between 200 µm and 1µm), but also exposes heavy materials concentration such as iron on the surfaces of site 3, as show the Figure 1.

Table 3. Quantitative analysis of clay structural composition.

Phase		Name	Quantitative (% weight)
Crystalline	SiO_2	Quartz	47.400
	$KAl_3Si_3O_{10}(OH)_2$	Muscovite	10.700
	TiO_2	Anatase	0.400
	$Al_2(Si_2O_5)(OH)_4$	Kaolinite	14.400
	$Ca(CO_3)$	Calcite	Not quantifiable
	Fe_2O_3	Hematite	1.100
	$CaO_2(Al, Mg)_2Si_4O_{10}(OH)_2H_2O$	Montmorillonite	Not quantifiable
	$K(AlSi_3O_8)$	Microcline	0.900
Total crystalline			74.900
Amorphous and others			25.100

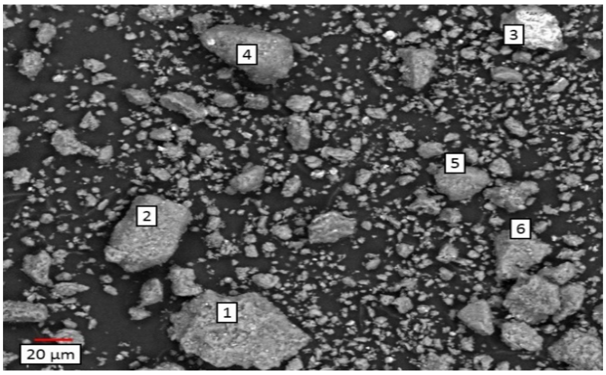

Figure 1. Clay micrograph obtained from scanning electron microscopy SEM. [10].

Despite the clay, coffee husk presents low quartz content, revealing that is an amorphous material. Chemical characterization registers high percentages of LOI (98.240%), due to organic composition of material; nevertheless, residues by calcination may partially replace clay, thanks to alkali and alkaline earth properties for vitrification process optimization of new products. On the other hand, low sulfur concentrations are also recorded, which could be reflected in efflorescence, as show the Table 4.

Table 4. Quantitative analysis of the structural composition of the coffee cisco.

	Phase	Name	Quantitative (% weight)
Crystalline	SiO_2	Quartz	0.400
Total crystalline			0.400
Amorphous and others			99.600

Morphological characterization of coffee husk is less uniform than clay. Figure 2 shows two types of particles that vary in shape and size; average particle size of elongated shape is 150 µm (length) by 60 µm (width), the others vary between 300 µm and 500 µm. On account of LOI high percentages, this formal quality of grains may have a negative effect on water absorption and resistance properties.

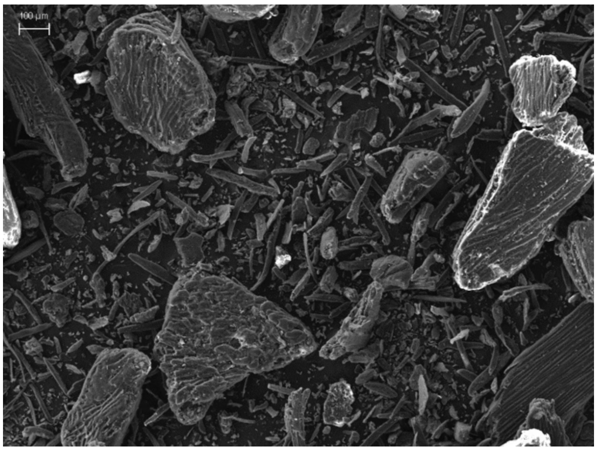

Figure 2. Micrograph of coffee husk obtained from scanning electron microscopy SEM.

3.2. Technological properties of the specimens

H10 blocks manufactured in laboratory scale of CIMAC were assayed by linear shrinkage, water absorption and mechanical compression strength. Figure 3 shows part of extrusion manufacturing processes of H10 block in M CCH-5, this process was repeated in mixtures M C and M CCH-10.

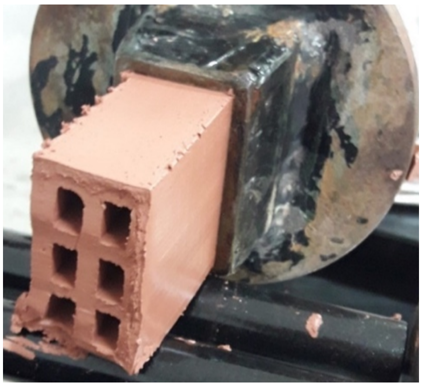

Figure 3. Extrusion process of H10 block in laboratory scale.

Table 5 reports result obtained in tests of linear shrinkage, water absorption, and mechanical resistance of products manufactured in M C, M CCH-5, and M CCH-10 at 900 °C, 1000 °C, and 1100 °C; drying shrinkage decreases as coffee husk concentration in the mixtures increases. Otherwise, firing shrinkage is affected by firing temperature and nutrient concentration, it is observed a direct relationship between both parameters since samples in M CCH-10 triple firing shrinkage compared to the samples in M C.

In contrast to firing shrinkage, water absorption has an inversely proportional relationship between firing temperature and coffee husk concentration in ceramic paste; since, as firing temperatures increase, absorption capacity significantly reduces between 16% and 44%, this change was observed in cooked samples at 1100°C. Nevertheless, such property intensifies with coffee husk concentration [1,9]. According to NTC 4205 [12], M C samples do not meet minimum requirements but samples with coffee husk reach minimum percentages for exterior horizontal drilling masonry units (M CCH-5 at 900 °C and 1000 °C; M CCH-10 at 1100 °C) and interior (M CCH-10 at 1100 °C).

Finally, it is observed that mechanical compressive strength is also conditioned with firing temperature variation and percent concentration of coffee husk. Nevertheless, this case differs with absorptive capacity behavior against these factors; due to, resistance increases with increasing firing temperatures in each of mixtures but decreases with increasing additive, coffee husk; like other authors [1,5], compressive strength weakens depending on percentage of substitute material. Despite this mechanical disadvantage, M CCH-5 and M CCH-10 samples comply with regulations for non-structural masonry units in horizontal drilling typology in NTC 4205 [12].

Table 5. Properties of linear shrinkage, water absorption and compressive strength.

Material	Temperature (°C)	Drying shrinkage (%)	Firing shrinkage (%)	Water absorption (%)	Compressive strength (Kg•f/cm^2)
	900		0.310	12.030	35.330
M C	1000	8.350	0.180	11.210	36.420
	1100		0.460	6.790	38.290
	900		0.890	14.710	25.500
M CCH-5	1000	6.730	0.850	14.160	28.710
	1100		1.060	11.730	29.540
	900		2.770	18.220	24.790
M CCH-10	1000	6.570	3.230	17.860	25.610
	1100		3.980	15.180	26.980

3.3. Thermal validation

Thermal validation defines energy transfer and fluxes according to the material conductivity. For example, the presence of polystyrene demonstrates that the more concentration of additive is less the conductivity of the material and therefore, it is less the energy transference [13]; it is well-known fact that new materials innovation is regulated taking into account various parameters, including energy efficiency leads the list [2]; that being said, simulation of temperature distribution and heat fluxes is a great approach to possible behavior of H10 blocks with coffee husk. Figure 4 presents heat transfer profiles of H10 blocks M C (Figure 4(a)), M CCH-5 (Figure 4(b)) and heat fluxes of H10 blocks M C (Figure 4(c)) and M CCH-5 (Figure 4(d)).

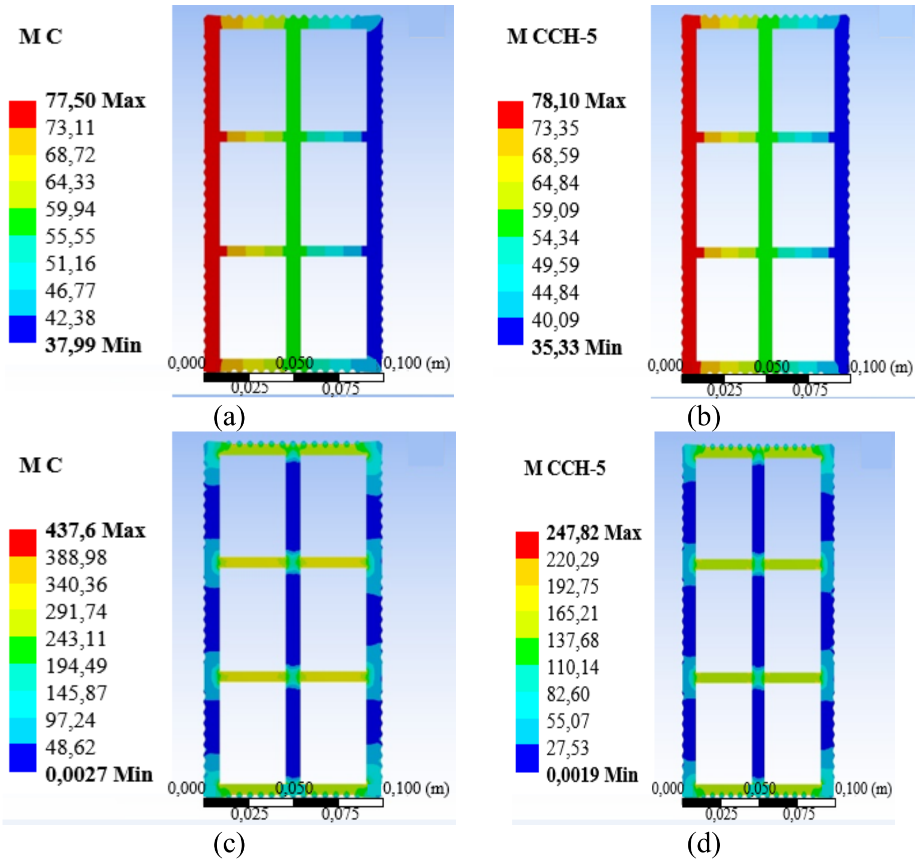

Figure 4. Temperature distribution, (a) M C, (b) M CCH-5; heat flux (c) M C, (d) M CCH-5.

The temperatures of internal surfaces of H10 block in M CCH-5 are heated 2.660 °C less than a brick in traditional clay although outer surface is heated 0.600 °C more than M C. As for heat fluxes, energy accumulates mainly in the horizontal axes and decreases as it conducts to vertical axes. According to information reported in Table 6, it is concluded that a 28% decreased in maximum energy concentration contributes to the decrease in the temperature distribution towards the inner surface of the product.

Table 6. Thermal properties of H10 blocks in M C and M CCHb-5.

Material	Temperature (°C)		Heat fluxes (W/m^2)	
	Exterior	Interior	Maximum	Minimum
M C	77.500	37.990	437.600	0.002
M CCH-5	78.100	35.330	316.010	0.002

4. Conclusions

Coffee husk implementation in the manufacturing processes of block H10 means a contribution to energy efficiency for the ceramic industry in Norte de Santander, Colombia, due to M CCH-5 conductivity is lower than M C. According to results obtained in raw materials characterization, the coffee husk is an organic material with high percentages by LOI, which can affect the structure of the material and weaken mechanical resistance to compression.

This fact was evidenced in the characterization of the technological properties of samples manufactured. Because structure affectation in the firing process, not only implied changes in the strength of the material but also in the absorptive capacity and linear shrinkage (drying and firing). Although each property reacts differently to the concentration percentages of the coffee husks, the relationship between each of them is clear.

Fortunately, the weakening of compressive strength maintains minimum ranges standardized by NTC 4205 for structural masonry units in horizontal drilling products. Additive concentration reduced resistance of samples between 29% and 32%, however, the temperature of block interior surface in M CCH-5 improved by 7%. These advances extend possibilities of improving a traditional product through the design of new material with low impact environmental characteristics and high energy efficiency.

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