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Experimental and numerical thermal assessment of EPS concrete hollow blocks in Lebanon

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Abstract

Hollow concrete blocks can be thermally improved either by modifying their cavities shapes or by adding insulation materials into these cavities. It is also possible to improve the thermal conductivity of concrete solid matrix by incorporating some materials to its composition like recycled solid wastes for example.

This paper offers a solid and comprehensive study for thermally improved hollow blocks through a case study from the Lebanese context and provides a scientific basis for improving the thermal performance of these blocks. The effect of adding EPS (expanded polystyrene) beads to the concrete solid mixture was investigated in this work through numerical and experimental approaches. The experimental and numerical results were in good agreement and the potential thermal improvement by adding EPS beads to concrete mixture was examined on both numerical and experimental levels.

The numerical results for the 3D model allow the visualization of the heat flux and temperature distribution in the block as well as the air velocity and convective heat exchanges inside the cavities of the block.

The results showed that the block thermal resistance can almost double by adding 18g of polystyrene bead the its concrete mixture.

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Introduction

The ever growing international concerns related to energy and resource conservation have led to many scientific and industrial efforts towards the improvement of masonry units and many research studies are working on developing new hollow blocks with improved thermal properties.

The effect of the geometry on its thermal performance was studied by many researchers. Urban B. et al. 2011 compared six commercially available geometries of 12 inches (300 mm) thick Concrete Masonry Units including solid-block, two-core hollow block, cut-web block, multicore block, solid block with interlocking insert, and solid block with serpentine insulation insert. Fogiatto et al. 2016 numerically investigated the best cavity configuration for 10 different block configurations with defined external dimensions that promotes the lowest thermal transmittance. Coz Diaz et al. 2009 also compared numerically five different hollow blocks for internal floors with constant external dimensions by varying the number of vertical and horizontal intermediate bulkheads to optimize their thermal performance.

Other than the internal geometry of the blocks, the thermal conductivity of the block material as well as the thermal conductivity inside the holes are important factors allowing the improvement of hollow blocks. Zhang et al. 2014 found that the main factors influencing thermal performance in descending order, were: the thermal conductivity of the solid matrix, the thermal capacity of the solid matrix, the thermal conductivity of the infill material inside holes, the block thickness, and the number of hole rows (maintaining small hole thickness).

Many studies discussed the potential of thermal, and/or mechanical improvement of building blocks by using recycled waste materials in the concrete mixture. Caruana et al. 2014 provided an overview of testing methodologies for thermally improved hollow core concrete blocks by discussing testing methodologies for the load bearing as well as thermal characterization of hollow concrete blocks. These techniques were applied for a new building block with improved thermal properties by maintaining comparable compressive strength, physical dimensions and manufacturing process (Caruana et al. 2017). Meng et al. 2018 provided a review about using aggregates from solid wastes such as crushed brick, ceramic and tile waste, crumb rubber, etc.) in the production of concrete blocks. The results underlined a good potential without compromising the compliance with standard requirements. Mohammed et al. 2011 evaluated miscellaneous physical properties including compressive strength thermal conductivity and acoustic absorption for crumb rubber hollow concrete blocks (39 cm x 19 cm x 19 cm) using different amounts (0%, 10%, 25% and 50%) of crumb rubber for replacing fine aggregates. Xu et al. 2019 investigated the effect of wood fibers content on

the physical properties of autoclaved aerated concrete. He found that adding wood fibers into Autoclaved aerated concrete (AAC) was better than adding of polyester fibers.

Concrete hollow blocks are widely used in Lebanon due to their advantages such as lifespan, low cost, low maintenance, fire resistance, and simplicity in implementation; however, their thermal performance is relatively poor and requires some improvements to meet today's needs in terms of comfort and energy efficiency. The potential of improving these blocks by incorporating polystyrene EPS beads is discussed in this paper through experimental and numerical approaches.

In developing countries, a very large quantity of EPS wastes is either sent to landfill or illegally dumped in open areas. The use of EPS as substitution of concrete aggregates in construction applications would reduce the amount of materials sent to landfill, and preserve natural material for future use by improving the thermal performance of the building through its low thermal conductivity (Pacheco-Torgal F. et al. 2018).

Many research studies investigated the mechanical behavior of EPS concrete (Bai et al. 2019, Cui et al. 2015, and Li et al. 2018) trying to assess and improve its compressive strength in different engineering application. Sayadi et al. 2016 found that increasing the volume of EPS in foamed concrete causes a significant reduction of thermal conductivity, fire endurance and compressive strength of concrete. Also, a micro-tomographic study realized by Maaroufi et al. 2018 allowed the assessment of a representative elementary volume for the polystyrene mortar in order to evaluate its total porosity and to have access to the pore size distribution. Dixit et al. 2019 tested the mechanical and thermal properties of samples made of 3–5mm diameter EPS beads mixed in Ultra High Performance Concrete in five proportions by volume of 0, 16, 25, 36, 45%.

In this paper, hollow blocks made of four different concrete mixtures with different EPS beads ratios (0g, 6g, 12g, and 18g) were investigated numerically and experimentally. A comprehensive understanding about the thermal performance of hollow blocks made of EPS concrete mixture is provided through a case study from the Lebanese context which brings a scientific basis for thermal improvement of traditional Lebanese hollow blocks.

Experimental aspect

The initial concrete mixture used for concrete hollow blocks was mixed with polystyrene EPS beads having a density of 12 kg/m³ forming a new concrete mixture with a better thermal performance (lower thermal conductivity) as shown in Fig. 1. Then, the hollow block samples were molded with the same manufacturing process as the traditional Lebanese hollow block to

end up with blocks having the same geometry: external dimensions of 10cm x 20cm x 40cm with elliptical and circular holes.



(a)

(b)

Figure 1- Preparation of the concrete mixtures (a) and the blocks (b)

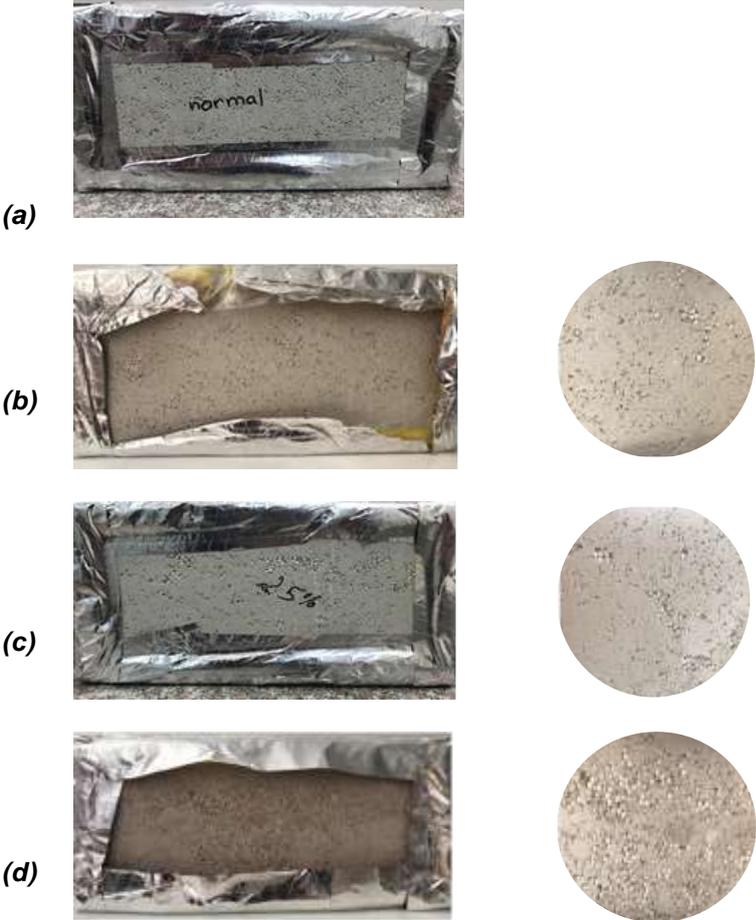


Figure 2- Investigated samples of hollow concrete blocks different EPS beads dosages: 0g (a), 6g (b), 12g (c), and 18g (d)

Four different concrete mixtures (Fig. 2) with different EPS beads ratios (0g, 6g, 12g, and 18g) were investigated representing respectively 10.4%, 20.9% and 31.3% volume fractions in the total concrete solid matrix mixture. A 10 cm Rockwool lateral insulation was applied to the samples to guarantee 1-dimensional heat transfer.

Preparation of the samples

The blocks, are generally manufactured in a traditional craft way, with unknown thermal properties. The blocks mixture consists aggregates mixed with cement and water. The mixture is then transported with a large wheelbarrow to the various artisans, working on in-line production presses.

The aggregate mixture is made of 25% of fine gravel aggregates (4 - 8 mm) and 75% of powdered stone dust (0.5 - 4 mm). One cubic meter of aggregates is mixed with 50 kg of Portland cement and 50 liters of water to form the solid matrix mixture.

A solid mixture sample was prepared by gluing two flat concrete pieces from the same mixture to have a thickness of 55 mm in order to determine the thermal conductivity of the concrete matrix of the hollow block (Fig. 3).



Figure 3- Experimented solid mixture sample

Experimental measurements

Experimental method

The guarded hot plate method was considered for thermal characterization (Fig. 4). An imposed temperature is set on each face of the sample and simultaneous measurements of the temperature and exchanged heat flux variations allow the determination of the sample thermo-physical properties, namely the thermal conductivity λ and the specific heat c_p .



Figure 4- Experimental test cell

Two T-type thermocouples and two heat flux sensors were used to measure temperature and heat flux on both surfaces of the sample.

An Arduino micro controller was used for data acquisition and connected to a computer device.

An imposed temperature on each sample edge is set and simultaneous temperature and heat flux measurements are registered in order to determine its thermal resistance (Younsi et al. 2011).

The heat flux and the temperature on both sides of the sample are measure simultaneously. Fourier's law applied to a unidirectional system in steady state conditions gives:

$$R = \frac{\Delta T}{\varphi} \quad (3)$$

Where ΔT represents the temperature difference applied at the sample's boundaries, φ represents the heat flux crossing the sample, and R the thermal resistance of the sample.

Experimental results

The thermal resistance can be determined when steady state conditions are achieved (constant boundary temperatures and constant heat flux) by using Eq. 3.

- a.) Concrete solid mixture

The thermal conductivity of the solid mixture is deduced from Fig. 5 and is $1.4 \text{ W.m}^{-1}.\text{K}^{-1}$.

- b.) Regular hollow bloc

Based on the experimental results shown in Fig. 6, the thermal resistance of the regular hollow block is $0.16 \text{ m}^2.\text{K.W}^{-1}$

- c.) Hollow block with 6g of EPS beads

Based on the experimental results shown in Fig. 7, the thermal resistance of the hollow block with 6g of EPS beads is $0.2 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$

d.) Hollow block with 12g of EPS beads

Based on the experimental results shown in Fig. 8, the thermal resistance of the hollow block with 12g of EPS beads is $0.25 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$

e.) Hollow block with 18g of EPS beads

Based on the experimental results shown in Fig. 9, the thermal resistance of the hollow block with 18g of EPS beads is $0.31 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$

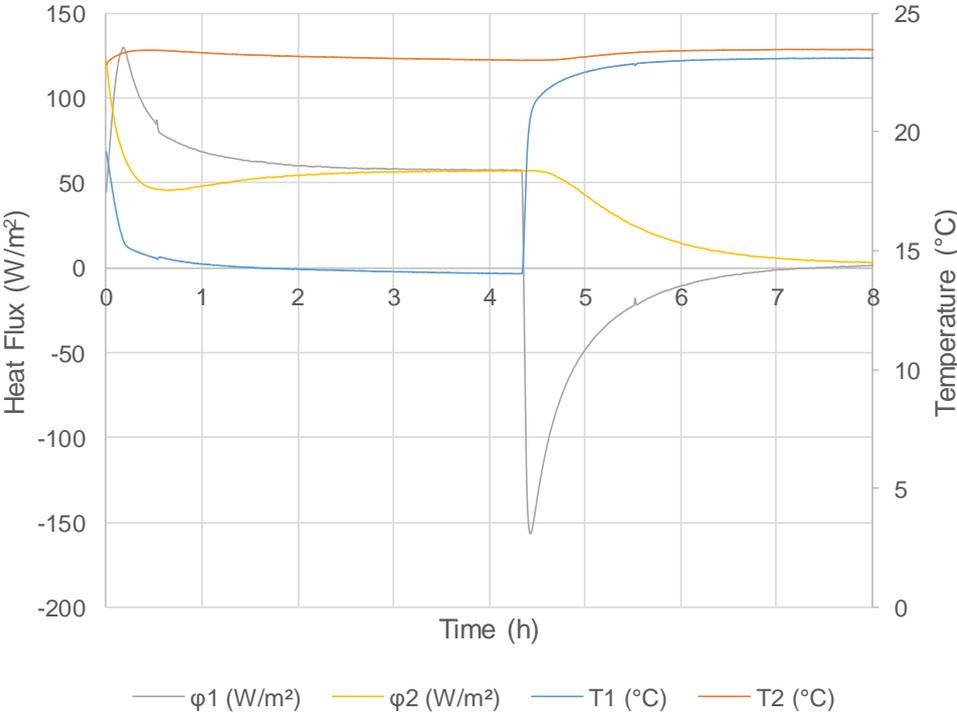


Figure 5- Experimental results for the concrete mixture of the block

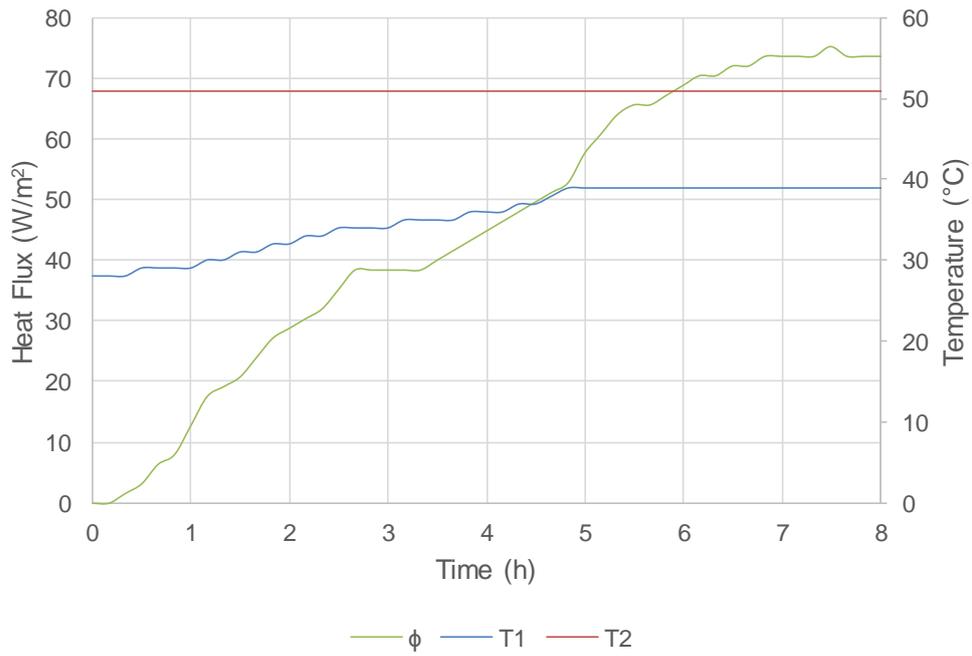


Figure 6- Experimental results for the regular hollow block

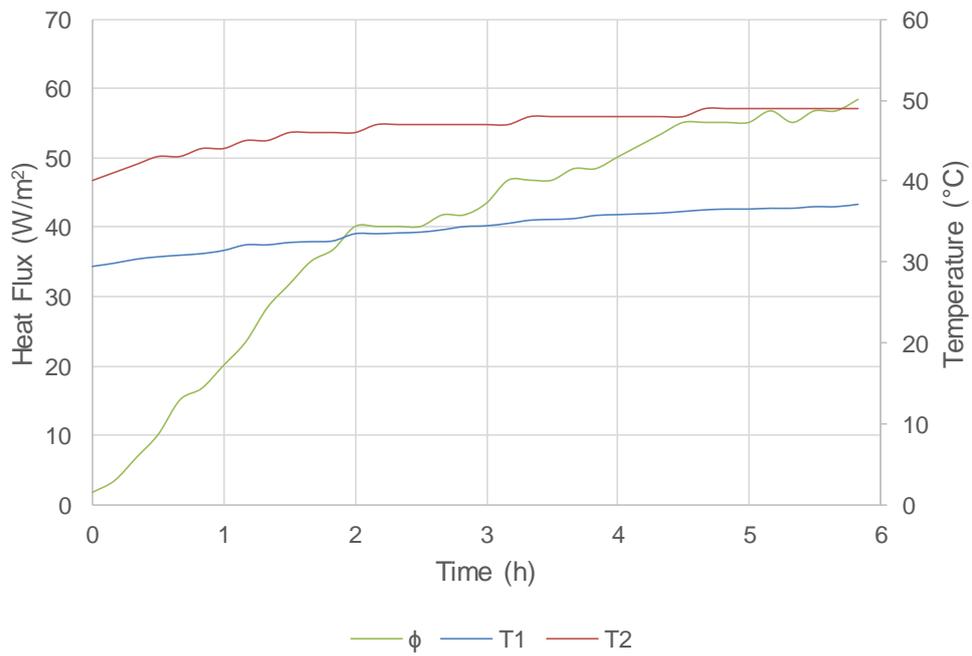


Figure 7- Experimental results for the 6g EPS beads hollow block

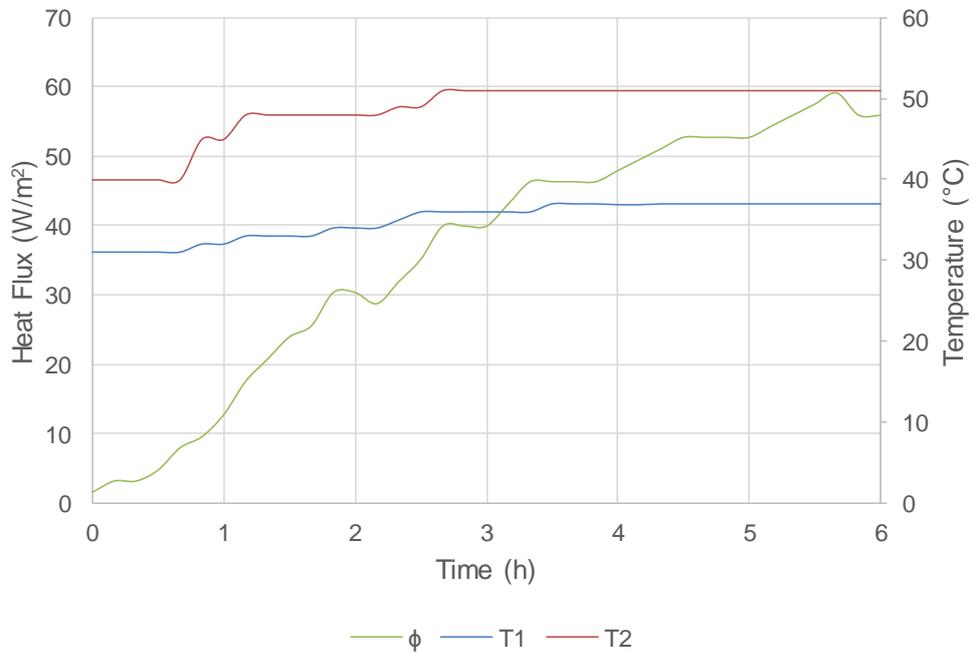


Figure 8- Experimental results for the 12g EPS beads hollow block

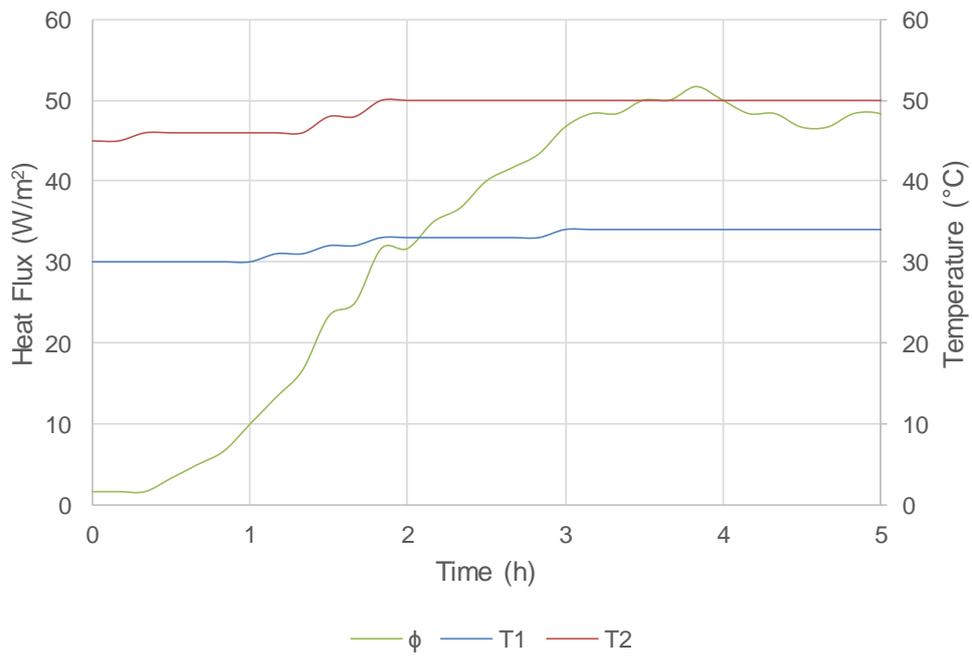


Figure 9- Experimental results for the 18g EPS beads hollow block

Numerical aspect

Numerical method

Existing thermal conductivity approaches for two phases solid mixtures

a.) Thermal Conductivity Bounds (TCB)

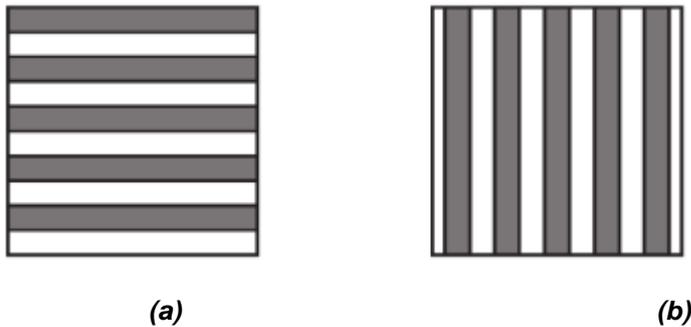


Figure 10- Parallel (a) and series (b) models [18]

The parallel model shown in Fig. 10 and Eq. (2) provides the upper bound of effective thermal conductivity for two phases solid mixtures, and the series model shown in Fig. 10 and Eq. (3) gives the lower bound (Xu et al. 2016).

$$\lambda = V_1\lambda_1 + V_2\lambda_2 \quad (2)$$

$$\lambda = \frac{\lambda_1\lambda_2}{V_1\lambda_2 + V_2\lambda_1} \quad (3)$$

Where λ is the effective thermal conductivity, λ_1 and λ_2 are thermal conductivities of each phase, and V_1 and V_2 are their respective volume fractions.

b.) Campbell-Allen and Thorne Model (CATM)

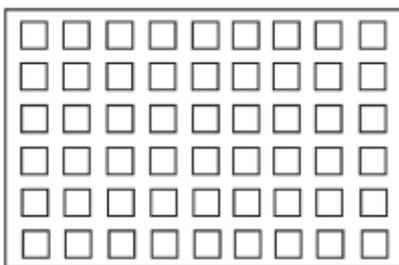


Figure 11- Campbell-Allen and Thorne model configuration [18]

Campbell-Allen and Thorne 1963 proposed a theoretical model assuming that the concrete was composed of continuous mortar phase and dispersed coarse aggregate phase (Fig. 11). According to this model, the effective thermal conductivity is expressed by:

$$\lambda = \lambda_1 - (2M - M^2) + \frac{\lambda_1 \lambda_2 (1 - M)^2}{\lambda_2 M + \lambda_1 (1 - M)} \quad (4)$$

Where

$$M = 1 - V_2^{1/3} \quad (5)$$

λ_1 is the thermal conductivity of continuous phase, λ_2 is the thermal conductivity of dispersed phase, V_2 is the volume fractions of dispersed phase.

c.) Maxwell-Eucken Model (MEM)

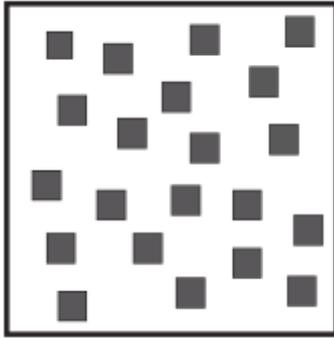


Figure 12- Maxwell-Eucken model configuration [18]

The Maxwell-Eucken model (Wang et al. 2008) suggests one continuous phase and one or more randomly dispersed phases without relevant interaction (Fig. 12). The expression for thermal conductivity of this model is given by:

$$\lambda = \lambda_1 \frac{2\lambda_1 + \lambda_2 - 2(\lambda_1 - \lambda_2)V_2}{2\lambda_1 + \lambda_2 + (\lambda_1 - \lambda_2)V_2} \quad (6)$$

d.) Generalized effective medium theory



Figure 13- Generalized Effective Medium Theory model configuration [18]

The Effective medium theory model (Wang et al. 2006) is based on the phases being mutually dispersed (Fig. 13); it is expressed by:

$$\lambda = \frac{1}{4} \left((3V_2 - 1)\lambda_2 + (3(1 - V_2) - 1)\lambda_1 + \sqrt{((3V_2 - 1)\lambda_2 + (3(1 - V_2) - 1)\lambda_1)^2 + 8\lambda_1\lambda_2} \right) \quad (7)$$

3D numerical modeling and simulation of the block

The simulations were performed using the software COMSOL® version 5.3a (COMSOL 2006). In this two-dimensional study, a structured mesh was considered using steady-state heat transfer.

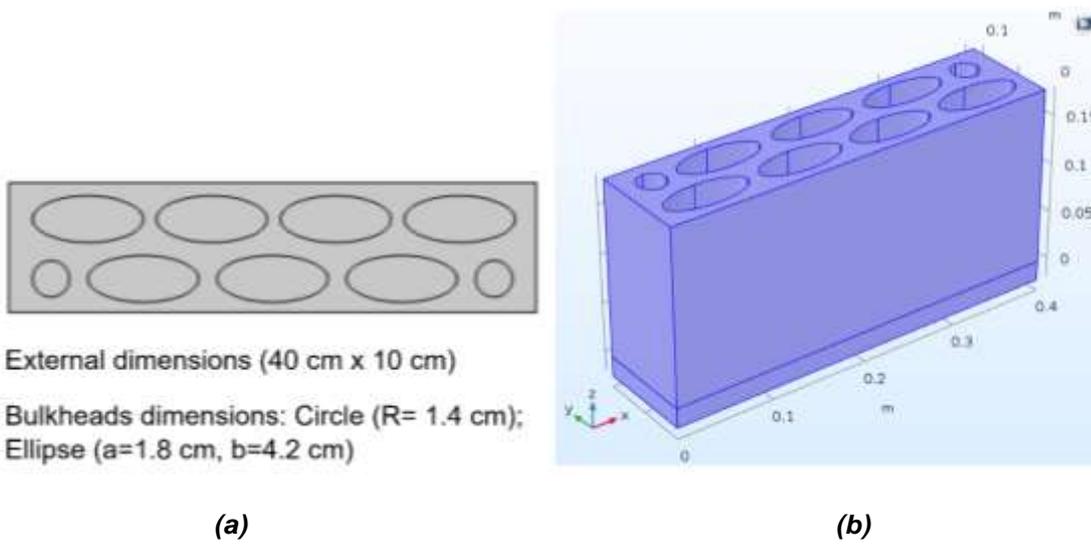


Figure 14- Dimensions (a) and numerical modelling (b) of the concrete hollow block

The dimensions of the studied wall are reported in Fig. 14. A temperature gradient of 20 °C is imposed on the long lateral faces of the block (273 K – 293 K) while the two other faces are remaining adiabatic.

Determination of the EPS volume fraction

The EPS volume fraction V_2 is determined by:

The solid fraction of the block is determined from the 3D block geometry and is equal to 59.8%, the total volume is equal to $V_t = 8000 \text{ cm}^3$ and the solid volume is $V_s = 4787 \text{ cm}^3$.

The volume of EPS beads is given by:

$$V_{EPS} = \frac{m_{EPS}}{\rho_{EPS}}$$

The EPS volume fraction V_2 is thus given by:

$$V_2 = \frac{V_{EPS}}{V_t} \quad (9)$$

Numerical results

Results for the solid mixtures

The concrete solid mixture thermal conductivity for the model was taken equal to the value found experimentally ($1.4 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) while the EPS beads thermal conductivity was assumed to be equal to $0.04 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ (Dixit et al. 2019, De Moraes 2019, and Gnip et al. 2012).

The comparison between the three models for determining the equivalent thermal conductivity of the two phases mixture (Table 1) shows that the three models provide comparable results with a maximum deviation of less than 10% for the four mixtures. In what follows, the Generalized Effective Medium Model was used.

Table 1- Equivalent thermal conductivities of the concrete mixtures for different numerical models for different EPS beads ratios

M_{pol} (g)	0	6g	12g	18g
$\%_{\text{pol}} (V_2)$, (-)	0	0.11	0.21	0.31
λ (Campbell-Allen and Thorne), ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	1.4	1.14	0.96	0.81
λ (Maxwell-Eucken), ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	1.4	1.19	1.02	0.86
λ (Generalized Effective Medium), ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	1.4	1.18	0.98	0.78
Maximum deviation (-)	0%	4.2%	5.9%	9.3%

Results for the concrete blocks

The numerical results for the 3D model allow a better understanding of the heat transfer and temperature distribution in the block in quantitative and qualitative manners. Fig. 15 shows that the temperature gradient within the block decreases progressively from the cold side to the hot side. The air velocity inside the cavities is also determined through the CFD free convection buoyancy modelling; it reaches maximum values of around 4 cm/s (Fig.16) which shows that convective heat exchanges are taking place.

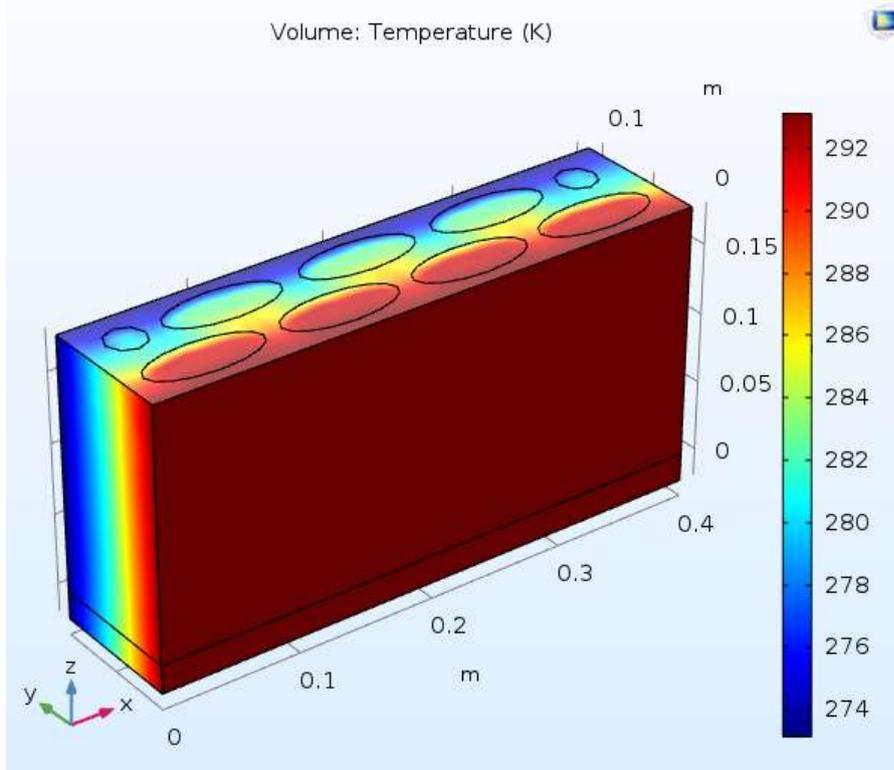


Figure 15- Temperature distribution inside the hollow block

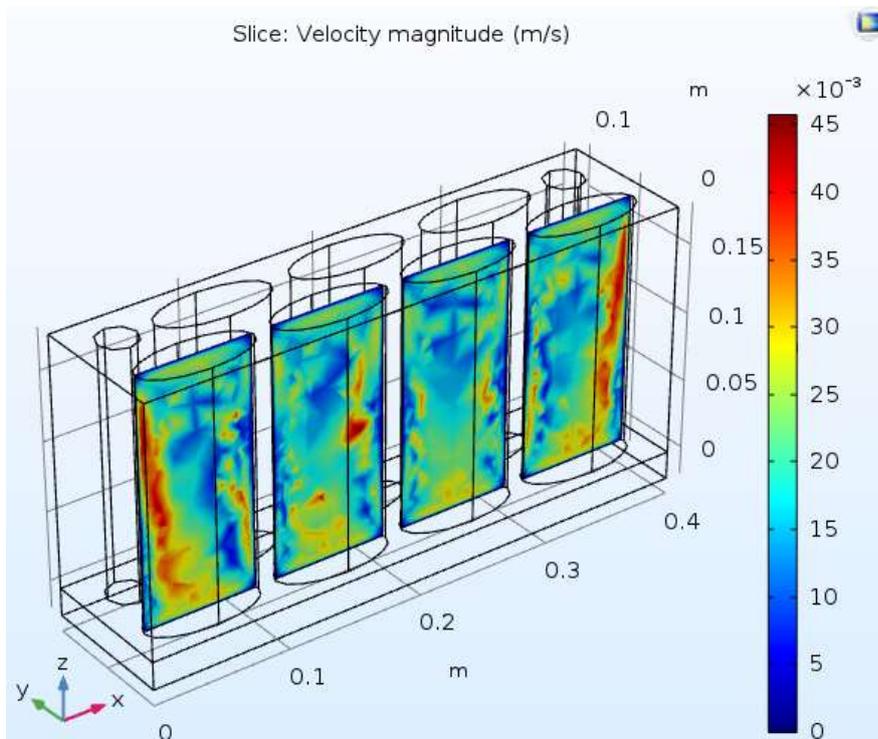


Figure 2- Air velocity inside the cavities of the block

The 3D heat flux in the hollow block concrete is provided in Fig. 17 confirming that maximum heat flux occurs at the edges of the block where the absence of cavities promotes conductive heat transfer, the solid matrix is thus the seat of the main heat stream in the block.

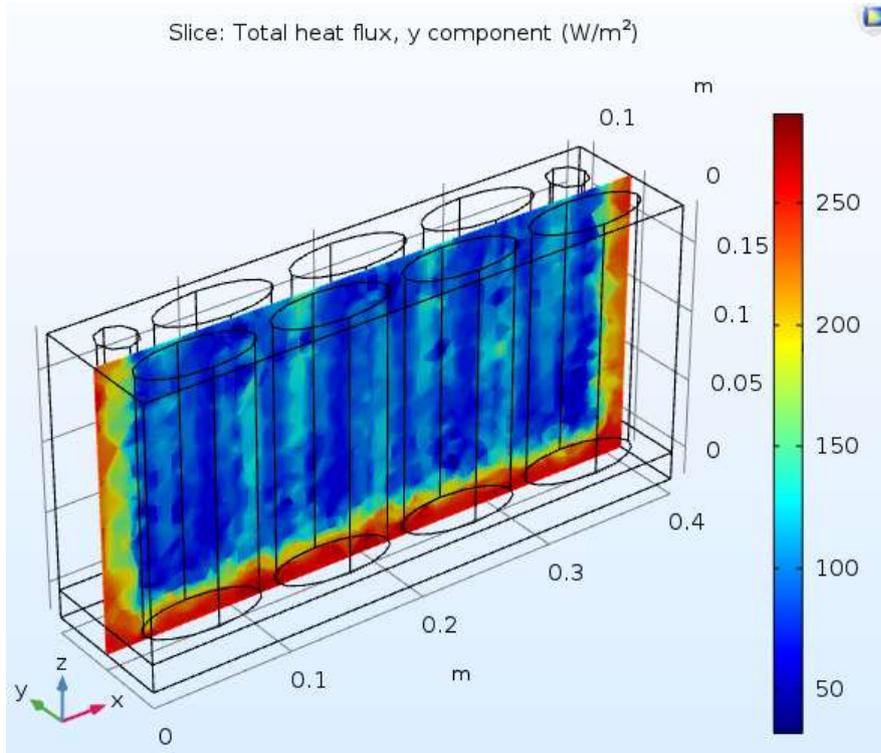


Figure 3- Heat flux distribution across the middle plan of the block

3D numerical modeling and simulation allows a better understanding of different thermal transfer phenomena in the hollow block where conduction, convection and even radiation take place simultaneously. The solid concrete mixture is the seat of the conduction heat transfer while convection and radiation occur in the cavities of the block.

Comparison between numerical and experimental results

The comparison between numerical and experimental results (Fig. 18) shows the validity of the numerical approach for the 4 studied sample. It also allows to predict numerically the potential of improving the thermal resistance of the hollow blocks.

The relation curve between the thermal conductivity of the solid mixture and the equivalent thermal resistance of the hollow block (Fig. 18), shows that reducing the thermal conductivity of the concrete mixture from 1.25 to 0.5 W/m.K increases the thermal resistance of the block by more than 2 times (from 0.17 to 0.4 m².K.W⁻¹).

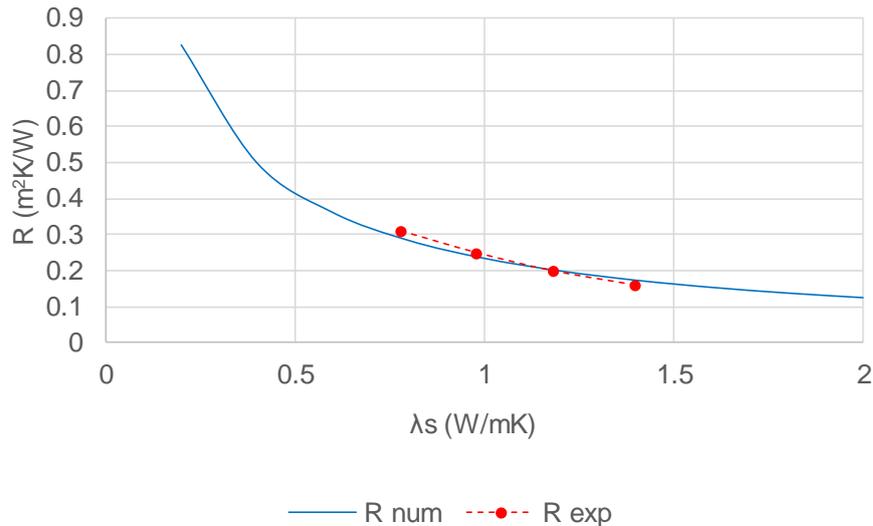


Figure 4- Relation between the thermal conductivity of the solid mixture and the equivalent thermal resistance of the hollow block for numerical and experimental results

The slight difference between experimental and numerical results could be due to many reasons such as:

- the error due to the homogeneity in the concrete mixtures
- the error due to inaccuracies in measurements
- the error due to the contact resistance between the heat fluxmeter and the blocks while measuring the heat flux experimentally.
- the precision and accuracy of the model as well as the assumptions considered (1-directional heat flux, uniform boundary conditions, homogeneous sample, etc...)

Parametric analysis by modifying the solid matrix

The thermal resistance of the hollow block can be linearly correlated to the overall solid mixture density ρ_s as shown in Fig. 19. Note that the maximum theoretical mass of EPS that can be incorporated is 57 g, this corresponds to a EPS volume ratio $V_2 = 1$. The maximum thermal resistance that can be reached is thus $0.655 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$ by using a block fully made of EPS beads.

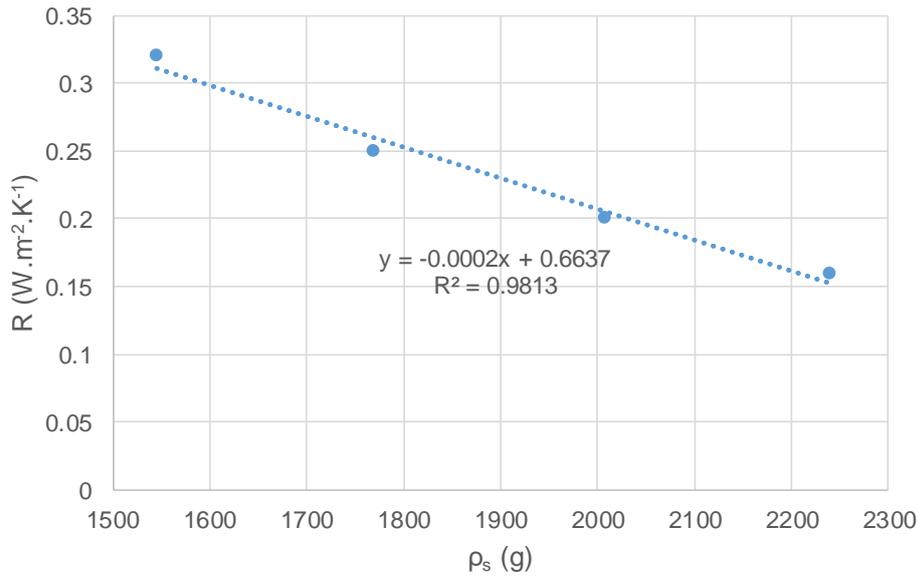


Figure 5- Relation between the bloc thermal resistance and overall solid mixture density ρ_s

Conclusions and perspectives

The effect of adding EPS beads to the concrete mixture was investigated in this work through numerical and experimental approaches.

Four different hollow block samples with different EPS beads ratios (0g, 6g, 12g, and 18g) were prepared and experimented to determine their thermal resistance.

Three different numerical models for determining the equivalent thermal conductivity of the two phase concrete and EPS beads mixture were successfully confronted, then a 3D block modeling and simulation was also performed for understanding the main heat transfer phenomena inside the concrete hollow block.

The experimental and numerical results were in perfect agreement and the potential thermal improvement by adding EPS beads to concrete mixture was investigated on both numerical and experimental levels. A linear correlation was noticed between the bloc thermal resistance and overall solid mixture density ρ_s . The potential thermal improvement through the usage of EPS beads in hollow blocks is proven by showing that adding a very low mass of EPS (18g) to the concrete mixture of a hollow block can almost double its thermal resistance.

Moreover, the numerical results for the 3D model allow the visualization of the heat flux and temperature distribution in the block as well as the air velocity and convective heat exchanges inside the cavities of the block.

This paper offers a solid and comprehensive study for thermally improved hollow blocks through a case study from the Lebanese context and provides a scientific basis for improving the thermal performance of these blocks.

The results seem promising on the thermal level showing how adding just 18g of polystyrene beads can increase the thermal resistance of hollow blocks from 0.16 to 0.31 m².K.W⁻¹. The next studies will focus on mechanical optimization along with thermal optimization of the concrete hollow block by focusing on the geometry and the concrete mixture composition. It is also of great interest to understand the interaction between aggregates components and the properties of binder-aggregate interface (Gua et al.2016, Guo and Tan 2019). This will allow ending up with an efficient and marketable prototype able to compete and even replace the existing traditional hollow block that is widely used in Lebanon and the neighboring countries.

Data Availability Statements

All data, models, and codes that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgements

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