THERMAL PERFORMANCE OPTIMIZATION OF LIGHTWEIGHT CONCRETE/EPS LAYERED COMPOSITE BUILDING BLOCKS

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ABSTRACT

The aim of this paper is to study and optimize the thermal performance of new lightweight and insulating composite blocks (CBlocks). These CBlocks are made up of a central expanded polystyrene (EPS) layer and two lightweight concrete layers with cavities. The aggregate of the lightweight concrete is pumice. A complete corner wall composed of six composite blocks and a specific corner block is numerically analyzed for different thermal conditions. Numerical methods were used in order to obtain the thermal behavior of these CBlocks. On the one hand, material thermal conductivity, convection and radiation inside the cavities were considered in this problem. On the other hand, the variation of the cavities was also taking into account. Finite Element Method (FEM) and Design of Experiments (DOE) have been used to study and analyze this problem. This numerical study reaches the thermal behavior of these new insulating CBlocks and provides new useful information for researchers and builders.

Keywords: finite element modeling; optimization; insulating composite blocks; eps; concrete-pumice; thermal performance.

1. INTRODUCTION

The energy and natural resources consumptions are one of the worries of the people, scientists and other experts. The increase of consumptions is able to destroy the natural environment, as well as contribute to the greenhouse phenomenon and other environmental issues. In this sense, building energy consumptions have to be reduced for both new and old constructions. Besides, other solutions can be applied in the construction field in order to reduce the environmental impact of the constructions such as the use of recycled materials or the reduction of energy demands in the construction process. The construction field needs to improve the life-cycle of the construction elements. One of the main solutions to reduce the environmental impact of constructions is the use of sustainable materials. These can be

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recycled materials, lightweight materials, materials that can be reused without high cost of operation, and so on. For decades recycled materials have been investigated in different ways. the most usual solution is the use of recycled aggregate instead of the conventional aggregate [1,2]. Last years, some different researches on sustainable materials for construction were done. These studies are mainly focused on local and natural materials in order to reduce the pre-process costs. Some examples of these works are the optimization of the “adobe bricks” reinforced with natural fiber, in terms of mechanical and thermal properties [3]. The results show that the thermal conductivity of the bricks decreases with the increase of the percentage of fibers. They proved also that the thicker natural fibers improve the thermal insulation. The authors of this paper have been working on new building blocks in order to decrease the environmental impact and reach more efficient materials. Previous research papers studied the thermal behavior of lightweight concrete. The hygrothermal properties of the lightweight concrete have been studied both, experimental and numerically in several works[4,5,6]. Different geometries of lightweight concrete blocks have been studied. Arrangement and geometry of internal cavities in the blocks decrease the weight of the structures, reducing the cost of the construction, and improving the thermal performance of different building components, such as walls, roofs, slabs, etc [4,5,7]. Optimizing the insulation thickness of external wall by a novel 3E (energy, environmental, economic) method, studied optimization of material and optimum thickness of insulation for the external wall of an office building in point of 3E (energy, environmental, economic). They observed that polyurethane with the thickness of 8 cm, EPS with the thickness of 20 cm and Rockwool with the thickness of 7 cm were optimum [8]. A novel lightweight gypsum composite with diatomite and polypropylene fibers was used to manufactured gypsum composite wall element for insulation. Fibers were added to improve mechanical strength and diatomite for the insulation properties [9]. Experimental and numerical analysis of new bricks made up of Polymer Modified-Cement Lightweight Using Expanded Vermiculite. Results showed that the increment of vermiculite ratio in the bricks improves its thermal performance [10]. Other authors studied the influence of glazing area on the thickness of insulation for different wall orientations in different climatic conditions [11]. Physical, thermal and mechanical properties of foam concretes with granulated blast furnace slag as fine aggregate were also studied to improv insulation properties of concrete blocks. The use of waste materials to produce foam concretes improves also sustainability. The authors of this work compared foam concretes with waste materials and concretes using pumice, and results showed that the use of waste reduces up to3 times the thermal conductivity [12]. Insulation properties of mortars produced with expanded vermiculite and waste expanded polystyrene evaluated the combination of waste expanded polystyrene and expanded vermiculite. Although compressive strength was reduced, thermal conductivity was significantly reduced [13]. The main objective of their study was to study the effects of foam content on the workability, mechanical properties and thermal conductivity of EPS foamed concrete. In the experimental studies, mixtures were prepared by partially replacing EPS beads with foam with a bubble diameter of 25–100 μm; the resulting densities of the EPS foamed concretes in a fresh state were 400 $kg.m^{-3}$ and 800 $kg.m^{-3}$. The test showed that proper foam content introduced into the EPS mixture can greatly improve the workability, strength and thermal conductivity of EPS foamed concrete [14].

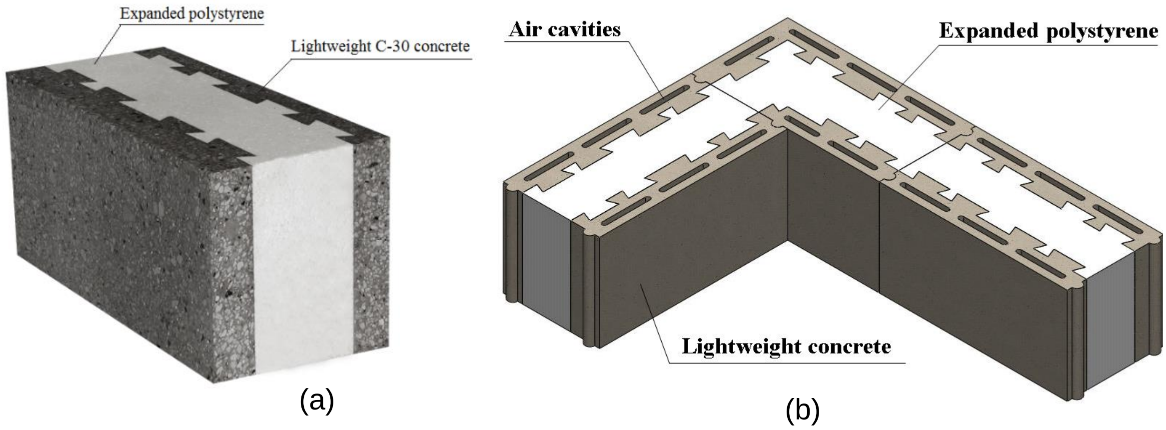
The importance of this topic is also shown in other papers where the authors analyzed efficiency and sustainability of construction materials. The combination of lightweight concrete and EPS has been an efficient solution to improve the thermal transmittance of blocks [15,16]. Both materials have good insulating properties and are lightweight materials. These properties are very important to improve sustainability and workability, as well as reduce costs of constructions. The use of pumice and other lightweight aggregates are very useful to decrease the block weight and improve the thermal behavior of this type of blocks.

The work presented in this paper numerically studied the thermal behavior of composite blocks made up of lightweight concrete and EPS. The aggregate used for the lightweight concrete was pumice. The numerical study includes several details that have not been taken into account before, as the study of corner blocks. Cavities were included inside the composite blocks to improve the thermal insulation. As it was proved in previous works, cavities are able to improve the thermal behavior of lightweight concrete bricks due to the heat transfer phenomena through the air cavities [12,17,18,19]. In addition, this paper studies a corner wall to increase the knowledge of thermal response of this critical points in a building. Other previous studies are focused on the block behavior considering a flat wall, but no corner walls have been studied until now.

In summary, this paper presents a high nonlinear numerical study of composite blocks with cavities and EPS. The most efficient geometry is reached, taking into account the effect of a corner wall. Different geometrical parameters, such as the thickness of concrete or EPS, the size of cavities or different thermal conductivities were studied in this research. The optimum block dimensions to reach the best thermal behavior was determined using the goal optimization method based on a design of experiments methodology (DOE) over a finite element model [14,17,20]. The combination of EPS and lightweight concrete, both with low thermal conductivity, increases the thermal insulation of the wall. The optimization of the parameters is a relevant contribution to this field and the study of a corner wall is an original contribution of this work. All in all, the final proposed design of these composite blocks is a very important contribution for the manufactured companies in order to reduce costs, as well as improve the quality of the construction components in terms of efficiency and sustainability.

2. DESCRIPTION OF THE BLOCKS

The blocks studied in this work are made up of lightweight concrete and expanded polystyrene (EPS) layered composite to build a corner wall. The composite blocks are composed of lightweight concrete with pumice aggregates and they have a central core of EPS, as it is shown in Figure 1. The aim of this paper is to study the thermal performance of a corner wall made of composite blocks using Finite Element Method (FEM).



(a)

(b)

Figure 1. (a) Composite block and (b) CBlock modelled

Block models manufactured by the producers have the same overall lengths (390 mm) and different thicknesses, 140 mm and 200 mm. In this paper, we have modeled a corner wall made up of two different composite blocks. Furthermore, in order to improve their thermal insulation properties, the corner wall is modeled using different concrete thickness and including air cavities inside both concrete layers. In order to study the thermal properties of the materials, the thermal conductivity of the lightweight concrete and the EPS were measured using experimental tests. The concrete used has a specific composition which is shown in Table 1.

Table 1. Composition for 1 m^3 of the concrete used to make the composite block.

Concrete mixture	Amount (kg)
Cement	300
Waste sludge	400
Bims (10-13 mm)	200
Bims (13-18 mm)	100
Waste aggregate particles	400
Superplasticizer	4.5
Water	61

Physical properties of materials are basic to numerical models. In this specific case, accurate measurements of thermal properties are necessary for reliable results. For this reason, Non Destructive Tests (NDT) were developed to determine the thermal properties of each material: lightweight concrete and EPS. The equipment used in this work includes a thermal conductivity analyzer based on the Modified Transitory Plane source (MTPS) technique and applies a transient and constant heat source to the specimen using an interfacial heat reflectance sensor [REF]. Using this technology, thermal conductivity of the materials were measured quickly and directly. In addition, physical properties of the materials were measured to use actual properties in the numerical models. The compressive strength of concrete was determined following the European Standard EN 12390-3:2019. Testing hardened concrete – Part 3: Compressive strength of test specimens. The apparent density of the lightweight concrete studied was determined from the weight and volume of three normalized samples of Φ15x30 cm. The manufacturer of the EPS provided compressive strength and density of this material. The physical properties of the composite blocks are summarized in Table 2.

Table 2. Physical properties of the composite blocks.

Properties	C30 concrete	EPS	Composite block 140 mm	Composite block 200 mm
Density ($kg.m^{-3}$)	1465	30	810	560
Thermal conductivity ($W.m^{-1}K^{-1}$)	0.48	0.042	0.099	0.076
Compressive strength ($N.mm^{-2}$)	30	0.2	6.3	4.6

3. NUMERICAL MODELS

The numerical studies understand the thermal behavior of composite blocks and optimize these products. In this section, numerical models based on the finite element method (FEM) are explained where the geometry, loads and boundary conditions, and main results are shown [21,22,23]. The methodology of these mathematical models are based on two advanced numerical techniques, steady-state thermal analysis using FEM and Design of Experiments (DOE) methodology [24,25,26]. The influence of several parameters on the thermal behavior as well as the optimization of the CBlocks thermal performance are studied using these methodologies.

The geometrical model used is a wall with a corner that is composed of CBlocks as it is shown in Figure 2. The numerical model includes the conduction thermal properties of each material, the thermal conductivity value, λ, as well as the convection and radiation properties for each cavity. Furthermore, geometrical parameters are considered in this study in order to obtain its influence on the CBlocks thermal behavior. Two different thicknesses of the blocks used, 140 mm and 200 mm, can be studied using DOE. The influence of the cavities size is also studied by this technique, as well as thermal conductivity of both EPS and lightweight concrete [14,17].

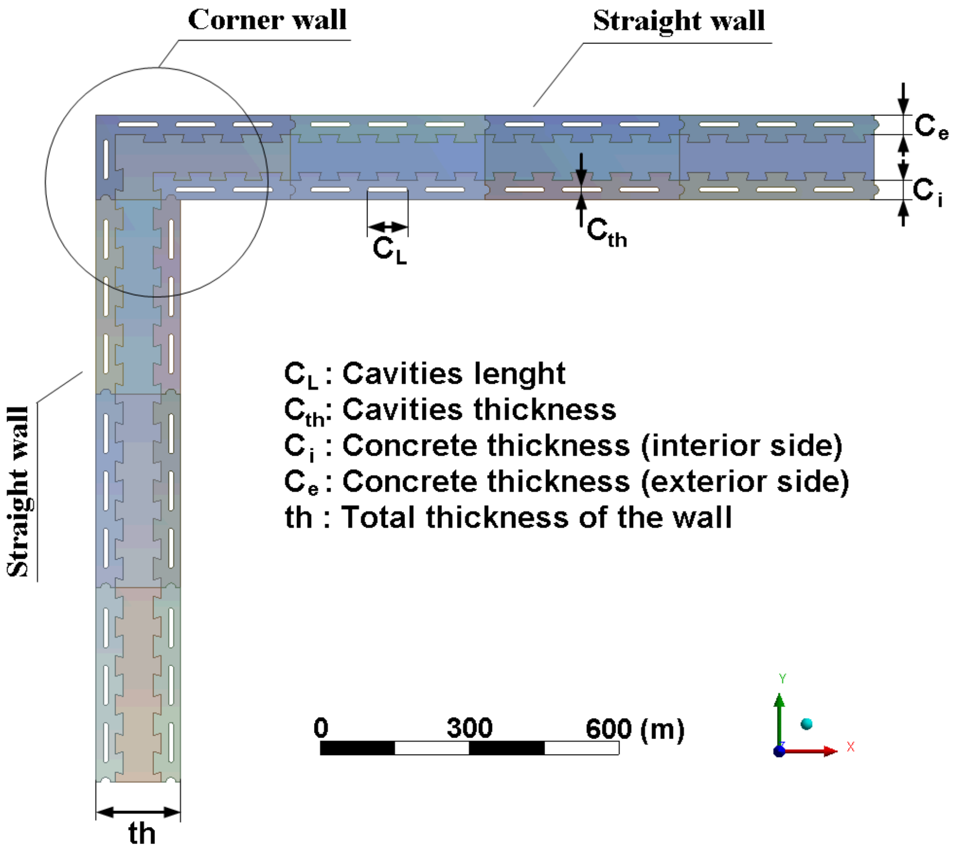


Figure 2. Geometrical model used in the numerical model and parameters studied.

3.1. Geometrical model and material properties

The geometrical model is a corner wall composed of two different blocks made up of concrete and EPS. The influence of the cavities inside the concrete blocks has been studied for the authors of this paper in previous works [11,13,14,18]. The geometrical model of this work has been parameterized in order to obtain the most efficiency thermal behavior of the wall. The main geometrical parameters which are studied in this work are shown in Figure 2.

- C_e and C_i represent the concrete thick, which define also the EPS thick in the middle of the block. This parameter is very important for the thermal transmittance due to the influence of the thermal conductivity for each kind of material, the concrete and the EPS.
- $C_L$and C_{th} which are the dimensions of the cavities, length and thickness, are also influential in the thermal transmittance of the composite block due to the heat transfer phenomena which are produced inside the air cavities.
- The total thickness of the composite blocks are important for the manufacturing process. The design of these composite blocks must have a good thermal behavior, besides of a standard size. In this sense, several commercial thickness dimensions, from 140 mm to 180 mm, have been studied in order to obtain the best value.

The materials used in the numerical simulation are the same as in the experimental study, lightweight concrete for the external sides of the brick and expanded polystyrene for the center of the brick.

3.2. Finite element mesh and boundary conditions

The finite element model was developed using the following types of finite elements:

- PLANE 55 to simulate the material and its properties. It was used for both materials, the concrete and the EPS.
- CONTA 172 y TARGE 169 for the contact between the concrete and the EPS.
- SURF 151 to simulate the heat transfer phenomena inside the cavities, including convection and radiation.

The total numerical model is composed by 54012 nodes and 66031 elements. A mesh detail of the corner wall is shown in 0 3.

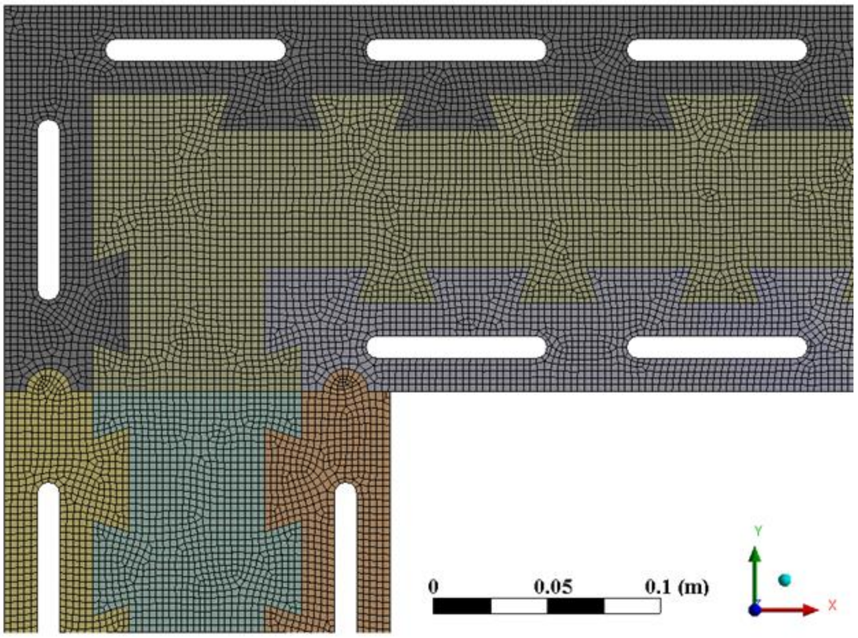


Figure 3. Numerical mesh of the corner of the wall.

In addition to the input parameters of the geometrical model, boundary conditions and load applied are needed to study the thermal behavior of the corner wall, see Figure 4. These values were obtained from the ISO 6946:2012 International Standard. This Standard explains the calculation method of the convection and radiation coefficients for different structural elements.

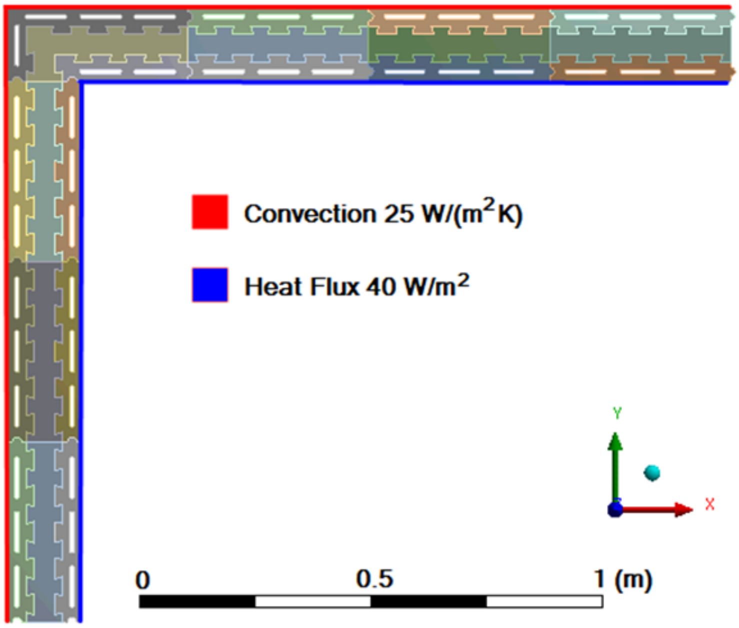


Figure 4. Loads applied on the numerical model.

- Exterior convection of 25 W $m^{-2}K^{-1}$ has been applied on the exterior side of the wall, see Figure 4.
- Interior heat flux of 40 W m^{-2} has been applied trough the wall, from the interior to the exterior, see Figure 4.
- Radiation and convection have been inside the cavities following the European Standard EN ISO 10456:2007. The value of the load applied inside the cavities depends on the dimension of those cavities. The authors of this paper have a lot of experience in the numerical simulation of heat transfer through cavities inside the blocks [19]. In previous works, the authors explained this numerical model using SURF 151 [22-26]. This element simulates the convection and radiation phenomena in small cavities without ventilation.

In this work, the values of these loads depend on the geometry of the blocks and the cavities [17]. In this section, the parameterization of the convection and radiation loads applied in the cavities is explained.

The transmittance of the inner air cavities depends on the radiation and the convection phenomena. Both loads, which also depend on other parameters, have to be taken into account to obtain the effect of the cavity inside the block. The equations to define these variables are the following:

$$H = h_r + h_a \qquad (1)$$

$$h_r = \frac{h_{r0}}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 2 + \frac{2}{1 + \sqrt{1 + d^2/b^2} - d/b}} \qquad (2)$$

$$h_a = 0.025/d \qquad (3)$$

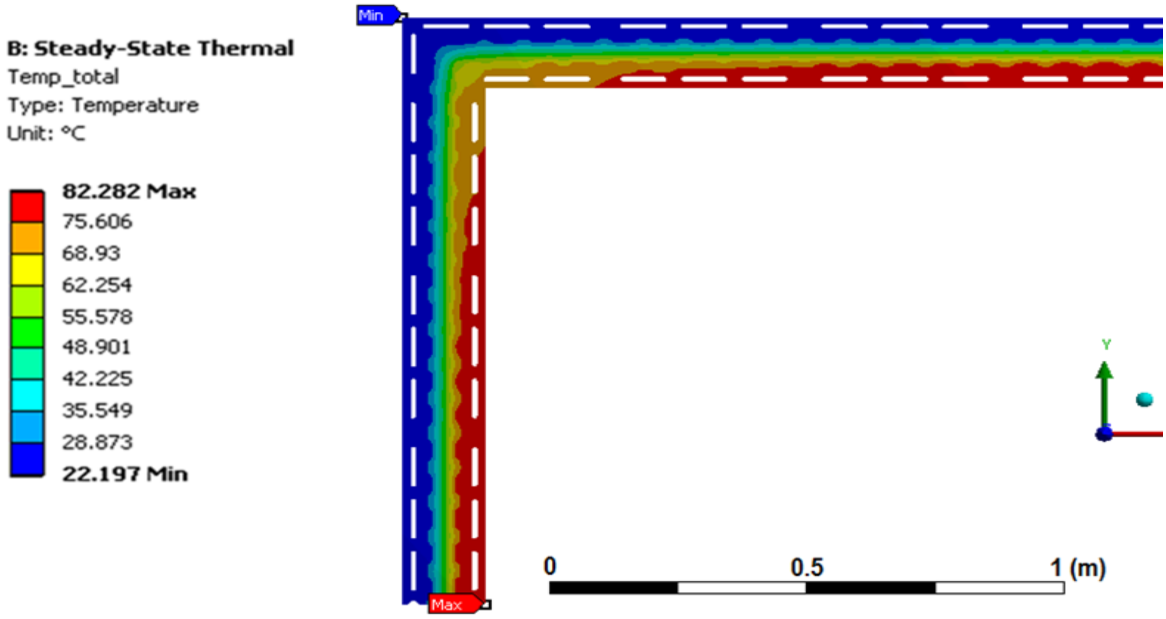
Where:

H: The load applied inside the cavities taking into account convection and radiation in W/(m^{2}K).
***h$_r$*:** Radiation coefficient inside the small cavities without ventilation in W m^{-2}K^{-1}.
h$_a$: Convection coefficient inside the small cavities without ventilation in W m^{-2}K^{-1}.
ε_1 and ε_2: Emissivity of the materials which made the walls of the cavities. In this case: $\varepsilon_1=\varepsilon_2$.
h$_{r0}$: Coefficient radiation of a black body for 20ºC in W m^{-2}K^{-1}.
d: Cavities thickness (in the same direction of the flux) in (m) (C$_{th}$).
b: Cavities length (perpendicular to the flux direction) in (m) (C$_L$).

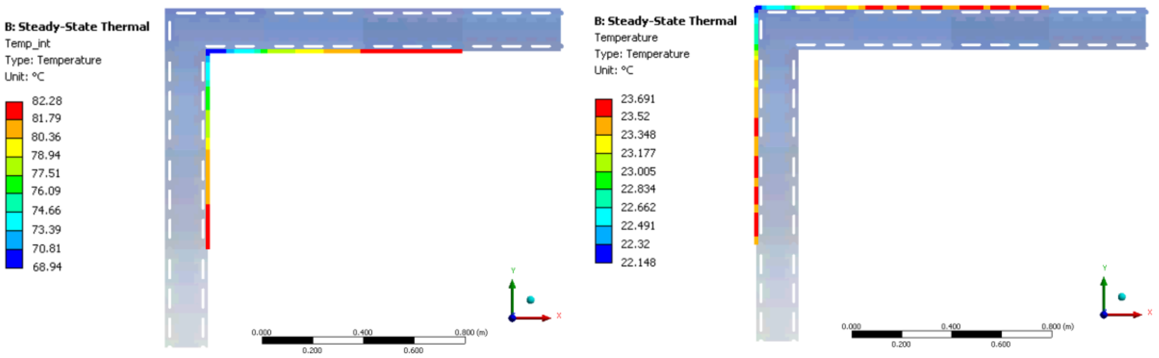
In this work, the dimensions of the cavities are variable, so the values of the convection and radiation coefficients also must be modified for each value. The values of *d* and *b* correspond to C$_{th}$ and C$_L$ respectively.

4. NUMERICAL RESULTS

The results obtained in the numerical simulations are shown in this section, see 0 5. These results present the thermal behavior of the corner wall as well as its thermal transmittance taking into account the internal cavities. Firstly, the total temperature distribution along the corner wall is presented, see Figure 5(a). Secondly, the temperature values on the interior side of the wall are shown, see Figure 5(b). Finally, the temperature values on the exterior side of the wall are indicated, see Figure 5(c).



(a)



(b) **(c)**

Figure 5. Numerical simulation results of the corner wall: (a) temperature distribution; (b) interior side temperatures; (c) exterior side temperatures.

As it is shown in Figure 5, the exterior and internal temperatures obtained in both cases are very similar as it was expected. In this sense, the thermal transmittance of both blocks is calculated following the same equations:

$$U = \frac{Q}{\Delta T} \tag{4}$$

Where:

U: is the thermal transmittance of the wall (W $m^{-2}K^{-1}$).
Q: is the heat flux applied in the interior side of the wall (W m^{-2}).
ΔT: Temperature difference between the exterior and interior sides of the wall (K).

In this work, the geometrical parameters and the material properties are varying in order to obtain the best thermal behavior. The advanced technique Design of Experiments (DOE) was used to reach the most efficiency design of the composite blocks.

5. NUMERICAL DOE

The numerical DOE analysis of this research relates the geometrical parameters and the thermal properties of the material with the thermal behavior of the composite blocks. In this sense, the input parameters used in the DOE analysis and its range of variation are shown in Table 3.

Table 3. Geometrical parameters values of the DOE.

Parameter	Min Value	Initial Value	Max Value
W: block thickness	140	160	180
C_L: Cavities length	70	80	90
C_{th}: Cavities thickness	6	10	14
C_i: concrete thickness interior side	50	57	65
C_e: concrete thickness exterior side	50	57	65
C_c: concrete thermal conductivity	0.432	0.48	0.528
EPS_c: EPS thermal conductivity	0.0378	0.042	0.0462

The initial, maximum and minimum values of each parameter is selected by the following procedure:

Firstly, the variation of the geometrical parameters, such as the block thickness, geometry of cavities and concrete thickness, are obtained from the manufacturing processes.

Secondly, the range of variation of the material thermal conductivity is obtained from our own laboratory experiments by means of the Modified Transitory Plane Source (MTPS) technique.

The output parameter selected of the DOE analysis is the thermal transmittance of the corner wall. In this sense, it is possible to understand the influence of each input parameter in the thermal transmittance of a specific composition of these hollow bricks [27]. In this sense, the sensitivity analysis is presented in Figure 6, showing the different influences of each parameter over the thermal transmittance.

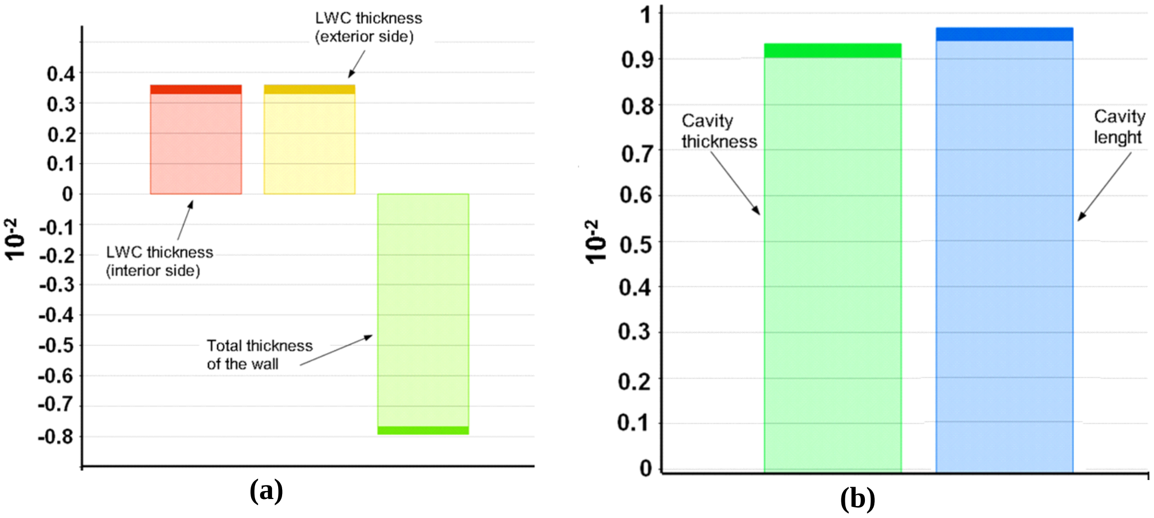


Figure 6. DOE Sensitivity analysis - influence of the input parameters on thermal transmittance.

Conclusions of the sensitivity analysis reveal the following points:

- The thickness of the wall of the composite block is the most influential parameter in the thermal transmittance, as it was expected. When the total thickness of the wall increases, thermal transmittance decreases.

- The same influence on the thermal transmittance is due to the LWC interior and exterior thickness. When the LWC thickness increases the thermal transmittance increases.

-With respect to the geometry of the cavities, its variation in length affects slightly more than the cavity thickness.

The good properties of the lightweight concrete as insulate material have been also proved in other papers of these authors [12,19,20,28]. Response of Surface Method (RSM) has been used in order to understand these influences in the thermal transmittance of the composite blocks. 0 7 shows the most important influential parameters on the thermal transmittance of the total block.

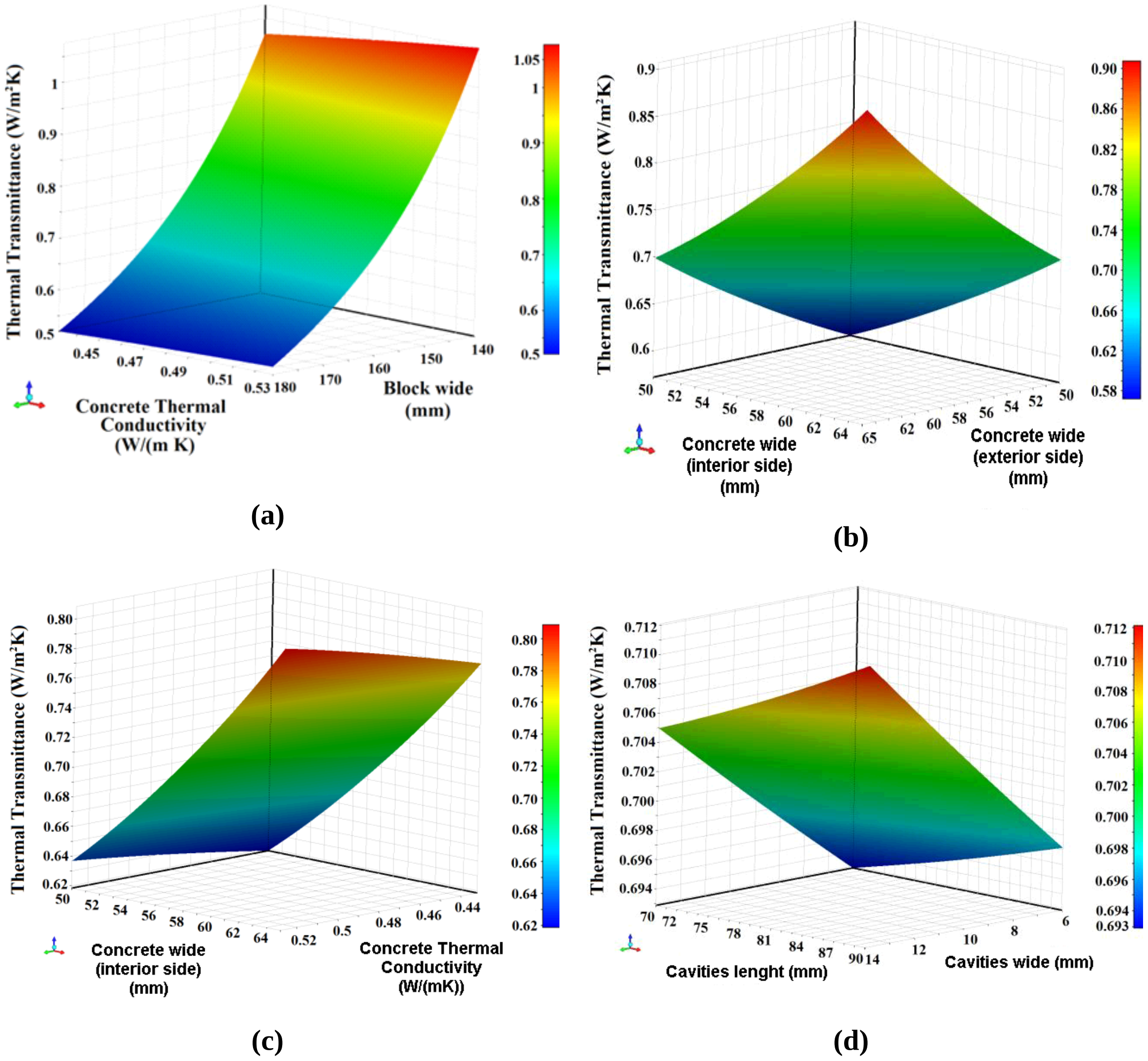


Figure 7. Response Surface of the DOE for the thermal transmittance: (a) concrete thermal conductivity versus block thickness; (b) Concrete thickness of the interior side versus concrete thickness of the exterior side; (c) concrete thickness of the interior side versus concrete thermal conductivity; (d) cavities length versus cavities thickness.

5.1. Optimization based on DOE

The optimization of the Response of Surfaces obtains the best values of the input parameters from the thermal point of view. This technique reaches a thermal efficient composite block. The case studied provides a lightweight block as well as a good insulation component with a thermal transmittance of 0.4 W $m^{-2}K^{-1}$. The optimization of the RS provides several values for input parameters of the DOE with the objective to minimize the value of the thermal transmittance. As it was shown in the different RS, see Figure 7, the maximum value of the thermal transmittance obtained has been below to 0.6 W $m^{-2}K^{-1}$. In this sense, the response surface optimization has been used to do a goal optimization analysis in order to get the minimum thermal transmittance value in the corner of the composite block.

The optimization developed in this work led a minimum value for the thermal transmittance of 0.4 W $m^{-2}K^{-1}$, which is an important improving respect to the previous studies. The optimum values obtained for the input parameters are presented in Table 4.

Table 4. Optimum configuration to obtain the highest thermal insulation in the corner wall of composite blocks.

Parameter	Optimum Value
W : Block thickness (mm)	180
C_l : Cavities length (mm)	70
C_{th} : Cavities thickness (mm)	3
C_i : Concrete thickness interior side (mm)	50
C_e : concrete thickness exterior side (mm)	50
C_c : Concrete thermal conductivity W/(mK)	0.432
EPS_c : EPS thermal conductivity W/(mK)	0.0378

6. CONCLUSIONS

This study provides important relations between the geometrical design of the lightweight concrete/EPS layered composite block and its thermal transmittance. Furthermore, it is able to combine different parameters in order to understand the relation between them, as well as explain the thermal behavior of a corner wall which never had been studied before. This study has reached the best thermal insolated blocks without increasing their cost of manufacturing. Besides of this, the improvement of the environment using sustainable materials such as lightweight concrete is also an important advantage in the construction field.

The main conclusions of this study are explained as follow:

- The corner wall has different behavior than the straight wall as it is shown inFigure 5. Numerical simulation results of the corner wall: (a) temperature distribution; (b) interior side temperatures; (c) exterior side temperatures.
- This study identifies different thermal transmittances in the blocks near the corner from the blocks in straight walls. In this sense, to know the actual thermal transmittance using a numerical model, it is important to take into account the whole building structure instead of just one single block.
- The numerical simulation results show that both straight walls have the same thermal behavior. The difference between them is always less than 10%, which is negligible, see Figure 5.
- The sensitivity analysis of the DOE concludes that block thickness is the most influential parameter in thermal transmittance, while the dimensions of the cavities are the least important parameters in terms of thermal resistance, see Figure 6.
- The concrete thicknesses on both the interior and exterior sides of the block are studied independently. For this reason, Figure 7 (a) shows the influence of each one in the same response surface (RS). This graph shows that the contribution of the concrete thickness is symmetrical on both sides.
- Although thermal conductivity is a property of each material, it is possible to obtain different values of the conductivity of lightweight concrete by varying its composition. In this sense, the numerical study by DOE, see Figure 7 (c), determines the optimum value for the concrete thermal conductivity to obtain thermal transmittance values of 0.62 W $m^{-2}K^{-1}$.
- Finally, although the size of the cavities is not as influential as other parameters, its influence must be taken into account, see Figure 7 (d).

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