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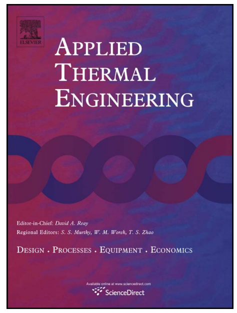

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A FEM comparative analysis of the thermal efficiency among floors made up of clay, concrete and lightweight concrete hollow blocks

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Abstract
This paper presents a comparative nonlinear thermal analysis for a total of eighteen different in situ cast floors varying both the constituent materials of the hollow blocks (clay, concrete and lightweight concrete) and the shape and number of recesses (six different block types) using the finite element method (FEM). Based on the non-linear thermal analysis of the different configurations by FEM and considering both upward and downward heat flows, it is possible to choose the best candidate floor from the thermal point of view. Mathematically, the non-linearity is due to the radiation boundary condition inside the recesses of the blocks. The comparative analysis of the floors is carried out from the finite element analysis through the two important parameters: the average mass overall thermal efficiency and the equivalent thermal conductivity. Finally, the results and conclusions reached in this work are exposed.

Keywords: Hollow block; Finite element modelling; Non-linear complex heat transfer; Energy savings.

1. Introduction

In recent years, many researchers have studied the thermal behavior of the different construction elements in buildings, such as: walls, roofs, floors, windows and so on [1-7]. This study seeks responses to the following questions: what is the difference of the thermal performance when the number and shape of the block recesses is varied? And, what is the best constituent material of blocks to obtain the biggest energy savings?

It is evident that there are many differences between construction elements in building today [8]. However, to the best of our knowledge, there is a little information available concerning the thermal comparative behavior between the same or similar blocks made up of different constituent materials. Thus, two purposes of this study were proposed: firstly, this work provides the information through numerical studies that it is possible to obtain the thermal performance of complex structural elements and secondly, a comparative analysis of floors made up of different materials and recesses was conducted, which will be assist in the recommendation of the sustainable and ecological products, with respect to the energy efficiency, for industrial and housing in the world in the future.

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During the last years, experimental and numerical studies have been developed to study two and three dimensional heat transfer phenomena in construction elements made up of hollow blocks [1-3]. Most interests are involved in the optimization process applied to obtain the best design from the thermal point of view in case of clay and lightweight concrete bricks [4-8]. In this paper, the thermal analysis of reinforced concrete one-way spanning slabs for internal floors is carried out, taking into account both upward and downward heat flows, in which all heat transfer processes for every constituent materials are considered [9-15]: conduction, convection and radiation inside enclosures.

The FEM [16-20] is a good choice for solving the heat partial differential equation over complicated domains like hollow blocks, when the domain changes, when the constituent materials vary, when the desired precision varies over the entire domain, or even when the solution is continuous but not derivable. This complex problem was solved in this work by means of the finite element analysis.

2. Geometry and materials considered in the multilayer floor

In Spanish industrial and housing buildings, different types of multilayer floors are used [7]. In this way, the most used construction solution is the *in situ cast floor with one-way spanning slabs*. Therefore, this work is applied to the thermal study of this type of floors when different bricks and different constituent materials are used, in order to find the best one from the thermal point of view.

Fig. 1. Structural components of an in situ cast floor with one-way spanning slabs.

The usual constituent components of this kind of floor are as follows (see Fig. 1): plant produced concrete, weldmesh reinforcement, prestressed concrete joists, multi-holed blocks and gypsum plaster (or other different covering materials). The physical properties of the constituent materials of the in situ cast floor are indicated in Table 1 [11-12].

Table 1
Physical properties of the constituent materials.

Fig. 2. Geometrical models and dimensions (in millimetres) of the clay multi-holed blocks *CF1, CF2, CF3, CF4, CF5* and *CF6*.

In order to study the thermal behavior of the in situ cast floors made up of different multi-holed blocks, we have modeled a total of eighteen different types of floors keeping the same overall dimensions and varying, on the one hand, the number of recesses of the blocks (see Fig. 2): *CF1* (three recesses), *CF2* (six recesses), *CF3* (nine recesses), *CF4* (four recesses), *CF5* (eight recesses) and *CF6* (twelve recesses). On the other hand, we have considered three different constituent materials for the multiholed blocks: concrete, lightweight concrete and clay.

Secondly, we have built an entire floor with each one of the eighteen different blocks described above. The one-way spanning slab is made of five multi-holed blocks with four joists, including the weldmesh reinforcement, the plant-produced concrete and the gypsum plaster (see Fig. 3).

Fig. 3. Two-dimensional FE in situ cast floor: overall view (upper) and a detail (lower).

The minimum thickness of the intermediate bulkheads is 15 mm for both plant-produced and lightweight concrete blocks, and 8 mm for the clay blocks. This fact is a consequence of the greater mechanical resistance of the clay comparing with the other two materials studied: normal concrete and lightweight concrete. Finally, it is possible to classify the blocks *CF1* to *CF6* from the number of intermediate bulkheads. Therefore, there are two main groups [7]:

- The first group has two intermediate bulkheads including blocks *CF1* to *CF3*.
- The second group has three intermediate bulkheads and it includes blocks *CF4* to *CF6*.

3. FEM results and discussion

The above in situ cast floors made up of different multi-holed blocks are discretized by the FEM [16-18] and then the thermal behavior of reinforced concrete one-way spanning slabs for internal floors is calculated.

In order to check the thermal performance of the different types of multiholed (*CF1* to *CF6*), eighteen floors (one per each type of block) have been considered. Then, we have built the two-dimensional finite element model, using a two-dimensional 8-node quadrilateral finite element for the solid area of blocks to simulate the thermal conduction phenomenon, a one-dimensional 3-node (plus an extra node) finite element for the recesses of blocks to calculate the thermal convection phenomenon and, finally, a one-dimensional 3-node finite element in order to solve the thermal radiation phenomenon inside the recesses of blocks [21-22] (see Fig. 3 above).

With respect to the external thermal boundary conditions, we have taken the following ones [23]:

- Downward heat flow: a $q/A = 10$ W/m^2 heat flow in the upper floor side, a $h_l = 1/R_{sl} = 5.88$ W/m^{2}K film coefficient in the lower floor side, a $R_{su} = 0.17$ m^{2}K/W surface resistance in the upper floor side and a 273 K ambient temperature.
- Upward heat flow: a $q/A = 10$ W/m^2 heat flow in the lower floor side, a $h_u = 1/R_{su} = 10$ W/m^{2}K film coefficient in the upper floor side, a $R_{sl} = 0.10$ m^{2}K/W surface resistance in the lower floor side and a 273 K ambient temperature

The internal boundary conditions inside the recesses are as follows [23-24]:

- Downward heat flow: The film convection coefficient inside the recesses in this case is:

$$h_a = \max\left\{0.12 \times d^{-0.44}, \frac{0.025}{d}\right\} \quad (1)$$

- Upward heat flow: The film convection coefficient inside the recesses in this case is:

$$h_a = \max\left\{1.95, \frac{0.025}{d}\right\} \quad (2)$$

where d is the thickness of the recesses in the vertical direction.

Next, the eighteen different FEM models are solved and the temperature distribution is determined (see Fig. 4).
In order to determine the block's thermal performance it is necessary to define two important parameters [3-4]:

- The mass overall thermal efficiency, $e_{thermal\_p}$ (m^2 K/W/kg): this parameter is defined as the ratio between the overall thermal resistance and the mass of the block.
- The equivalent thermal conductivity, λ_{equi} (W/m K): it is defined as the ratio between the thickness of the multilayer floor and the thermal resistance.

Both parameteres are calculated from the previous thermal numerical results and they are shown in Fig. 5.

Fig. 4. Temperature distribution in floors made up of hollow block types *CF3* (left) and *CF6* (right) for the downward heat flow: lightweight concrete (a and b), normal concrete (c and d), and clay (e and f).

On the one hand, specifically Fig. 5 (left) show the mass overall thermal efficiencies in all analyzed cases, both for downward and upward heat flows, and it is evident that the worst material is the plant-produced concrete (about 0.2 and 0.15% for downward and upward heat flows, respectively). Moreover, there are several differences between multiholed blocks, being the blocks *CF1* and *CF4* the worst of them. It is also possible to observe that the best block from the thermal performance point of view is the block *CF3* made up of lightweight concrete as the constituent material, since its average value (0.3% and 0.37% for upward and downward heat flows, respectively) is the biggest one.

Fig. 5. Mass overall thermal efficiency (left) and equivalent thermal conductivity (right) for downward heat flow (upper) and upward heat flow (lower) for the three analyzed materials and six different models.

On the other hand, it is shown the numerical results for the equivalent thermal conductivity in Fig. 5 (right). From the point of view of this parameter, the best blocks is *CF3* made up of lightweight concrete.

After examining the results obtained numerically, it can be assumed that the numerical procedure constitutes a reasonable approach to choose the best type of block from the thermal point of view. The finite element model used in this work reproduces accurately the heat transfer for in situ cast floors made up of different constituent materials and different recesses with complex shapes.

5. Conclusions

In the first place, a numerical thermal analysis technique (by FEM) has been carried out to study eighteen different in situ cast floors, made up of three different constituent materials for the hollow blocks. Taking into account the variation of the dimensions of the recesses, it is possible to modify the thermal efficiency of the blocks and, consequently of the full floor. Based on the mass overall thermal efficiency and the equivalent thermal conductivity, it is possible to select best candidate floor from the thermal point of view.

In the second place, the equivalent thermal conductivity depends on both the number of the vertical and horizontal intermediate bulkheads and the constituent material. Therefore, if the number of horizontal intermediate bulkheads is increased and the material is changed, the thermal transmittance grows more than if the number of vertical intermediate ones does.

Thirdly, the overall heat transfer coefficient increases if material conductivity increases and the number of recesses decrease. The bigger mass overall thermal efficiency, the better thermal insulation and the lower floor's weight. Therefore, the support structure of these floors will be subjected to smaller dead loads and the best block from the average mass overall thermal efficiency point of view was the block *CF3*.

Finally, there is an increasing interest to use materials with good physical properties with respect to an energy savings, which also fulfil all strength and serviceability requirements for housing and industrial structures. From this point of view, the architect or engineer can use the results shown in this research work to obtain the best candidate floor configuration according to their thermal requirements.

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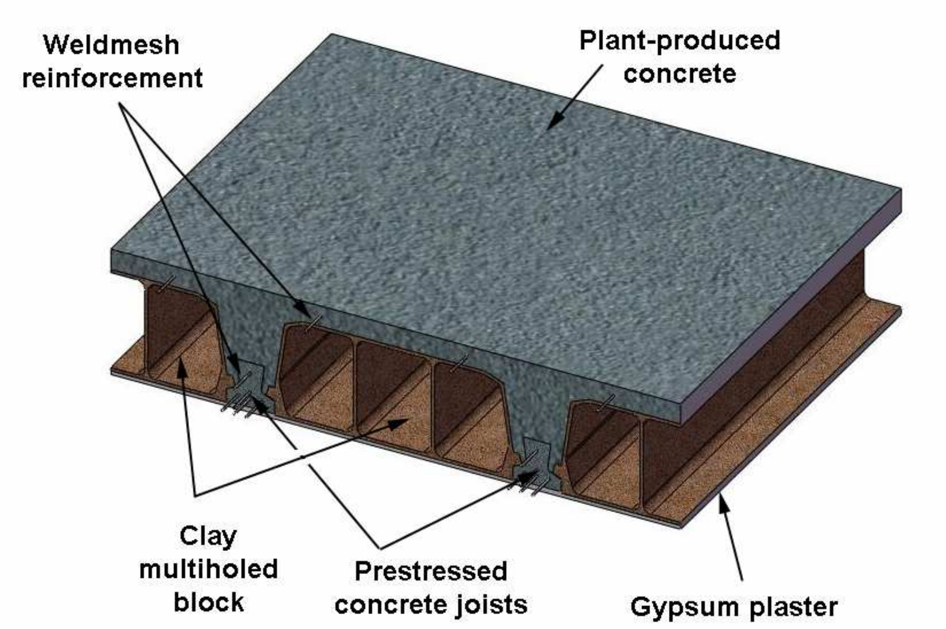
Table 1
Physical properties of the constituent materials.

Item	Density [kg/m^3]	Conductivity λ [W/m K]
Plant-produced concrete	2,200	1.600
Weldmesh reinforcement	7,850	60.000
Prestressed concrete joist	2,200	1.600
Clay	1,500	0.510
Lightweight concrete	1,000	0.347
Gypsum plaster	1,100	0.280



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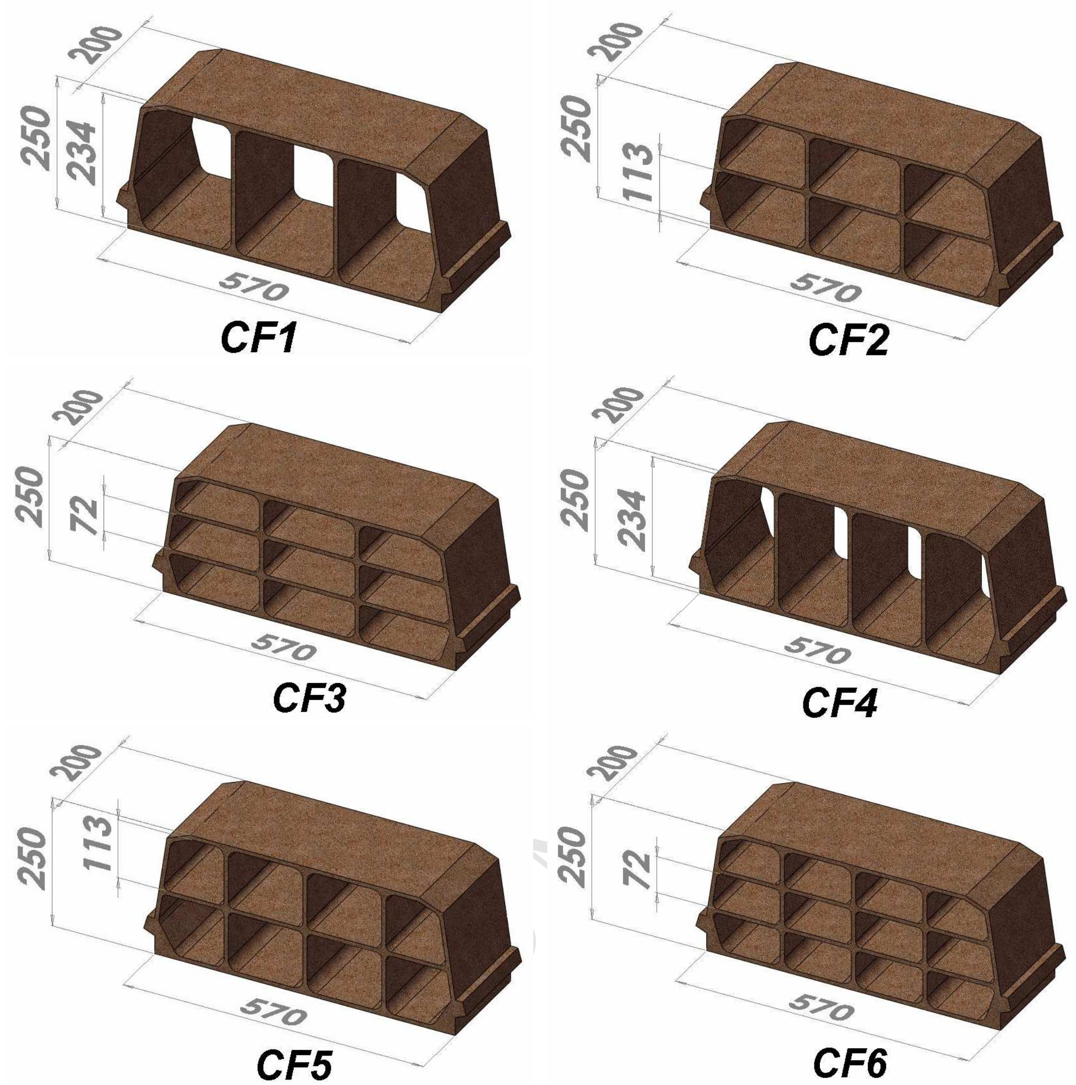

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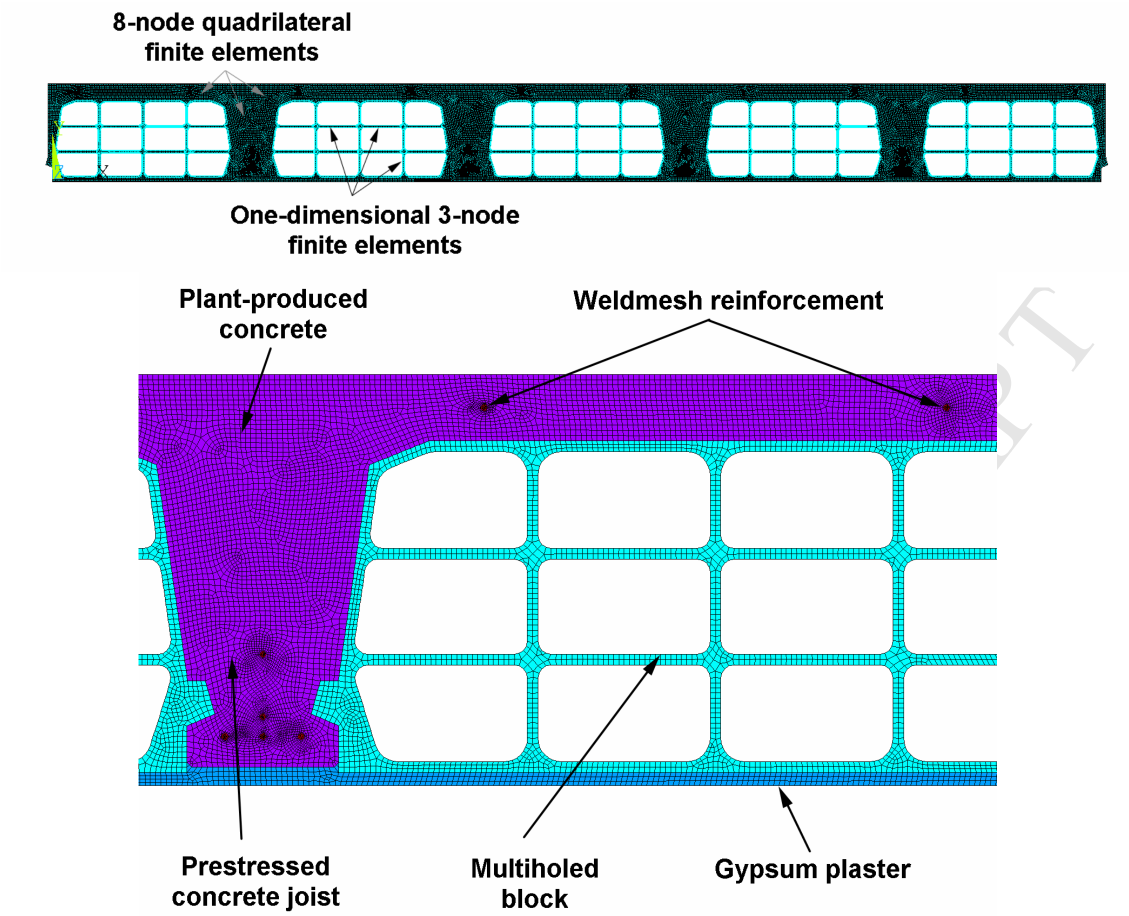

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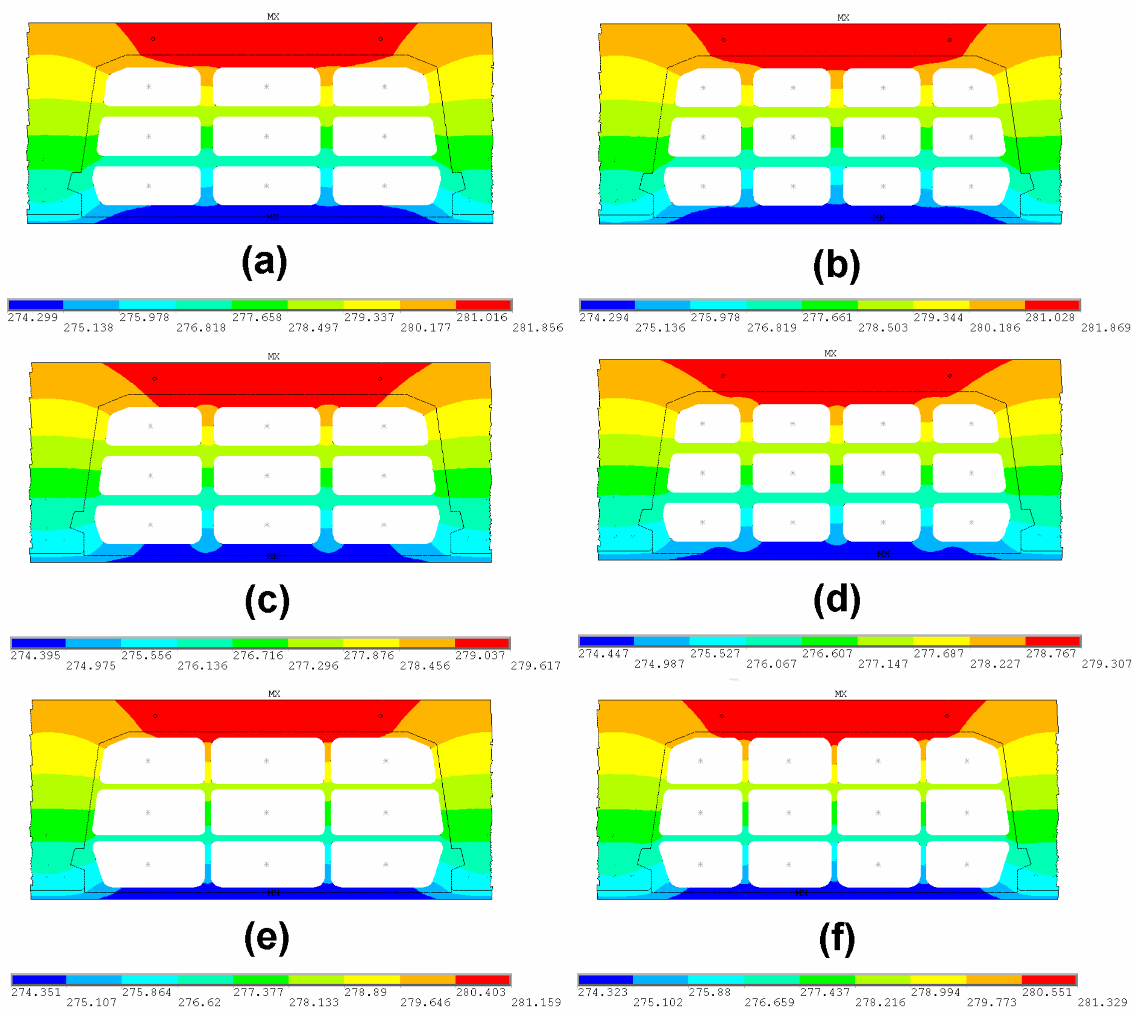

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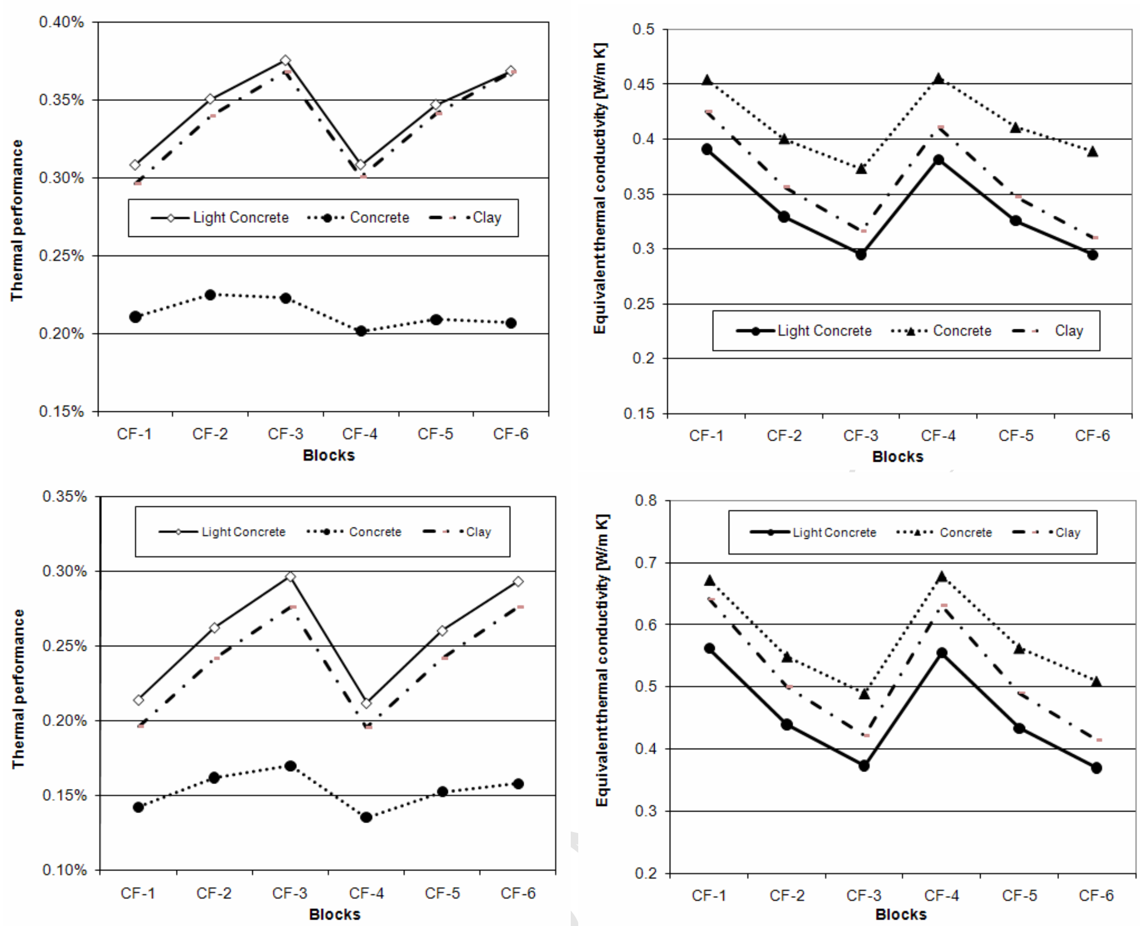

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