RESEARCH ON SINGLE-LEAF WALLS MADE WITH LIGHTENED CLAY BRICKS

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Abstract: This paper explains the studies conducted on the subject by RADEB (Research and Development in Energy and Buildings) Research Group at the University of La Rioja. The aim of this work is to study the possibility of improving the thermal transmittance of a single-leaf wall made with lightened clay bricks. A first aspect is to study the possibility of lightening the clay by using additives, reducing the clay's conductivity without decreasing its resistive ability. The internal and external geometry of the bricks has been studied by the Finite Element Method (FEM). Different wall assemblies with these bricks have been studied.

Keywords: lightened clay brick, thermal transmittance, single-leaf walls, energy efficiency

1. INTRODUCTION

Buildings today are not ecologically sustainable. They do not respect their surroundings and are detrimental to the environment, due to the high consumption of energy resources resulting in a large amount of harmful atmospheric emissions [1].

Buildings consume a vast amount of thermal energy. In fact, the residential and tertiary sectors account for approximately 26.8 % of the total energy consumed in EU-28, which amounts to 478.6 million-ton oil equivalent (Mtep) [2]. Much of this energy is used for the heating and air conditioning of buildings.

This study aims to optimize the energy efficiency of a particular type of enclosure that is increasingly used on buildings: single-leaf enclosures with low-density materials, known as lightened materials. The quality of the enclosures determines the amount of energy required to provide the target thermal comfort design.

Recent studies have reported the impact these wall-cladding materials on buildings have on CO_2 emissions, and their energy performance [3]. Other studies have reported on the influence the porous structure of clay bricks has on improving the enclosure's thermal features [4].

A single-leaf enclosure consists of a single leaf, without an air chamber. The lightened ceramic blocks used in this case have good acoustic insulation, high mechanical resistance, and an exceptional resistance to fire, with remarkable insulation properties and thermal comfort (thermal inertia) [5].

In Spain, following the entry into force of the Technical Building Code (CTE, in its Spanish initialism), efforts are being made to adapt domestic legislation to the Community Directives on energy efficiency in buildings to bring it in line with the legislation of other Member States. The Code's adoption in 2006 involved a significant change for building materials. The increasing demands in building performance and, particularly the ones proposed by the basic document on energy savings [6], are a pressing invitation to search for better building products and systems.

Research conducted by RADEB Research Group at the University of La Rioja intends to analyze and optimize the thermal performance of single-layer ceramic enclosures built with lightweight clay bricks. This work analyzes all the components of a single-layer enclosure, optimizing them until thermal transmittance values are reached that comply with the regulations in force.

A first aspect is to study the possibility of lightening the clay by using additives, reducing the clay's conductivity [7-8] without decreasing its resistive ability. The mineral composition of argillaceous masses used and the different processes that is subjected, together with the additive, influence the thermal conductivity values, density and mechanical strength due to the variation of the porosity of the material [9-11].

A second part of the research involved the study by Finite Element Method (FEM) of internal and external geometry of the bricks in order to optimize the equivalent thermal transmittance of a wall. Likewise, different types of wall assemblies were studied. Analyzed existing studies in the literature on internal geometric distribution, tongue and groove system and different types of assembly [12-18] was concluded that it was possible to optimize them.

2. OBJECTIVES AND METHODOLOGY

Figure 1 shows all the components on a perforated clay block that can be adjusted to decrease the equivalent transmittance of an enclosure:
- Thermal conductivity of the clay;
- Internal geometry of the brick;
- External geometry of the brick (Vertical tongue-and-groove joint);
- Type of wall assembly (Horizontal joint).

The first part of the research involves decreasing the thermal conductivity of the clay by adding lightening additives. A lightened clay brick has high macroscopic porosity, and air cells between its clay sheets to prevent the convective flow. In addition, low porosity due to gas bubbles within the clay is generated when the added combustible materials volatilize during firing [19-20].

Several studies have been carried out in order to decrease this conductivity, showing how the additive in the mass decreases its thermal conductivity based on the generation of micropores in the volume of the baked clay [7-8]. The heterogeneity of the materials used and the different set values of the processes render it expedient to conduct more studies to precisely define the variables that influence the outcomes [21-22].
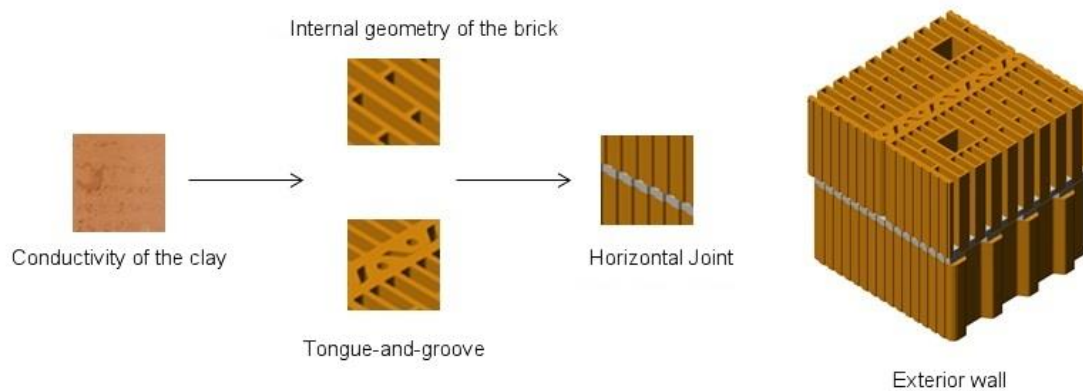
Fig. 1. Modifiable wall components.

Further cross effects of using lighteners are as follows: firstly, the energy savings due to their use, since the energy dissipated by the lightening materials during spontaneous combustion in the furnace is incorporated into the enthalpy balance inside the firing system, thereby reducing the energy the furnace needs to maintain the temperature; secondly, the elimination of certain wastes from other industries [23-27].

The second part of the research involves applying the finite element method (FEM) to study the internal and external geometry of the lightened clay bricks in order to optimize the equivalent thermal transmittance of a wall. Following an analysis of the existing literature on the interior and exterior geometrical distribution (tongue-and-groove) of the bricks [12, 15-18, 27-29], it has been concluded that its optimization is possible.

The third part studies different types of wall assemblies. As regards walls made with lightened clay bricks, mortars are one of the weakest points due to their thermal bridge effect. For this reason, when using traditional horizontal joints, namely, those with mortars that penetrate into the brick voids, it is important to use lightened mortars with thermal conductivities lower than those of standard mortars, and if this is not possible, it is important to use discontinuous joints, either with air chambers or with an insulating material.

One alternative for traditional horizontal joints is to make thinner joints with bonding mortars. This decreases both the amount of mortar applied and its penetration into the brick voids, minimizing the thermal bridge in the horizontal joint. In this case, the use of a bonding mortar should be considered, which requires a good lay-flat property of the brick in order to ensure a good bonding of the mortar; in other words, rectify the brick.

3. MATERIALS AND METHODS

3.1. Study of the properties of the bricks according to the percentage of additive
This section studies the conductivity of the clay, based on the addition of a lightening additive, in this case cellulose pulp [28]. In addition, the mechanical properties are studied.

Test samples of the clay were made with cellulose pulp as an additive, taking special care to reproduce the same manufacturing conditions to enable the extrapolation of the results.

The percentages of additive to be tested have been selected based on the experience of the industrial manufacturers. Different percentages from 0 % to 17 % have been chosen to cover the spectrum recommended by prior experience and previous studies, which addressed this additive in a more general manner [30-31].

Five series of six pieces were made, each one with a different percentage (0 %, 5 %, 7 %, 11 % and 17 %), denoted as AA00, AP05, AP07, AP11 and AP17, respectively.

Considering that the brick's mechanical strength decreases as it is lightened, and in addition to the thermal study of the test samples to find their thermal conductance, it is also necessary to conduct a mechanical study that will show us how far we can lighten the brick while still meeting the regulatory requirements on mechanical resistance [32]. The following studies have therefore been conducted.

3.1.1. Thermal studies
The pieces were first prepared in accordance with EN-771-1:2011 [33]. The thermal conductivity test applied the guarded hot plate and heat-flow meter methods, in accordance with EN 12664-2001 [34], using the WL-376 device manufactured by GUNT [35], according to DIN 52612.

With this test for characterizing the clay pieces, the conductivity value was calculated at 10 ℃ ($\lambda_{10,dry}$), all in accordance with EN 1745:2002 [36] (Masonry and masonry products - Methods for determining design thermal values).

3.1.2. Mechanical Study
When we consider the type of stresses on the enclosure, we may conclude that the clay piece will be subjected mainly to a compression load resulting from the actual weight of the clay bricks.

For this reason, a compression test was conducted on the test samples used after the thermal conductivity test. We proceeded to randomly select cylinders from among all the test samples by using a rhomboidal bit on a column drill to mill an internal diameter of 19 mm ±2 %.

The pieces, as in all the other tests, have been prepared. Once the test samples are measured in lower/upper height and diameter, they are inserted into a universal compression testing machine built in accordance with EN ISO 7500-1:2004/AC: 2009 [37]. This universal compression-testing machine works with an accuracy of ± 1 %.

3.2. Brick geometry
The study has been conducted with two types of clay: non-lightened clay with a conductivity of $\lambda = 0.740$ W/m·K, and lightened clay with a conductivity of $\lambda = 0.50$ W/m·K, a value only slightly higher than the better conductivity obtained in the previous section. This is a standard value in Europe.
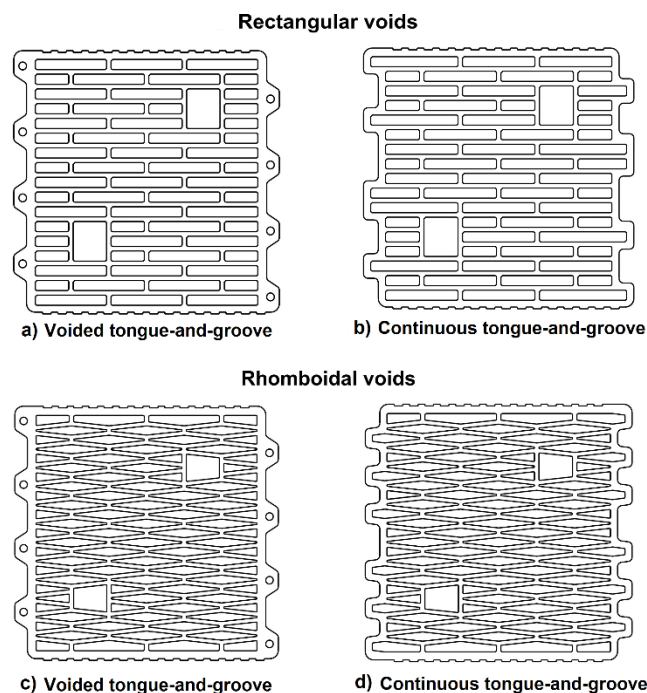

Rectangular voids

a) Voided tongue-and-groove   b) Continuous tongue-and-groove

Rhomboidal voids

c) Voided tongue-and-groove   d) Continuous tongue-and-groove

Fig. 2. Block sections.

The brick model under study has the following dimensions (Lx W x H): 300 x 290 x 250 mm^3. Four types of bricks have been characterized in this work: one type of brick, with internal rectangular voids, is widely used in buildings and has already been studied [4-5, 12-14] (Figure 2a and 2b), along with a second brick with rhomboidal voids, also previously studied [14-17, 38-39] (Figure 2c and 2d). For these two types of bricks, two types of tongue-and-groove systems have been classified; one with separate circular voids, and one with continuous voids that run from inside the brick to the limit of the tongue-and-groove, which gives continuity to the brick's interior voids.

3.3. Wall assembly

Simultaneously to the study of the brick, we have proceeded to study the different types of wall assembly, calculating the thermal resistance of each cross-section, which reveals the equivalent thermal transmittance of the enclosure [40].

The target model to be analyzed by numeric methods is the part of the wall represented by the assembly of two bricks, as shown in Figure 3, which shows the assembly's three characteristic cross-sections and the height of each one: section of the brick with the voids full of air, called clay-air cross-section (height, h_1); section of the brick with the voids full of binding mortar, called clay-mortar cross-section (height h_2), and the section called horizontal joint, composed of binding mortar with height, h_3.

These heights correspond to a type of standard assembly with binding mortar and penetration into the bricks.
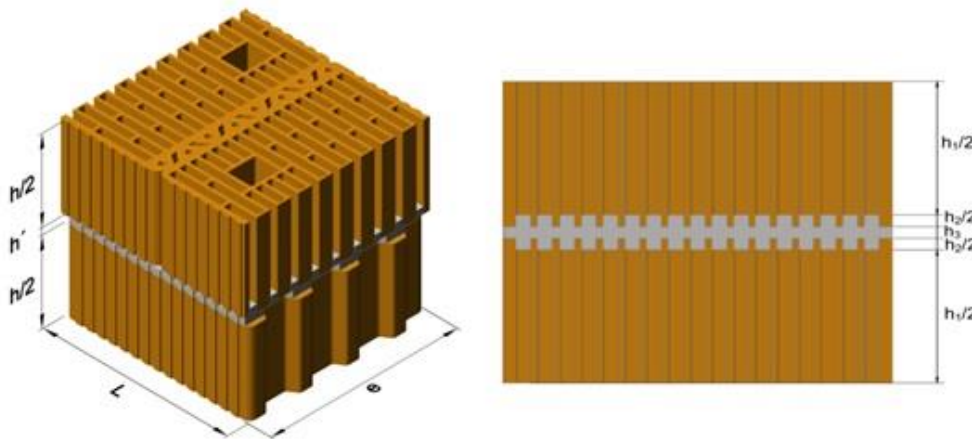

Fig. 3. Section of the wall featuring the assembly of two blocks and the heights of each characteristic cross-section according to standards (AENOR RP 34-14).

The building conditions are as follows: inner coating of plaster, with a thickness of 15 mm and a conductivity of 0.57 W/m·K; outer coating of standard mortar with a thickness of 15 mm and a conductivity of 1.3 W/m·K, and no vertical joint, as it uses a tongue-and-groove arrangement.

Each wall is studied with two types of assembly:
- Traditional assembly using standard mortar $\lambda_m = 1.3$ W/m·K, with a discontinuous joint of 30 mm gap. The penetration, h_2, is 20 mm, and the height of the string line, h_3, is 10 mm, according to Figure 6.
- Assembly with thin horizontal joint using bonding mortar $\lambda_m = 0.83$ W/m·K. The assembly has two advantages: there is no penetration into the bricks, i.e., h_2 is zero, and the horizontal joint, h_3, is 3 mm, since it is a thin joint. This means the characteristic clay-air cross-section has a useful height of h (the sum of h_1 and h_2).

The building's comfort conditions and the calculations of equivalent thermal transmittance, Ueq [W/m²·K], were obtained in all cases as per the CTE.

3.4. Thermal calculations

To conduct this study, heat-flows through the characteristic cross-section of the two-brick assembly are initially obtained by means of FEM [41-42] according to the use of the boundary conditions specified in the relevant standard. This gives the thermal conductivity of the uncoated clay blocks. Although COMSOL gives a relative accuracy of about 16 significant digits, the output results have been recorded with three significant digits.

The thermal calculations are performed according to the following standards: the Spanish UNE CTE [6] and AENOR [43], the European EN [44], and the international ISO 10456:2007 [45]; ISO 8990:1994 [46]; EN 12939:2000 [47]; EN 12664:2001 [34]; EN 1745 [36]; EN ISO 6946 [48], EN ISO 10 211-1 [49] and EN ISO 10 211-2 [50].

4. RESULTS

4.1. Results of the Study of Conductivity and Mechanical Resistance

Figure 4 shows an example of conductivity obtained using the WL-376 device manufactured by GUNT [35].
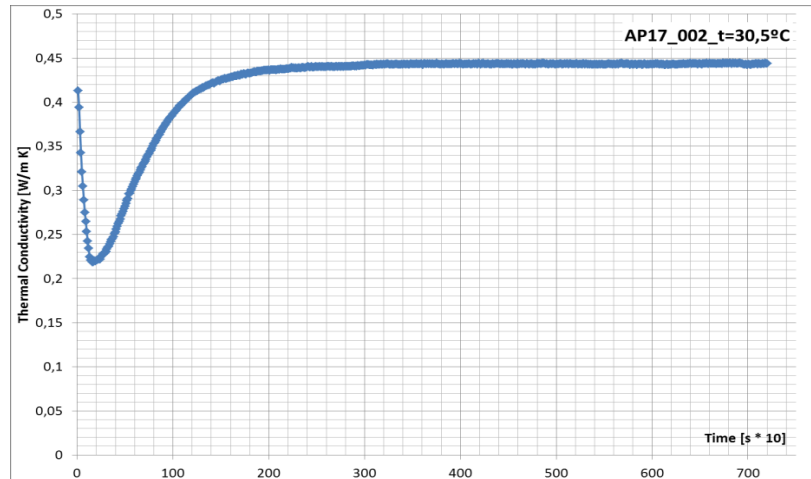

Fig. 4. Example plot of conductivity obtained.

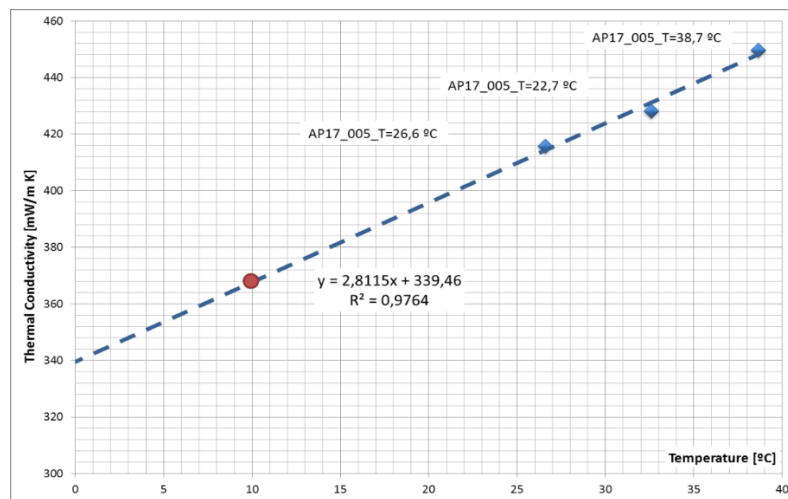Figure 5 shows an example plot of calculation of $\lambda_{10,dry}$.

Fig. 5. Calculation of $\lambda_{10,dry}$, in accordance with EN 1745.

Figure 6 shows an example plot of results of mechanical test.

The full results obtained in both tests are shown in Table 1. The values correspond to the medians provided by the software Statistica 8, after running the ANOVA. These have used the values of six test samples for each series of percentage of additive.

Table 1. Average values for the series analyzed.

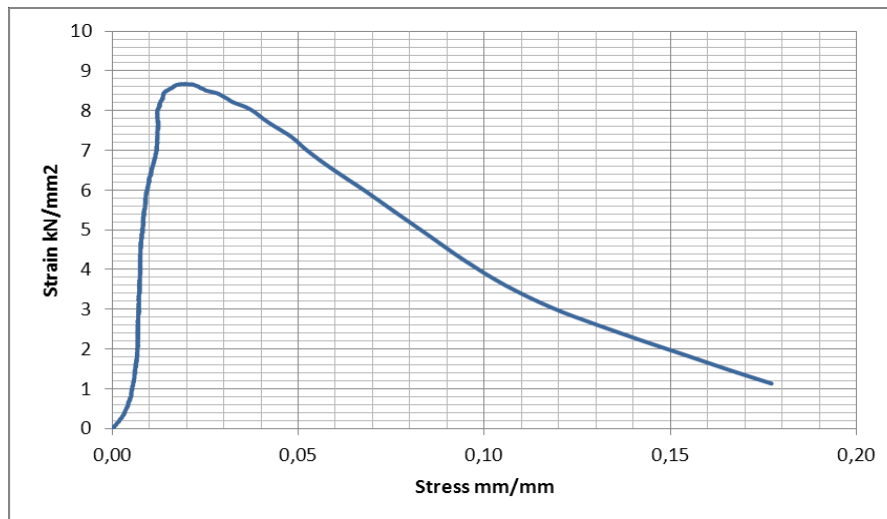| Series	Median breaking stress [N/mm^2]	Median thermal conductivity [W/m·K]	Dry density of the piece [kg/m^3]
AA00	39.67	0.74	1,684
AP05	31.62	0.70	1,620
AP07	22.69	0.64	1,574
AP11	15.64	0.53	1,528
AP17	7.72	0.39	1,412

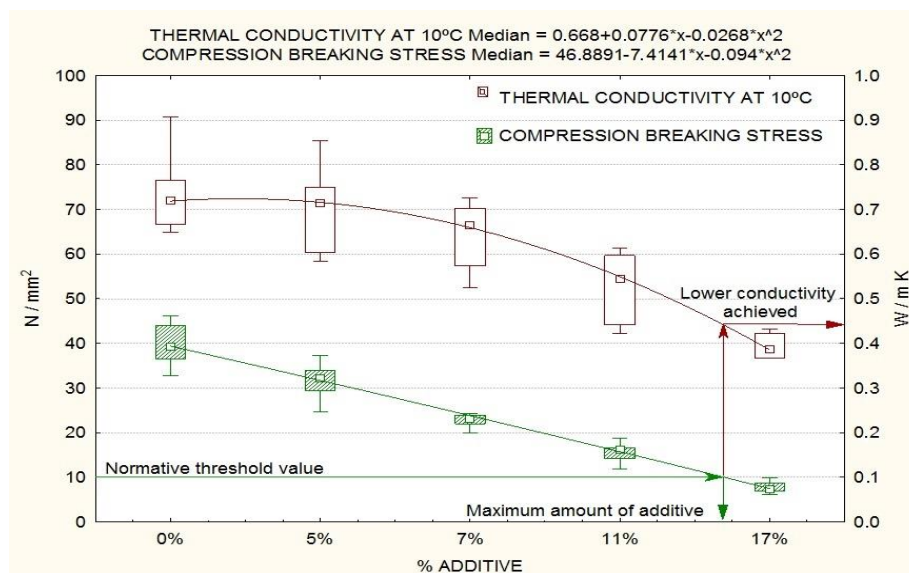Fig. 6. Example plot of results of mechanical test.

Fig. 7. Comparison of conductivity evolution and breaking stress, showing the minimum admissible value for breaking stress.

Figure 7 features a comparative analysis of the thermal and mechanical behavior according to the percentage of additive. It also shows the normative threshold value, 10 N/mm^2, of the mechanical resistance [6], and the maximum amount of pulp mill. The maximum percentage admissible is approximately 15%, which means a 39.69 % decrease in the conductivity of clay, obtaining a thermal conductivity of 0.45 W/m·K by extrapolation.

4.2. Thermal Conductivity Results of Different Bricks with Different Tongue-and-Groove

The study was carried out with the two types of clay mentioned: lightened clay with conductivity $\lambda = 0.50$ W/m·K, and non-lightened clay with conductivity $\lambda = 0.74$ W/m·K.

Figure 8 shows the heat-flow charts for the characteristic two-brick cross-section assembly for each selected brick made with lightened clay, as an example. It shows the areas with more heat-flow.

It can be clearly seen that a significant thermal bridge occurs in blocks with perforated tongue-and-groove. Similarly, Table 2 shows that the conductivity of bricks with the same interior void and different tongue-and groove is less in the block with continuous tongue-and-groove.

Both heat-flow charts and the results in Table 2 show that the conductivity of the brick is less in blocks with internal rhomboidal voids, and that the block with the best performance is the one with continuous tongue-and-groove. The same is true of the bricks made with non-lightened clay.

It is also apparent that the conductivity of the brick with the same type of void and clay improves from 10 % to 17 %. A comparison of all the study's alternatives reveals that the total improvement in brick conductivity is 35 %.

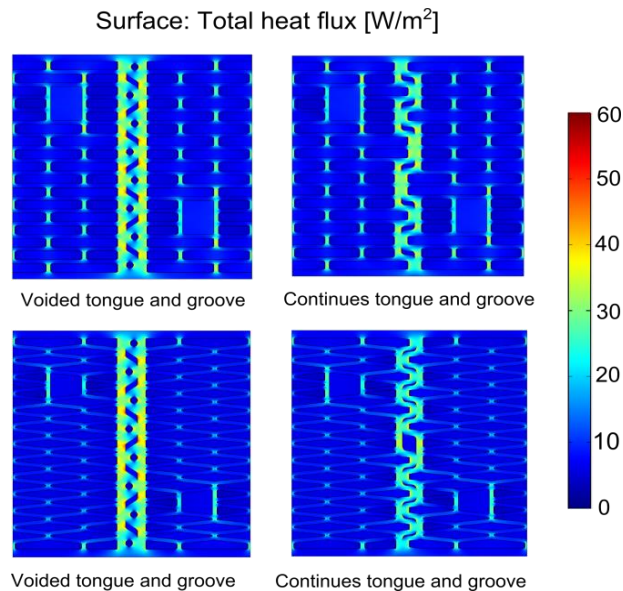Surface: Total heat flux [W/m^2]

Fig. 8. Heat-flow chart of clay-air cross-section for the blocks studied.

Table 2. Conductivity of the brick for each type of block with the two clays selected.

	Block with internal rectangular perforations		Block with internal rhomboidal perforations	
Perforated tongue-and-groove	λ_{clay} = 0.74 (W/m·K)	λ_{clay} = 0.50 (W/m·K)	λ_{clay} = 0.74 (W/m·K)	λ_{clay} = 0.50 (W/m·K)
Conductivity of the brick λ brick (W/m·K)	0.186	0.155	0.169	0.139
Continuous tongue-and-groove	λ_{clay} = 0.74 (W/m·K)	λ_{clay} = 0.50 (W/m·K)	λ_{clay} = 0.74 (W/m·K)	λ_{clay} = 0.50 (W/m·K)
Conductivity of the brick λ brick (W/m·K)	0.163	0.140	0.140	0.121

4.3. Thermal Results of the Wall for the Different Arrangements of the Horizontal Joint
In order to study the influence of the different wall arrangements with the conductivity of the brick and the different types of assembly mentioned, the equivalent thermal transmittance of the wall is calculated. The results are shown in Table 3, revealing the importance of the type of assembly.

Table 3. Table of thermal transmittance of the wall according to the type of block, type of clay and type of assembly.

U_{eq} (W/m^2·K)		λ_{clay} = 0.74 (W/m·K)		λ_{clay} = 0.50 (W/m·K)	
		30 mm discontinuous air joint	Thin joint	30 mm discontinuous air joint	Thin joint
Rectangular internal perforations	Perforated tongue-and-groove	0.718	0.591	0.625	0.506
	Continuous tongue-and- groove	0.661	0.528	0.588	0.465
	Perforated tongue-and-groove	0.668	0.544	0.574	0.462

Rhomboidal internal perforations	Continuous tongue-and-groove	0.598	0.466	0.529	0.410

In the thin joint assembly where the mortar joint is smaller, the equivalent thermal transmittance of the wall decreases significantly. It follows that, for the same block and clay, decreasing the horizontal joint from 10 mm to 3 mm and eliminating the clay-mortar cross-section in an assembly with a thin joint decreases the thermal transmittance of the wall by 18-22 %, depending on the type of block used.

If we now compare what improves the equivalent thermal transmittance of the wall among all the alternatives studied, we notice that the improvement achieved is significant, 43 %. These results show how important it is to optimize all the variables studied, the conductivity of the clay, the type of geometry of the clay block, and the type of assembly.

5. CONCLUSIONS

By adding 15 % of pulp mill to the clay studied, we can decrease thermal conductivity from 0.74 W/m·K to 0.45 W/m·K, which is an increase of 40% in clay conductivity. This is the minimum thermal conductivity value we can obtain with the clay, and using bricks as structural elements.

The usefulness of the additive indirectly leads to a reappraisal of the waste generated by paper industries, which means a reduction in its environmental impact. Similarly, the energy contribution of the additive itself decreases the amount of energy required for firing.

For the four blocks studied, with rectangular and rhomboidal voids and perforated or continuous tongue-and-groove voids, and the two clays studied, a clay conductivity of 0.121 W/m·K was obtained, recording a 35 % of improvement.

When studying the type of wall assembly, we became aware of the considerable importance of the thin joint type. With this type of assembly, the improvement in the wall's equivalent thermal transmittance, for the same type of block and the same clay, ranged between 18 % and 22 %.

If we also take into consideration the type of block and the type of clay, the improvement in the equivalent thermal transmittance of the wall is 43 %, may conclude by stressing the importance of optimizing all the variables studied in order to save energy in buildings by improving the type of enclosure. Adding lightening additives to the clay improves its conductivity. The type of internal and external geometry of the clay block improves brick conductivity, and optimizing the type of assembly in turn improves the wall's equivalent thermal transmittance. By optimizing all the variables studied, the equivalent thermal transmittance of the enclosure obtained was 0.410 W/m²·K.

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