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Andreas Kyriakidis*, Aimilios Michael, Rogiros Illampas

University of Cyprus / Department of Architecture, Nicosia, Cyprus P.O. Box 20537, 1678, Nicosia, Cyprus

Rogiros Illampas

University of Cyprus, Department of Civil and Environmental Engineering, 75 Kallipoleos St.

P.O. Box 20537, 1678 Nicosia, Cyprus

*Corresponding author: **kyriakidis.andreas@ucy.ac.cy**

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The present study is part of a wider research program, which aims at the development of an innovative masonry construction system that integrates both environmental passive strategies and high energy efficiency. The paper focuses on the parametric computational investigation of the proposed system's basic modular construction component. The thermal performance achieved by alternative geometries of the masonry unit, as well as the use of different constituent materials and insulation fillings, are further examined. The optimum solutions, in terms of thermal performance, were achieved by performing a series of numerical heat flux analyses on alternative proposals, arising from the combination of the above features. Furthermore, the environmental impact, associated with the construction system, is assessed by estimating the total embodied energy of the modular component. It is concluded that the proposed system's thermal performance relies primarily on the characteristics of the constituent mixture composing the modular masonry unit, the geometry of the unit and the use of insulation. In terms of environmental impact, both the constituent mixture used, and the type of insulation material installed, have a considerable impact on the end-product's total embodied energy.

KEYWORDS: innovative masonry construction component, high energy efficiency, parametric study, numerical assessment.

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Introduction

Masonry walls account for 29%-59% of thermal loss occurring in buildings and are thus, responsible for increased energy use and greenhouse gas emissions (Balaras et al. 2000). Furthermore, 13% of the energy consumed by buildings results from masonry manufacturing and construction processes (e.g. transportation of products, on-site equipment and human resources and on-site waste materials) (Hammond and Jones 2008a, b).

In light of the above, there is a precipitated need for developing improved building construction systems that will be efficient in terms of energy performance and will require reduced natural and human resources for their production and construction (Phocas et al. 2011, Michael et al. 2012). Within this context, Michael et al. (2012) have conceived the idea of an innovative masonry component that offers customization potentials and can be used for the construction of structurally sound modular assemblies of variable forms. The proposed concept incorporates a series of passive design strategies, aiming at the improvement of indoor comfort conditions (Philokyprou et al. 2013a, b), as well as at the minimization of energy consumption of the building envelope. Depending on the prevailing climatic conditions and the occupants' needs, different modular assemblies (architectural configurations) can be adopted to enhance thermal insulation (buffer zone), ventilation (building ventilation/stack effect), shading (suitable for different orientations) and integration of active solar systems (Bougiatioti et al. 2015, Michael et al. 2011, Savvides et al. 2016).

This study provides a state-of-the-art review on the development of novel walling systems and conducts a parametric analysis in order to assess the thermal performance and environmental impact of the proposed modular masonry unit. Alternative geometries of the building component are taken into consideration and different constituent materials and insulation fillings are examined. In each case, the thermal properties of the resulting unit are determined through computational analysis and the environmental impact is estimated. Comparable results are obtained and useful conclusions regarding the composition and geometry of the proposed unit are derived. Furthermore, the study identifies areas that future research should address for the development of an integrated technical solution.

Review on the development of novel walling systems

Masonry materials include fired clay, concrete and calcium silicate brick units with variable properties (density = 450-2000 kg/m^3; compressive strength = 2.5-100 MPa; thermal conductivity = 0.1-1.5 W/mK) (Hendry 2001). Due to the fact, that the characteristics of many conventional and traditional masonry materials (e.g. fired-clay bricks, concrete or earth-based blocks) are not adequate for achieving good energy performance (Pacheco-Torgal et al. 2015), considerable research efforts are currently in progress for upgrading existing masonry systems and for developing innovative energy-efficient walling components (Miccoli et al. 2015, Gakiet al. 2015, Colombo et al. 2014). Up to-date, emphasis has been placed on: (a) developing masonry units with optimized properties and (b) examining the use of parametric design and optimization algorithms for decreasing energy consumption.

Significant experimental work has been carried out aiming at the design of constituent mixtures suitable for the production of energy efficient, environmentally-friendly masonry units. Velasco et al. (2016) considered the use of coffee ground wastes for the production of fired clay bricks. Results show that the addition of coffee grounds can decrease thermal conductivity by up to 50%, without reducing compressive strength below 10 MPa. Görhan and Simsek (2013) investigated the effects of rice husk addition on the porosity and thermal conductivity of fired clay bricks. Laboratory tests revealed that higher ratios of rice husk result to lower thermal conductivity coefficients and increased porosity and water absorption. Sutcu (2015) performed experiments on fired clay bricks containing varying amounts of expanded vermiculite. This researcher notes that vermiculite can reduce density, improve porosity and decrease thermal conductivity by 30%, but may also lead to lower compressive strengths. Wu et al. (2015) used shale along with building and industrial waste materials to manufacture fired hollow blocks. A compressive strength of 17.5 MPa and a U-value of 0.727 W/m^{2}K was assessed for the units produced, indicating that the material developed is suitable for the construction of thermally efficient load-bearing walls. After conducting an experimental and numerical investigation on the properties of fired clay bricks containing organic matter, Aouba et al. (2015) noted that the addition of wheat straw residue can improve thermal transmittance by more than 20%. Bumanis et al. (2013) tested concrete mixtures incorporating expanded glass aggregates that can potentially be used for the fabrication of lightweight masonry blocks. Although the compositions examined exhibited limited compressive strength (4.0-5.8 MPa), thermal conductivity values as low as 0.140 W/mK could be achieved. Ashour et al. (2015) used soil stabilized with cement and gypsum and reinforced with natural straw fibers to produce sustainable unfired earth bricks. The experimental outcomes obtained indicate that the thermal conductivity of the constituent material could drop up to 0.310 W/mK for 3% fiber content.

Many studies focused on improving the thermal performance of walls by optimizing the geometric characteristics of the masonry units and/or by considering alternative construction patterns. Sousa et al. (2014) conducted numerical analyses to determine the dimensions and the distribution of voids that would minimize the thermal transmittance of lightweight concrete blocks. Even though the compressive strength of the optimized blocks did not fulfil code-prescribed requirements for load-bearing masonry, the researchers succeeded in designing a walling system with a U-value of 0.50 W/m^{2}K. By performing Finite Element (FE) thermal analyses and by using the design of experiments and response surface methodology, Sutcu et al. (2014) investigated how the geometry, material properties and temperature distribution affect the thermal behaviour of fired clay hollow blocks containing paper waste. Reported data shows that modifying the distribution and size of the recesses within the blocks is adequate to attain U-values in the region of 0.50 W/m^{2}K. Diaz et al. (2014) also adopted FE simulation in combination with the response surface methodology to propose alternative geometrical configurations that would reduce the U-value of lightweight concrete hollow blocks. Again research results highlight that a decrease of the recesses' surface radiation emissivity can cause lower thermal transmittance. The influence of cavities on the dynamic thermal behaviour of fired clay bricks was studied in (Arendt et al. 2011) through numerical and semi-analytical assessment methods. According to Arendt et al. (2011), in order to achieve satisfactory thermal characteristics, the ratio of the total cavity area to the gross brick area should be between 30-65%, depending on whether the unit's constituent mixture has low or high thermal conductivity. Urban et al. (2011) investigated how the spatial arrangement of insulation layers influences the overall thermal resistance of concrete block masonry walls. It was found that thermal bridging through the solid webbing of the masonry units and the mortar joints can detrimentally affect thermal performance. Having examined the influence of mortar joints on the thermal properties of single-leaf walls constructed of lightweight clay blocks, Juárez et al. (2012) concluded that optimized geometric distribution of the masonry units and joints can lead to energy savings of up to 37%.

Promising solutions regarding the development of low-embodied-energy walling systems arise from studies focusing on interlocking building components. These systems present obvious advantages since they eliminate the use of jointing mortars and require less construction time (Sharath et al. 2013). Several researchers (e.g. Thanoon et al. 2004, Fay et al. 2014) developed self-aligned load-bearing blocks that can be interconnected by means of key connectors. A pilot application implemented at Universiti Putra Malaysia (Thanoon et al. 2004) verified that such mortarless masonry systems can reduce construction times by approximately 30%. A study by Deepak (2012) indicates that the embodied energy involved in the dry construction of interlocking blocks can be up to 65% lower than that required for the erection of conventional fired clay brick masonry.

In addition to the above, efforts concerning the exploitation of parametric design in the framework of bioclimatic architecture have been made. More specifically, certain researchers (Zemella 2011) considered the application of optimization algorithms based on Artificial Neural Networks to decrease the energy consumption in buildings, while others (Sarvani and Kontovourkis 2013) used parametric design to integrate bioclimatic criteria in the design of high-rise habitation units.

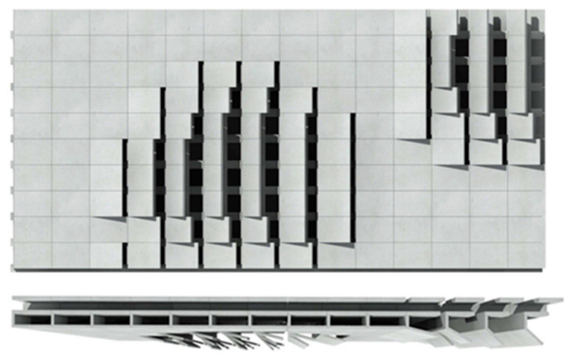


Fig. 1

Elevation and plan of the proposed modular brick assembly system

Within the framework hereby described, Michael et al. (2012) adopted principles of the dynamic adaptive envelopes theory (Velasco et al. 2015) to develop the novel idea of a multifunctional, customizable, modular brick assembly system (Fig. 1). The general concept lies on the design of an innovative brick unit that consists of two distinct components: (a) the main body that enables interlocking without the use of mortar and (b) the outer leaf, which can be adjusted at different angles and tilts. Depending on local environmental conditions and the particular needs of the building and its users, various different configurations and settings may be taken into consideration to improve the structure's energy efficiency. This paper examines the effect of different geometrical configurations and constituent materials on the system's thermal performance and embodied energy.

Method

The parametric analysis conducted in the framework of this study focuses on examining the thermal performance and environmental impact of the masonry unit's main body. Thermal performance was evaluated by computing the main body's U-value, while the environmental impact was assessed by estimating the component's embodied energy.

In order to obtain comparable results, alternative geometries of the masonry unit's main body were considered. The main body of the masonry unit is primarily composed of two components: (a) two interconnected longitudinal load-bearing sections and (b) a gap between them that can either act as an air gap, or may be filled with insulating material. The external dimensions of the main body are (height x length x width) 40 x 40 x 25 cm^3. By variating the width of the gap, two different configurations (Type A and B) are derived. The load-bearing sections of Type A geometry are 6 cm wide and have a 13 cm gap between them. In Type B geometry, the width of the load-bearing sections increases to 8 cm while the width of the gap reduces to 9 cm. The investigated geometries are presented in Fig. 2.

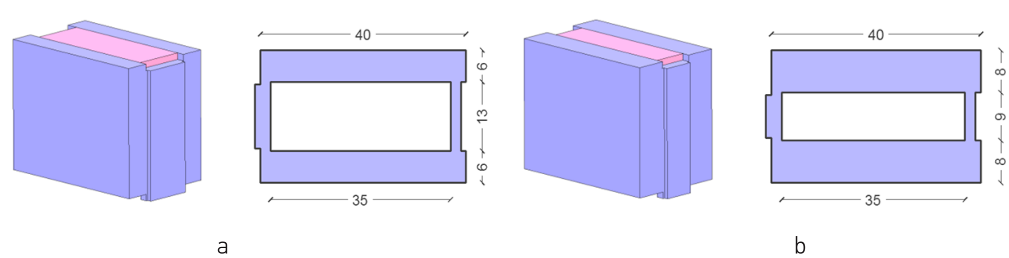


Fig. 2

Axonometric views and horizontal sections of Type A (a) and Type B (b) geometrical variations of the modular building component (dimensions in cm)

Table 1

Properties of the selected materials

Main body's component	Material	Embodied Energy (MJ/kg)	Embodied Energy (MJ/m^3)	Density (kg/m^3)	Conductive coefficient λ (W/mK)
Load-bearing sections	AAC	3.50	1750.0	500	0.012
	Fired clay	3.00	5700.0	1900	0.530
	Unfired earth (adobe)	0.45	585.0	1300	0.550
	Lime	0.85	1402.5	1650	0.650
	Concrete	0.95	1805	1900	0.900
Infill Insulation Material	Polyurethane	72.00	2160.0	30	0.025
	Polystyrene	88.00	2640.0	30	0.030
	Rock Wool	16.80	2352.0	140	0.035
	Cork	4.00	440.0	110	0.040
Air Gap	Gap 13cm	0.00	0.0	0	R_a = 0.180 m^{2}K/W
	Gap 9cm	0.00	0.0	0	R_a = 0.175 m^{2}K/W

For the purposes of the parametric investigation, different constituent materials were assumed to compose the load-bearing sections of the unit. The selected constituent mixtures include materials currently used in practice for the production of masonry units (i.e. autoclaved aerated concrete (ACC), fired clay and concrete) and materials used in research studies for the development of environmentally friendly building systems (i.e. unfired earth and lime). In addition, the effect of the gap between the load-bearing sections on the performance of the unit was examined by assuming that it can remain void or it can be filled with commonly used insulating materials i.e. polyurethane, polystyrene, rock wool and cork. The materials examined in this study are shown in Table 1 along with the properties adopted for assessing the masonry unit's energy performance and environmental impact. The values assigned to the materials' densities and conductive coefficients are based on data given in the EN1745 standard and on experimental results (Ioannou et al. 2013, Kyriakou 2014). Embodied energy values were estimated using data available in the literature (Hammond and Jones 2008a).

Assessment of thermal performance

To calculate the U-value of building members constructed of the masonry units under study, 2D numerical models were developed in Matlab R2014a (Fig. 3a, b). The models represent a plan-section of a wall 1.20 m long that is made of interlocking blocks laid without the application of jointing mortar. The simulated geometry is considered to be continuous throughout the height of the wall because the intended 'stack-bond' construction pattern involves placing one brick exactly above the other (Fig. 1). The models were discretized into 3-noded triangular elements. Adiabatic boundary conditions were assumed at the two side edges of the simulated wall. Surface resistances were taken as R_{si} =0.13 m^{2}K/W at the wall's interior and R_{se} =0.04 m^{2}K/W at the wall's exterior. The internal and external air temperatures were defined as T_{ai} = 22 °C and T_{ae} = 4 °C, respectively. The validity of the numerical analysis procedure was verified against the reference cases of the EN1745 and EN ISO 6946 standards. After being validated, the models were used for performing FE analysis to simulate in 2D the heat transfer through the component. This enabled the accurate simulation of the heat flux through the complex geometry of the unit (Fig. 3c, d).

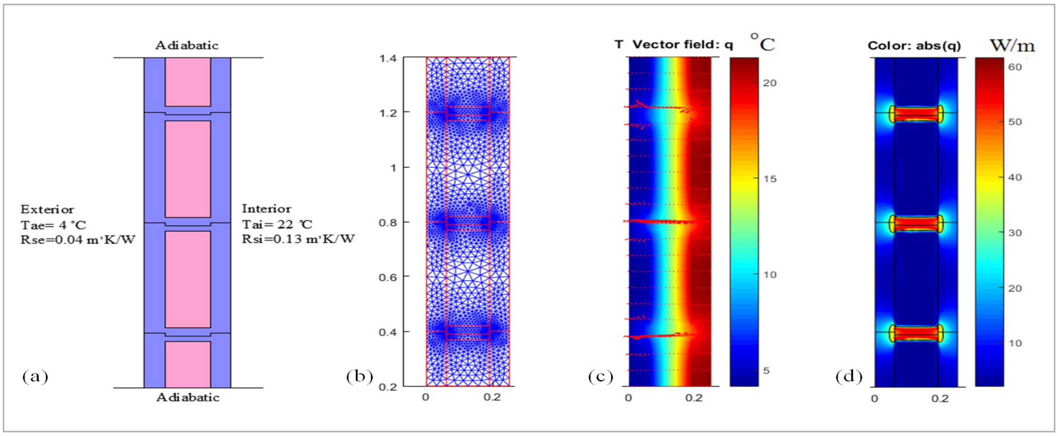


Fig. 3

Geometry, boundary conditions (a) and FE mesh (b) of the 2D models developed in Matlab R2014a. Contour diagrams of temperature distribution (c) and heat flux (d) obtained from the analysis of a wall constructed of Type A lime-based units that incorporate polystyrene core infill insulation

Assessment of environmental impact

Embodied energy was hereby adopted as the primary environmental impact indicator because, contrary to embodied carbon measurements, it does not depend on the type of energy used during a product's manufacturing process (Hammond and Jones 2008a). The embodied energy of the masonry component was estimated using the Inventory of Carbon and Energy (ICE) database of the University of Bath (Hammond and Jones 2008a). The system boundaries taken from the ICE are 'cradle-to-gate' and include all energy consumed until a product leaves the factory gate. In the ICE database, the embodied energy values are given per unit mass (kg) for each material.

The calculation of the mass (M) of each material for specific density (p) and volume (V) is given by the equation shown below in (1).

$$M = p \cdot V \tag{1}$$

The total embodied energy (e_E) of each modular component under study was computed as the product between the energies embodied in the mass of the unit's main body (e_{Eb}) and the insulation infill (e_{Ein}).

$$e_E = e_{Eb} + e_{Ein} \tag{2}$$

The embodied energy of the material used for the main body e_{Eb} for any certain case is the product between material's energy E_b (MJ/kg) and mass M_b (kg), i.e. $p_b \cdot V_b$. Similarly, the embodied energy of the infill insulation material for any certain case e_{Ein} is the product between material's energy E_{in} (MJ/kg) and mass M_{in} (kg), i.e. $p_{in} \cdot V_{in}$. The relative equations are shown below in (3) and (4).

$$e_E = E_b \cdot M_b + E_{in} \cdot M_b \tag{3}$$

$$e_E = E_b \cdot p_b \cdot V_b + E_{in} \cdot p_{in} \cdot V_{in} \tag{4}$$

Comparative factor estimation

In order to enable comparison between the results yielded by the different cases examined, a factor (f) accounting for both the U-value (U) and the embodied energy (e_E) was established. This is defined as:

$$f = (U \cdot e_E) \,/\, (\max\{U \cdot e_E\}) \qquad (4)$$

In the above equation, ($U \cdot e_E$) is the product between the U-value and the embodied energy for any certain case and ($\max\{U \cdot e_E\}$) is the maximum product between the U-value and the embodied energy of all combinations examined. A masonry unit is considered to have good energy efficiency and environmental impact performance when both the U-value and embodied energy are low. Hence, the optimum solution, in terms of geometrical configuration, constituent material and infill insulation material, is achieved when the minimum value of factor *f* is derived.

Results

U-value

The results obtained from the thermal numerical analyses are presented in Table 2, which reports the U-values assessed by considering that the units are composed of different constituent materials, have different geometrical configurations (Types A and B) and feature various types of core infills. Results are compared against the 0.72 W/m^{2}K limit value prescribed in the Cyprus regulations for minimum energy efficiency requirements (2013) for new buildings.

Computed U-values range from 0.20 W/m^{2}K to 2.09 W/m^{2}K, depending on the constituent material, the geometry of the masonry unit and the type of insulation used. The majority of alternative combinations satisfy local code requirements (U-value < 0.72 W/m^{2}K). In terms of material composition, the best results are achieved by the use of AAC. U-values for AAC units vary from 0.20 to 0.30W/m^{2}K for units incorporating thermal insulation at their core and from 0.58 to 0.72 W/m^{2}K for units with an air gap between their load-bearing sections. In all combinations examined, the thermal performance of AAC units is at least 50% better compared to other constituent materials. This was, to some extent, expected due to the low conductive coefficient of AAC. Plain concrete, on the other hand, has rather poor thermal performance. U-values for concrete units with no insulation exceed 1.95 W/m^{2}K. Reducing the width of the load-bearing sections (Type A), and introducing thermal insulation components in the case of concrete units, decreases the U-value up to 0.64W/m^{2}K. Minimal differences occur in the thermal performance of units composed by fired clay, unfired earth and lime. Masonry units of these types, that feature an air gap at their central section, have U-values from 1.55 to 1.86 W/m^{2}K. Installing an insulating infill into the core of units composed by the aforementioned materials can yield U-values from 0.45 to 0.71 W/m^{2}K.

The results of the analysis give evidence that the use of insulating materials has a significant effect on the U-value achieved. Filling the gap between the load-bearing sections of the unit with an insulation layer decreases the U-value by at least 50% compared to units with an air gap. It is worth pointing out that although the conductive coefficient of certain materials used as insulating infill differs by 60% (i.e. polyurethane has λ= 0.025 W/mK, while cork has λ= 0.040W/mK), corresponding U-values computed for the insulated masonry units differ only by 10-30%.

The U-value of the masonry is also affected by the geometry of its components. Insulated units of the Type A configuration generally exhibit better thermal performance, than Type B units. This

Table 2
U-value (W/m^{2}K) for all the cases under study

Constituent Material		AAC		Fired Clay		Unfired Earth		Lime		Concrete	
Geometrical Type		A	B	A	B	A	B	A	B	A	B
Infill Insulation Material	Polyurethane	0.20	0.24	0.45	0.55	0.46	0.56	0.51	0.62	0.64	0.77
	Polystyrene	0.22	0.26	0.48	0.58	0.49	0.59	0.54	0.65	0.66	0.80
	Rock wool	0.24	0.28	0.50	0.60	0.51	0.62	0.56	0.68	0.69	0.83
	Cork	0.26	0.30	0.52	0.63	0.53	0.65	0.59	0.71	0.71	0.86
Reference	Air gap	0.72	0.58	1.72	1.55	1.74	1.57	1.86	1.71	2.09	1.96

* Highlighted values correspond to U > 0.72 W/m^{2}K

is because Type A units have a larger distance between their load-bearing sections which allows for installation of thicker insulation layers. Therefore, insulated Type A units have U-values, which are approximately 15% lower than Type B insulated units. The Type B geometrical configuration generates better results in terms of thermal performance only in cases where no insulation is used. This may be attributed to the fact that the U-value of these units depends primarily on the thickness of its load-bearing sections, since the conductive coefficient of air does not change significantly for gap widths 9-13 cm.

Embodied Energy

The embodied energy values computed for the different types of masonry units examined are reported in **Table 3**. Results vary considerably, ranging from 12.8 to 189.4 MJ, depending on the geometrical characteristics of the unit, the thermo-physical properties of the constituent material and the insulating filling component used.

Table 3

Total embodied energy, e_E (MJ) for all the cases under study

Constituent Material		AAC		Fired Clay		Unfired Earth		Lime		Concrete	
Geometrical Type		A	B	A	B	A	B	A	B	A	B
Infill Insulation Material	Polyurethane	77.5	75.2	163.6	183.4	52.1	43.3	69.9	65.6	78.7	76.7
	Polystyrene	86.2	81.2	172.3	189.4	60.8	49.3	78.6	71.7	87.4	82.7
	Rock wool	81.0	77.6	167.1	185.8	55.6	45.7	73.4	68.1	82.2	79.1
	Cork	46.2	53.5	132.3	161.7	20.8	21.6	38.6	44.0	47.4	55.0
Reference	Air gap	38.2	48.0	124.3	156.2	12.8	16.0	30.6	38.4	39.4	49.5

Results show that the lowest embodied energy values i.e. 12.8-60.8MJ, can be obtained when unfired earth is used as the constituent material. This is due to the simple manufacturing processes involved in the fabrication of adobe bricks. The production of units composed of lime also has relatively low energy requirements, which range from 30.6 to 78.6 MJ. The embodied energy values for units composed by AAC and concrete are quite similar. Units of this type, which do not feature an insulating filling have embodied energy values from 38.2 to 49.5 MJ. The use of insulating materials along with AAC, or concrete, increases the end product's embodied energy to 46.2-87.4 MJ. Fired clay units have the highest embodied energy, as the firing procedure used when processing the raw materials significantly increases the energy required for production. In this case, the embodied energy of the units with no insulating filling is 124.3 and 156.2 MJ for Type A and B geometries respectively, while the use of polystyrene sections can increase the total embodied energy up to 189.4 MJ.

Since the industrial procedures involved in the manufacturing of insulating materials (i.e. polyurethane, polystyrene, rock wool) result to high embodied energies, their use tends to increase the end product's total energy requirements. An exception occurs when using certain types of insulation (e.g. cork) which have low environmental impact and can thus improve the unit's thermal performance without significant increase in the end product's total embodied energy. It is worth noting that in the case of fired clay units, the energy required for the production of the constituent material itself is significantly high and thus, the contribution of the insulation filling to the unit's total embodied energy is rather low.

Comparative Factor

The comparative factors (*f*) estimated using (Eq. 5) for all combinations of constituent material; geometrical configuration and infill insulation material are presented in **Table 4** and **Fig. 4**. Computed data shows that the optimum solution in terms of thermal performance and environmental impact is when the Type A geometrical configuration is adopted, unfired earth is used as the constituent material and cork infill is inserted among the unit's load-bearing sections for insulation. Promising solutions are also obtained when units composed of AAC and lime are insulated with cork. Fired clay units exhibit rather poor performance due to the high embodied energy associated with the raw material's fabrication process. The comparative estimated factors indicate that the use of concrete will not result to a thermally and environmentally efficient end-product. This is mainly attributed to the poor thermal performance of the constituent material. Furthermore, results show that the best insulating solution in all cases is cork. Although the conductive coefficient of cork is higher than that of polyurethane, polystyrene and rock wool the end-product's total U-value achieved by this type of insulation does not significantly differ from that obtained when using the aforementioned materials. In addition, cork has much lower embodied energy, thus, reducing the environmental impact of the masonry unit.

It is noted that the above comparisons account only for two factors associated with the overall behaviour of the masonry: (a) thermal performance and (b) environmental impact. In order to develop a reliable construction system, an integrated research approach must be adopted. This should investigate other important aspects, such as structural behaviour, fabrication process, building methodology etc. Having said that, it can be argued that although AAC and unfired earth appear to

Table 4

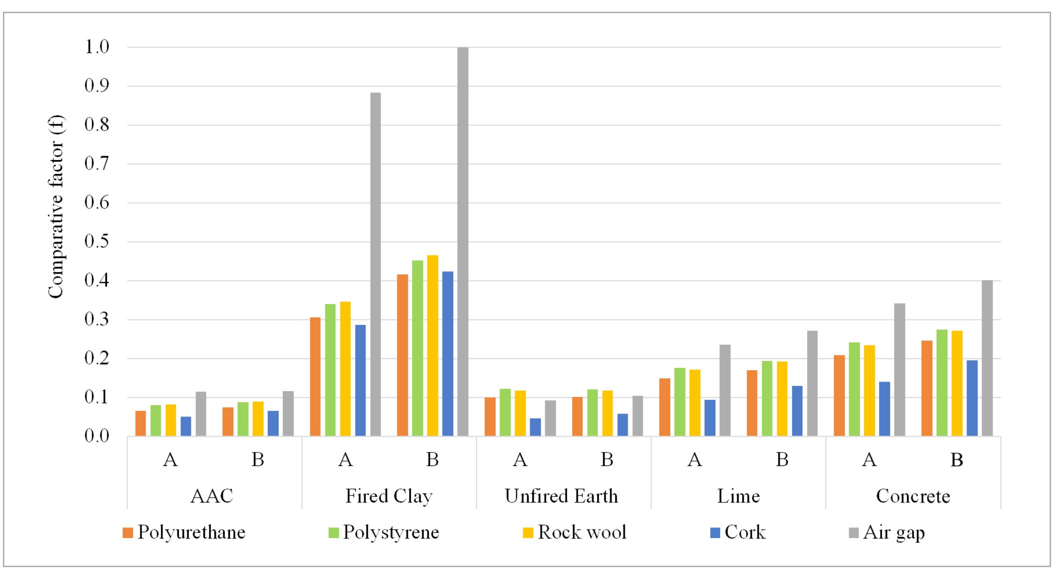
Comparative factor (*f*) for all the cases under study.

Constituent Material		AAC		Fired Clay		Unfired Earth		Lime		Concrete	
Geometrical Type		A	B	A	B	A	B	A	B	A	B
Infill Insulation Material	Polyurethane	0.065	0.075	0.305	0.415	0.100	0.100	0.149	0.169	0.209	0.245
	Polystyrene	0.080	0.088	0.339	0.452	0.122	0.120	0.176	0.194	0.241	0.274
	Rock wool	0.081	0.090	0.346	0.465	0.117	0.117	0.171	0.192	0.234	0.271
	Cork	0.050	0.066	0.286	0.423	0.046	0.058	0.094	0.129	0.140	0.195
Reference	Air gap	0.114	0.116	0.882	1	0.092	0.105	0.236	0.271	0.341	0.402

*Highlighted value corresponds to optimum combination (i.e. min{*f*})

Fig. 4

Graphic representation of the comparative factor (*f*) for all the cases under study.



produce thermally efficient and environmentally friendly units, these materials' limited load-bearing capacity is a detrimental factor which may preclude their practical use. Moreover, unfired earth tends to suffer from shrinkage upon drying (Ioannou et al. 2013) something that introduces further complications to the potential fabrication process. The superior mechanical properties of lime- and cement-based materials may compensate for their inferior thermal performance thus leading to more realistic solutions.

Discussion

The numerical data obtained in this study shows, that the thermal performance of walling systems is critically affected by: (a) the constituent mixture composing the masonry units (Velasco et al. 2016, Görhan and Simsek 2013, Sutcu 2015, Wu et al. 2015, Aouba et al. 2015, Bumanis et al. 2013, Ashour et al. 2015) and (b) the geometric configuration of the building component (Sousa et al. 2014, Sutcu et al. 2014, Diaz et al. 2014, Arendt et al. 2011, Urban et al. 2011).

The ratio between the core's void and the brick's total gross area is 52% for Type A geometry and 36% for Type B geometry. According to Arendt et al. (2011), low-thermal-conductivity materials are required for optimizing the thermal properties of hollow brick units with cavity-to-gross-brick-area ratios between 30-45%. This justifies why only the use of AAC resulted to U-values in the region of 0.7 W/m^2K when no insulation was considered. Based on the data reported in (Arendt et al. 2011), it is envisaged that in order to achieve similar results with unmodified fired clay, unfired earth, lime and concrete mixtures, the cavity-to-gross-brick-area ratio should increase above 65%. In practice, this would be difficult to realize since it would drastically reduce the load-bearing sections of the unit.

The heat flows computed by the FE analysis and the estimated U-values (Fig. 3 and 4) indicate that the solid webs connecting the load-bearing sections of the brick influence significantly the overall thermal performance. This is because the aforementioned areas tend to act as thermal bridges. The effect is more profound when insulation layers are incorporated into the core of the brick. In this case, the thermal resistance of the brick's constituent material is much lower than that of the insulation and a significantly higher heat transfer occurs at the areas of the webs. Taking into account thermal bridging in 2D FE, the heat analysis yields more conservative estimates of U-value compared to code-prescribed analytical calculation methods, which ride on the 1D heat flow theory. Relevant comments regarding the effect of solid webs on the heat flow generated at multicore and cut-web units have been made by Urban et al. (2011), who examined the thermal performance of concrete block masonry.

Despite the presence of thermal bridges, the proposed masonry system can attain U-values from 0.20 to 0.90 W/m^2K, given that thermal insulation materials are used. Corresponding results found in the literature for similar types of constructions range from 0.43 to 0.72 W/m^2K (Wu et al. 2015, Sousa et al. 2014, Sutcu et al. 2014, Diaz et al. 2014, Arendt et al. 2011, Urban et al. 2011). Considering that U-value is the primary indicator for a building element's thermal behaviour (Bikas and Chastas 2014a, b), it can be argued that the technical solution under development exhibits promising performance. The characteristics of the modular unit can be further improved by modifying the mix design of the constituent material (Velasco et al. 2016, Görhan and Simsek 2013, Sutcu 2015, Wu et al. 2015, Aouba et al. 2015, Bumanis et al. 2013) so that thermal transmittance would not rely heavily on the provision of space for the installation of insulation. For this purpose, the introduction of additives such as natural fibers (Ashour et al. 2015, Ioannou et al. 2013) and lightweight aggregates may be considered. Nevertheless, the constituent mixture must possess adequate fluidity to capture the complex shape of the modular unit and sufficient mechanical strength to ensure structural stability.

Moreover, the outcomes of the current study clearly show that the selection of an appropriate constituent mixture for the production of the modular units can significantly affect the building system's embodied energy. This observation is in total agreement with the comments of other researchers who conclude that the total life cycle energy of a structure depends on the materials used for its construction (Dixit et al. 2013, Optis and Wild 2010). As noted in (Monteiro and Freire

2010, Bribián et al. 2011) the use of firing manufacturing processes leads to considerably high embodied energy values. Many studies emphasize on the energy savings achieved when using unfired earth instead of ceramics (Pacheco-Torgal and Jalali 2012, Shukla et al. 2009, Reddy and Jagadish 2003, Udawattha and Halwatura 2016, Chrysostomou et al. 2015). However, questions are raised regarding the suitability of such mixtures for the production of load-bearing masonry units because unfired earth has low strength and is susceptible to moisture induced damage. The load-bearing capacity of AAC is also rather limited due to the high porosity of the material, while the use of mechanical autoclaves can increase the environmental footprint of the final product. Brick units composed of lime- and cement-based composites can develop adequate stiffness and strength (Kyriakou 2014, Turgut 2012). Although the energy involved in the fabrication of the two aforementioned binder materials is considerable, the total embodied energy of the mixture can be reduced by using industrial wastes as substitutes (e.g. fly ash, silica fume, etc.).

Lastly, calculations show that core insulation, apart from improving the thermal properties of the unit, it can increase of the construction system's embodied energy. Most researchers agree that the use of natural insulation materials such as cork can reduce environmental impact (Lucas and Ferreira 2010, Bribián et al. 2011). Nevertheless, it is noted that in areas where such materials are not available, the use of local resources can be considered so as to minimize the energy consumed during transportation (Sierra-Pérez 2016, Chrysostomou et al. 2015, Christoforou et al. 2016).

Conclusions

A parametric study regarding the thermal performance and environmental impact of a novel masonry unit under development has been conducted. The effects of alternative geometries, material compositions and insulation solutions on the U-value and total embodied energy have been examined.

U-value numerical analyses have shown that the proposed system's thermal performance relies primarily on the characteristics of the constituent material composing the modular masonry unit. Units composed of AAC exhibit superior thermal properties, while minimal differences occur in the thermal behaviour of fired clay, unfired earth and lime units. The geometrical configuration of the unit also affects the U-value achieved, but to a lower extent. The installation of insulating material at the core of the unit improves energy performance by significantly reducing the overall U-value. According to the outcomes of the analyses, this reduction in U-value depends mainly on the thickness of the insulating layer, rather than on the type of insulation material used.

In terms of environmental impact, both constituent mixture insulation materials used have a considerable effect on the end-product's total embodied energy. Bricks composed of unfired earth tend to be more environmentally friendly. Lime- and concrete-based mixtures can also form units with rather limited environmental impact, whereas the use of fired clay ceramic can significantly increase production energy requirements. Most insulating materials hereby considered (i.e. polystyrene, polyurethane, rock wool) have themselves high embodied energies and can thus adversely affect the environmental characteristics of the end-product. Nevertheless, certain types of insulation (i.e. cork) can offer better thermal performance without drastically increasing the unit's environmental impact.

A comparison of the results obtained indicates that thermally efficient units that have low embodied energy can potentially be produced using constituent mixtures composed of AAC and unfired earth. However, further research should be conducted in order to thoroughly investigate all aspects relevant to the proposed system's production method and practical application. The optimal form and size of the brick unit should be defined based on an integrated parametric analysis that will take into account bioclimatic, construction, structural, ergonomic and aesthetic aspects. Alternative manufacturing methods should be examined and different constituent mixtures should be designed, based on the specific requirements imposed by the unit's form. Furthermore, laboratory tests should be performed to assess the thermo-physical, hygric and mechanical properties of the proposed masonry units. Finally, the operational energy performance of the modular wall assembly system should be quantitatively evaluated and a detailed Life Cycle Analysis should be performed.

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About the authors

ANDREAS KYRIAKIDIS

Research Associate, PhD student

University of Cyprus, Department of Architecture

Main research area

Energy and environmental design, Sustainability and construction design, Innovative and sustainable construction components and materials, In situ and laboratory characterization of building materials,

Address

75 Kallipoleos Street, 1678, Nicosia, Tel. + 357 22 892977, E-mail: kyriakidis.andreas@ucy.ac.cy

AIMILIOS MICHAEL

Lecturer

University of Cyprus, Department of Architecture

Main research area

Energy and environmental design of buildings, Sustainability and construction design, Innovative and sustainable construction components and materials

Address

75 Kallipoleos Street, 1678, Nicosia, Tel. + 357 22 892977 E-mail: aimilios@ucy.ac.cy

ROGIROS ILLAMPAS

Post-Doctoral Researcher, Adjunct Faculty

University of Cyprus, Department of Architecture/Department of Civil and Environmental Engineering

Main research area

Experimental and numerical investigation of the structural response of masonry constructions, Conservation of historic buildings, In situ and laboratory characterization of building materials

Address

75 Kallipoleos Street, 1678, Nicosia, Tel. + 357 22 894589, E-mail: rilamp01@ucy.ac.cy