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RESEARCH

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Simulating the Thermal Behavior of Compressed Earth Brick Walls

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Abstract

The production of conventional bricks has negative impact on the environment due to CO_2 emissions. Therefore, the use of alkali-activated by-product materials as partial or full replacement of cement has been promising in producing eco-friendly compressed earth bricks for sustainable construction. This research aims to simulate the thermal behavior of an office building prototype composed of eco-friendly compressed earth brick (CEB) walls using Design Builder software to investigate the impact of CEB walls on the indoor thermal comfort, total energy consumption and CO_2 emissions. In addition to investigate the influence of the type and thicknesses of walls, and thickness of expanded polystyrene (EPS) insulating layer on the total energy consumption and (CO_2) emissions. The results indicated that using walls of compressed earth bricks (CEB) made by alkali-activated ground granulated blast furnace slag (GGBS) as soil stabilizer with full replacement of cement is promising for reducing the total energy consumption and CO_2 emissions with competitive compressive strength to those stabilized by cement. The results also revealed the noticeable effect of the type and thicknesses of walls in addition to the thickness of EPS insulating layer in reducing the total energy consumption and CO_2 emissions. This reduction reached about 21–25% for different wall types of thickness 120 mm when EPS thicknesses increased up to 50 mm compared to the same walls without EPS.

Keywords Compressed earth bricks, Thermal comfort, Energy consumption, Carbon dioxide emissions, Heating and cooling loads

1 Introduction

Human's thermal comfort is of great interest for people who spend most of their times indoor while performing their different activities. Thermal comfort is the thermal environment satisfactory threshold, which depends on many factors, such as humidity, metabolic rate, sun radiation, and air temperature (Chen et al., 2006; Mohd Nafiz Shaharon, 2012; Sherman, 1985; Wagner et al., 2007; Yao et al., 2009). The comfort zones was defined by ASHRAE (2010) based on calculating Fanger's predicted mean vote (PMV) that suites the majority of people as reviewed by many researchers (Ekici, 2013; Putra, 2017; Roshan et al., 2017; Schaudienst & Vogdt, 2017). Thermal comfort and indoor air quality can also be achieved by exploiting HVAC, but this cannot be considered a sustainable solution. It was reported that buildings consumes about 19–32% of the global energy consumption that leads to 19–33% of energy related CO_2 emissions through the buildings' whole life cycle (Ahmed & Mahmoud, 2017; Gustavsson et al., 2010).

Heat is transferred from outdoor to indoor through the building envelope, such as walls, roofs, doors and windows by conduction, convection, and radiation. Many researchers used Design builder software, which is an energy simulation program, to investigate the effect of using different building envelopes on the thermal comfort, total energy consumption and CO_2 emissions

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throughout the buildings' life cycle (Aydin & Mihlayanlar, 2020; Bachrun et al., 2019; Noori & Hwaish, 2015; Zhang, 2014).

Mahdy et al. (2013) investigated four different types of external walls; half red-brick wall, full red-brick wall, and limestone bearing-wall, and full red-brick with a 20 mm EPS layer. It was stated that full red-brick wall with a 20 mm EPS layer achieved the superior thermal comfort and least energy consumption when HVAC system was used. Fahmy et al. (2020) reported that using double reflective 6 mm glass-air gap filled gap, 0.5 overhang louvers, double roofing, and double skin in the facade with single brick wall of 250 mm improved the predicted mean vote (PMV) when the building is exposed to natural ventilation only in summer, while, in another research, a reduction in indoor temperature by 0.5 °C to 2.59 °C was obtained when light blocks were used instead of clay bricks (Ouf et al., 2019).

Morsy et al. (2018) investigated eight different insulating materials. It was concluded that the least energy consumption was achieved with the use of EPS layers, while the optimum thermal comfort was achieved using vermiculite cement. An-Naggar et al. (2017) reported that applying glass wool blanket thermal insulation of thickness 50 mm led to reduction in energy consumption and CO_2 emissions by about 40% and 30%, respectively, in the case of using HVAC system. Park et al. (2019) used seven materials with different thermal conductivity that ranged from 0.160 to 0.248 W/m K and were applied to the finishing interior layer of the external wall. It was revealed that the material with the least thermal conductivity, reduced the heating energy consumption, while the material with thermal conductivity of 0.214 W/m K, reduced the cooling energy consumption.

Ahmed et al. (2024) examined a new material for building walls as an alternative for the fired-clay bricks. Waste water sludge from industrial source (IWWS) was used in the fabrication of thermal insulated lightweight bricks. The research concluded that using ÏWWS improved the thermal comfort in buildings, and the most effective ratio was 20% IWWS as assessed by PMV and predicted percentage of discomfort. In addition, it was revealed that bricks with higher IWWS ratios resulted in increased energy savings.

Yu et al. (2024) studied the thermal properties of cement based materials incorporated microencapsulated phase change materials (PCMs) as partial replacement of sand. Capric acid and paraffin eutectic PCM (CA–PA) were prepared. Red-mud based geopolymer hollow microsphere (RMHM) was produced using CA–PA and the surface grafting of nano-SiO_2. It was concluded that indoor temperature fluctuation in buildings was reduced significantly by incorporating 20% CA–PA/RMHM@ SiO_2 in mortars, in addition to high annual energy savings and low CO_2 emissions.

The objective of this research is to simulate the thermal behavior of an office building prototype composed of eco-friendly CEB walls using Design Builder software to investigate the impact of CEB walls on the indoor thermal comfort, total energy consumption and CO_2 emissions. In addition to investigate the influence of the type and thicknesses of walls, and thickness of EPS insulating layer.

2 Simulation Methodology

Design Builder software commercial package (DesignBuilder, 2018) was used to simulate the thermal behavior of an office building prototype composed of eco-friendly CEB walls.

Five types of CEB walls were defined in the Design Builder software with four different thicknesses: 120 mm, 250 mm, 400 mm, and 600 mm. Each wall composed of CEB units of dimensions of 250 × 120 × 60 mm grouted with cement mortar which has thermal conductivity equals to 1.25 W/m°C.

The types of CEB walls were chosen according to the optimum thermal conductivity results for the CEB units previously produced and tested by the authors in another study (Hany et al., 2021). The control CEB unit composed of sandy soil stabilized with 10% cement. The other CEB types incorporated alkali-activated fly ash (FA) and ground granulated blast furnace slag (GGBS) as partial or full replacement of cement. Polystyrene foam (PS) was incorporated as partial replacement of soil by 0.25% by weight. The data for different CEB wall materials used throughout the study are illustrated in Table 1.

The CEB walls were modified by applying an insulating layer of EPS. The optimum EPS thickness was calculated to meet the required overall thermal transmittance (U value) stated in the Egyptian specifications for thermal insulation (Specifications for thermal insulation, items requirements for the design & implementation, 2008). It has been found that the required thickness of EPS used for the CL wall was 30 mm. The required thickness for GGBS–PF wall was less than that of CL wall which reflects the higher efficiency of these walls in fulfilling the U-design value. However, EPS with thickness 30 mm was used with the other wall types for the comparison purposes.

The weather data file used in Design Builder represents the actual climate data of year 2020 for a location at Kobri Al Kobba in Cairo (Mahmoud et al., 2020).

A preliminary simulation was performed using the natural ventilation system. It was revealed that natural ventilation only is not enough to achieve the indoor thermal comfort as the obtained predicted mean vote (PMV)

Table 1 Materials data for the used CEB walls throughout the study

Wall designation	Composition of CEB unit	Thermal conductivity of CEB (W/m.K)	Density (kg/m^3)	Dry compressive strength (N/mm^2)	Wet compressive strength (N/mm^2)
CL	90% soil 10% cement	1.262	1995	9.89	8.20
GGBS 100	90% soil 10% GGBS	0.977	1948	9.31	5.25
GGBS–PF	89.75% soil 0.25% PF 10% GGBS	0.698	1700	5.12	3.56
FA 80	90% soil 2% cement 8% FA	1.292	1933	9.30	6.04
FA80–PF	89.75% soil 0.25% PF 2% cement 8% FA	1.096	1680	7.51	4.74

values exceeded 4.0. Therefore, HVAC system was used in the model to achieve comfortability and thus "Packaged DX" type was selected to be implemented in the simulation methodology, as shown in Fig. 1.

3 Design Builder Model

An office building prototype that consists of two stories with a footprint area of 20 × 19 m^2 with a ceiling height of 3.5 m was modeled in Design Builder,

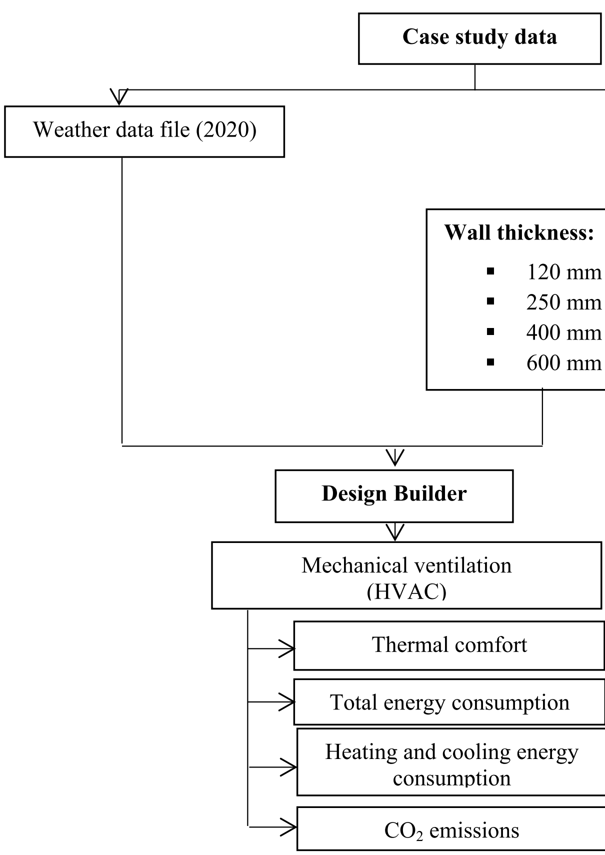

Fig. 1 Simulation methodology

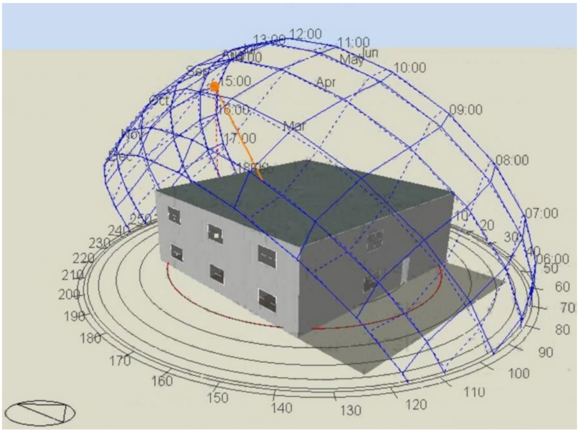

Fig. 2 Design builder model

Table 2 Thermal data for the used doors and windows

	Windows	Doors
Type	Double reflective clear	Wooden doors
Thickness (mm)	6 mm/13 mm air	35
U value (W/m^2 K)	2.301	2.823

as shown in Fig. 2. The building contains nine zones (eight rooms and a corridor) in each story. Each room contains a window of 1.5 × 2.0 m^2 and a door of 2.2 × 1.0 m^2. The corridor window is of dimensions 1.0 m × 1.0 m. Several modeling assumptions were made and fixed throughout the study. The HVAC system is "packaged DX" with a schedule turned on from 10:00 to 16:00, 6 days per week throughout the year. The heating and cooling set points are fixed to 22 °C and 24 °C, respectively, minimum fresh air per person is 10.0 l/s-person. The thermal data for the used doors and windows are given in Table 2. All results were extracted from Design builder software and then introduced into excel sheets to analyze the output data.

The roof layers were kept constant throughout the study. It consists of eight layers; 20 mm cement tiles, 20 mm mortar, 40 mm sand and gravel, 20 mm mortar, 50 mm polyurethane foam, 20 mm bitumen, 19.1 mm wood panels (plywood) and 355.6 mm wood, as shown in Fig. 3. The *U* value has been calculated and found to be 0.50 W/m^2.K.

The CEB walls consist of 4 layers; 5 mm external rendering, 20 mm mortar, thickness of CEB unit, and 20 mm mortar and painting, as shown in Fig. 4. In addition, an EPS layer of thickness 30 mm was added towards the outer surface to walls CL + 30 mm EPS, GGBS + 30 mm EPS and GGBS–PF + 30 mm EPS.

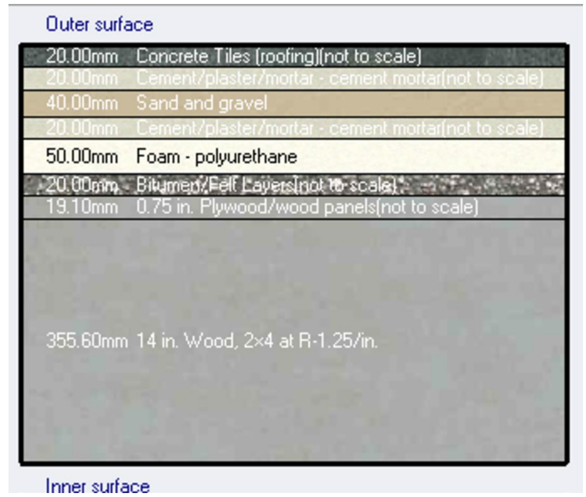

Fig. 3 Cross section of the roof

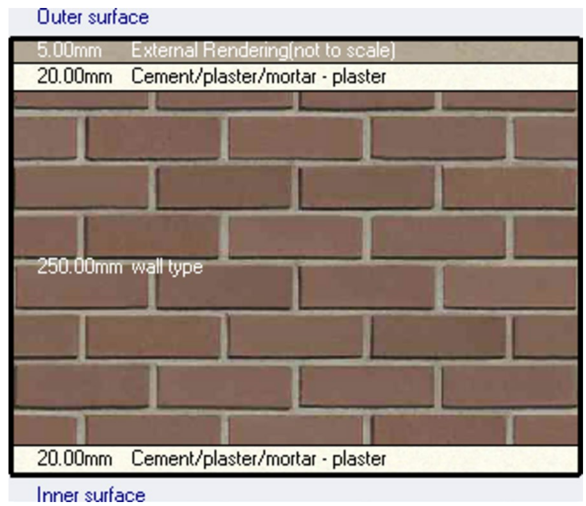

Fig. 4 Cross section of the CEB wall

4 Results and Discussion

4.1 Indoor Thermal Comfort

Fig. 5 shows that the average maximum indoor air temperature ranged from (21.7 °C to 24.7 °C), taking into consideration the indoor relative humidity, which lies into the comfort zone according to ASHRAE (2010).

The effect of wall types does not clearly appear in the indoor air temperature, because it is controlled by HVAC system and as an input parameter in Design Builder. It was observed that the maximum reduction in the indoor air temperature at peak; in July and August, was 0.25 °C when the GGBS–PF wall of thickness 600 mm was used compared to CL wall of thickness 120 mm.

Fanger's predicted mean vote (PMV) values are presented in Fig. 6. It can be seen that the average

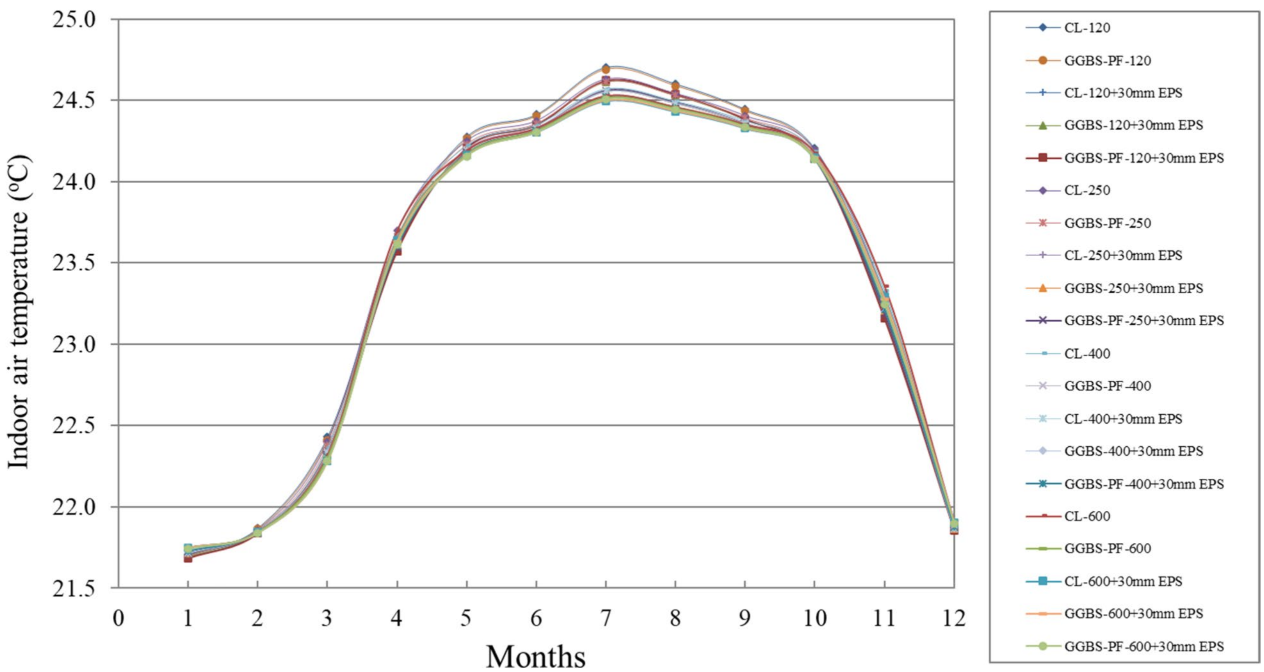

Fig. 5 Indoor air temperature using HVAC system

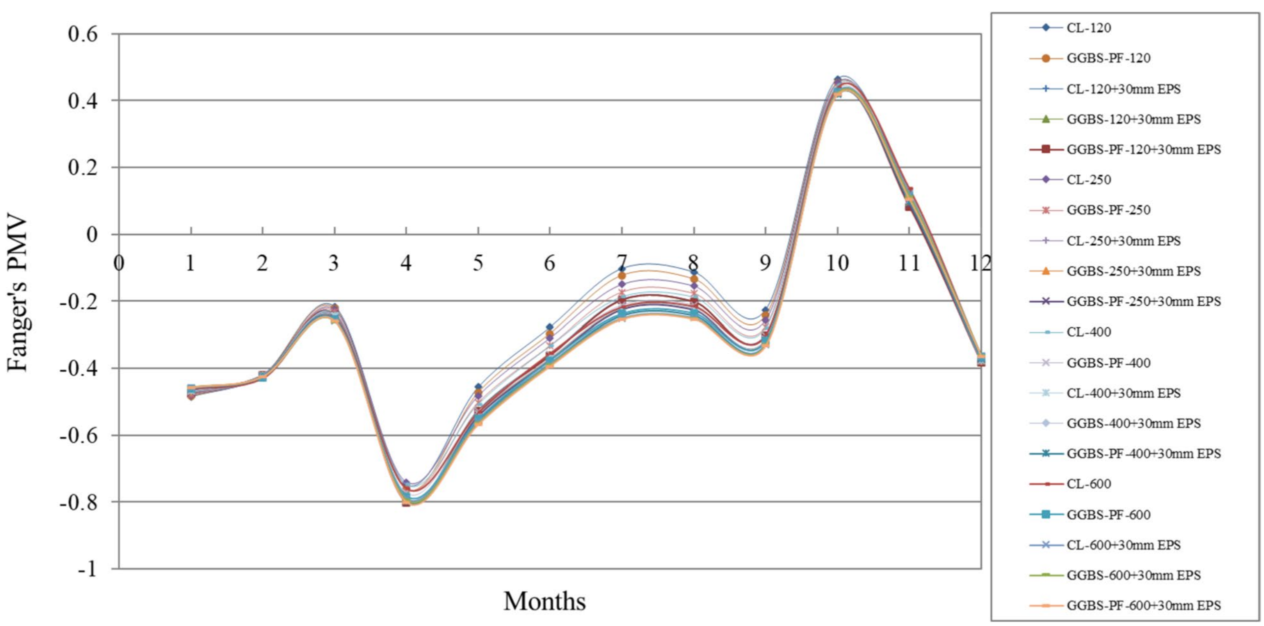

Fig. 6 Fanger's PMV using HVAC system

maximum absolute PMV value for the studied walls when using HVAC system was 0.80, which lies between "slightly cool" to "slightly warm" according to the seven sensation scales of PMV values (ASHRAE, 2010).

4.2 Total Energy Consumption

The energy consumption and CO_2 emissions are the factors used to differentiate and select the optimum wall type. Fig. 7 shows the results of the average annually total

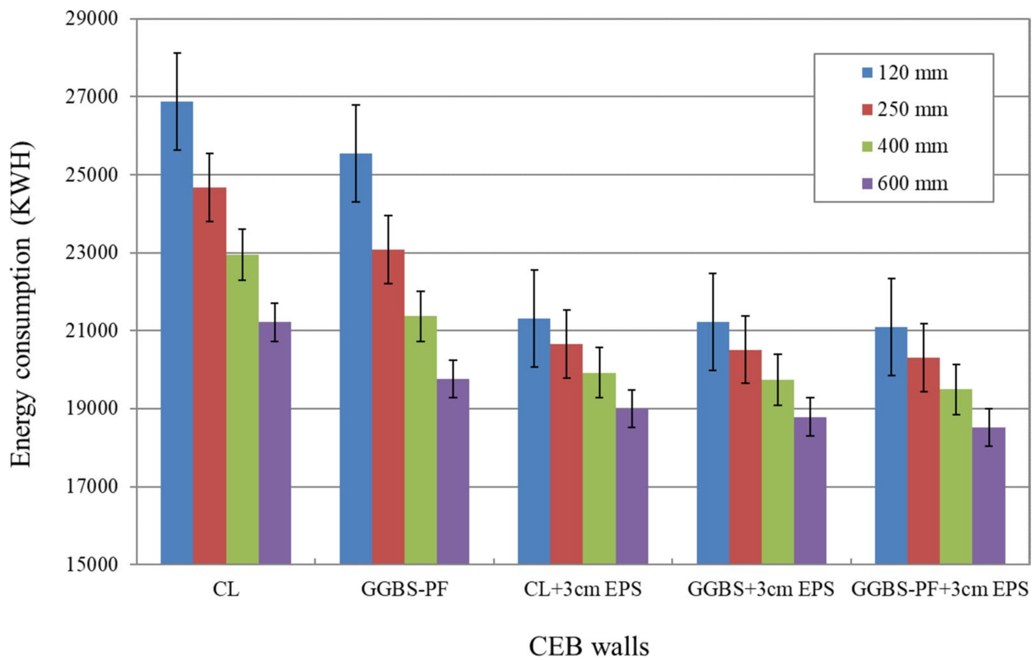

Fig. 7 Total energy consumption using HVAC system

energy consumption due to both heating and cooling loads.

The results showed that the total energy consumption for GGBS–PF walls of thickness 120 mm up to 600 mm was less than that of CL walls by 5.0–6.8%. While for CL + 30mm EPS, GGBS + 30mm EPS, and GGBS–PF + 30mm EPS walls, the reduction ranged from 20.0% to 10.5%, 21.0% to 11.5%, and 21.5% to 12.7%, respectively, compared to the CL walls.

It is obvious that the thickness of the CEB wall plays a vital role in reducing the total energy consumption, but the rate of reduction differs according to the increase in wall thickness. For example, the total energy consumption for CL wall was decreased by 8.2% when the wall thickness increased 108%, while the reduction was 21.1% when the wall thickness increased 400%.

It was also observed that applying a 30 mm EPS layer was dominant in reducing the total energy consumption unlike the type of wall material, where the variation in energy reduction was insignificant for GBBS–PF + 30 mm EPS, GBBS + 30 mm EPS, and CL + 30 mm EPS walls. Therefore, from the sustainability perspective, adding 30 mm EPS to GBBS and GBBS–PF walls is favored, since these CEB types do not consume cement in their production. However, GGBS CEB units is preferred rather than GGBS–PF CEB units for their superior mechanical properties; compressive strength, water resistance and pitting erosion resistance (Hany et al., 2021).

4.3 Average Monthly Energy Consumption

The energy consumption could be divided into two categories: energy consumption due to cooling and energy consumption due to heating. The results of the average monthly energy consumption due to cooling load, heating load and total energy consumption are shown in Figs. 8, 9, 10 and 11.

It was observed that the total energy consumption curve nearly coincides on the cooling load curve from April to October. This is due to the hot weather in Egypt that leads to turning on the HVAC for cooling, leading finally to that the cooling load represents almost 87% of the total energy consumption. Moreover, the HVAC was used as a heater from November to March for few hours to maintain indoor comfortability. However, this heating load could be replaced by wearing more suitable clothes.

It is perceived that the heating load percentages are very low and decreases with years, this may be because of the effect of global warming that result to changes in weather that becomes hotter. Therefore, the HVAC is much used as a cooler in Egypt. However, the total energy consumption increases with time due to the needed cooling load because of global warming.

4.4 Carbon Dioxide Emissions

The results of the annual average CO_2 emissions of CEB walls are shown in Fig. 12. The reduction percentages of CO_2 emissions for the different wall types compared to CL wall were the same as that of the total energy

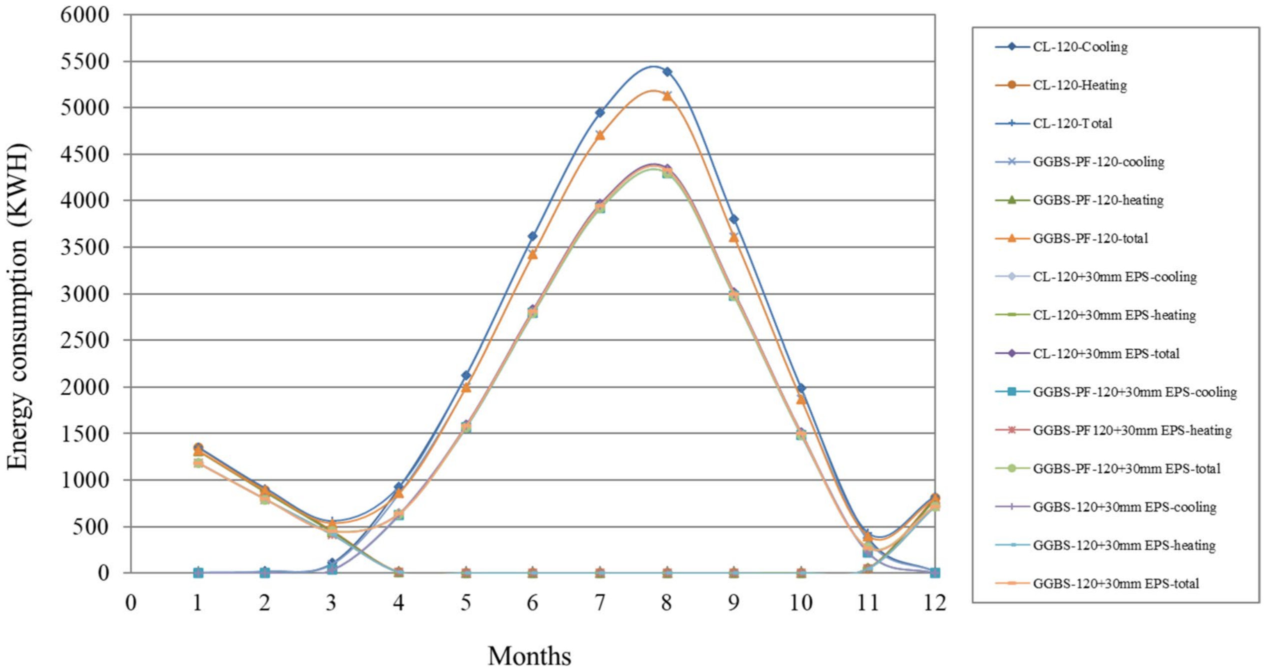

Fig. 8 Average monthly energy consumption using HVAC system for wall thickness 120 mm

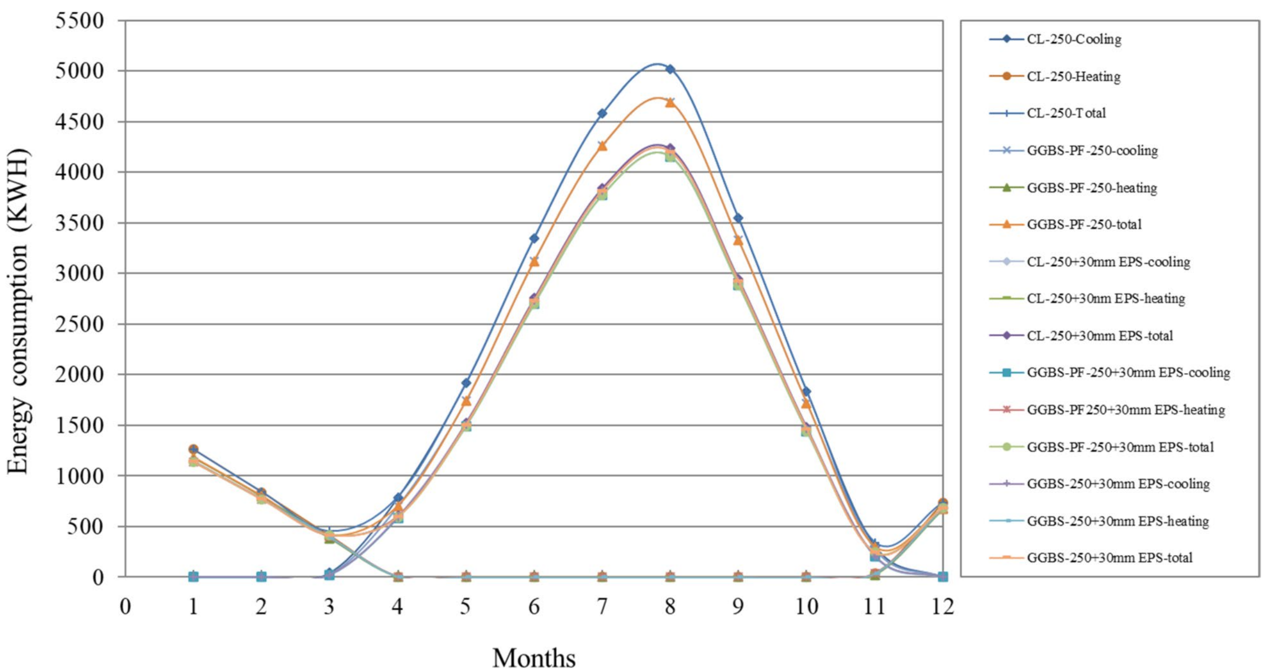

Fig. 9 Average monthly energy consumption using HVAC system for wall thickness 250 mm

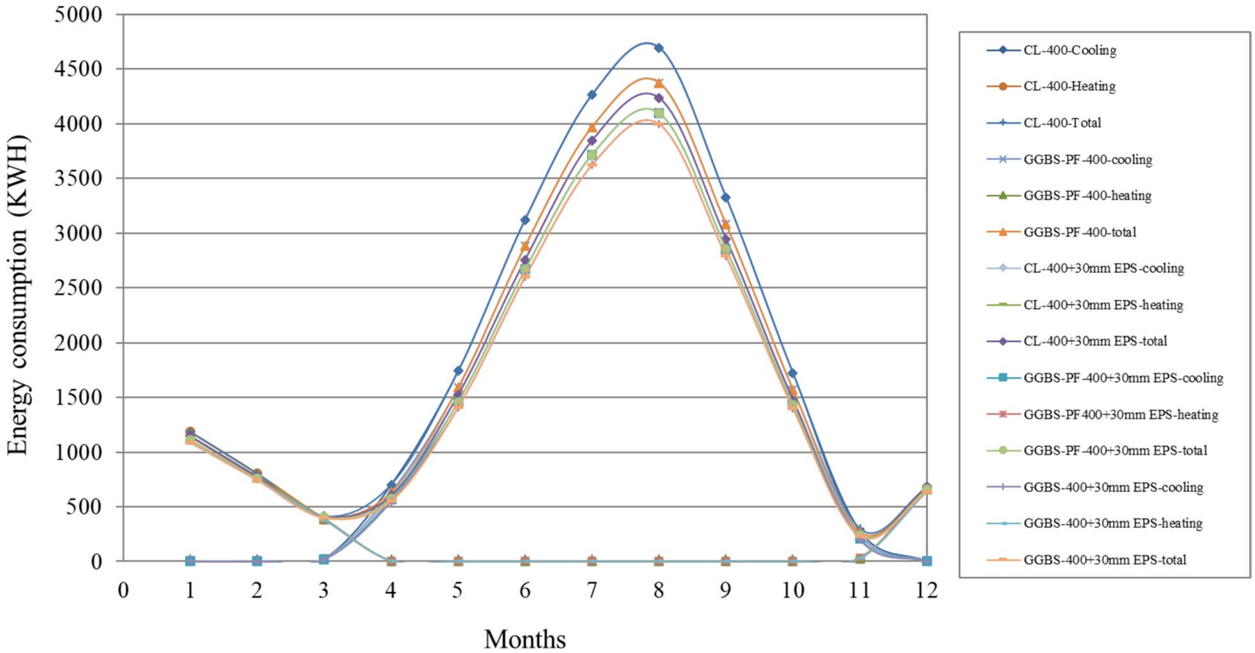

Fig. 10 Average monthly energy consumption using HVAC system for wall thickness 400 mm

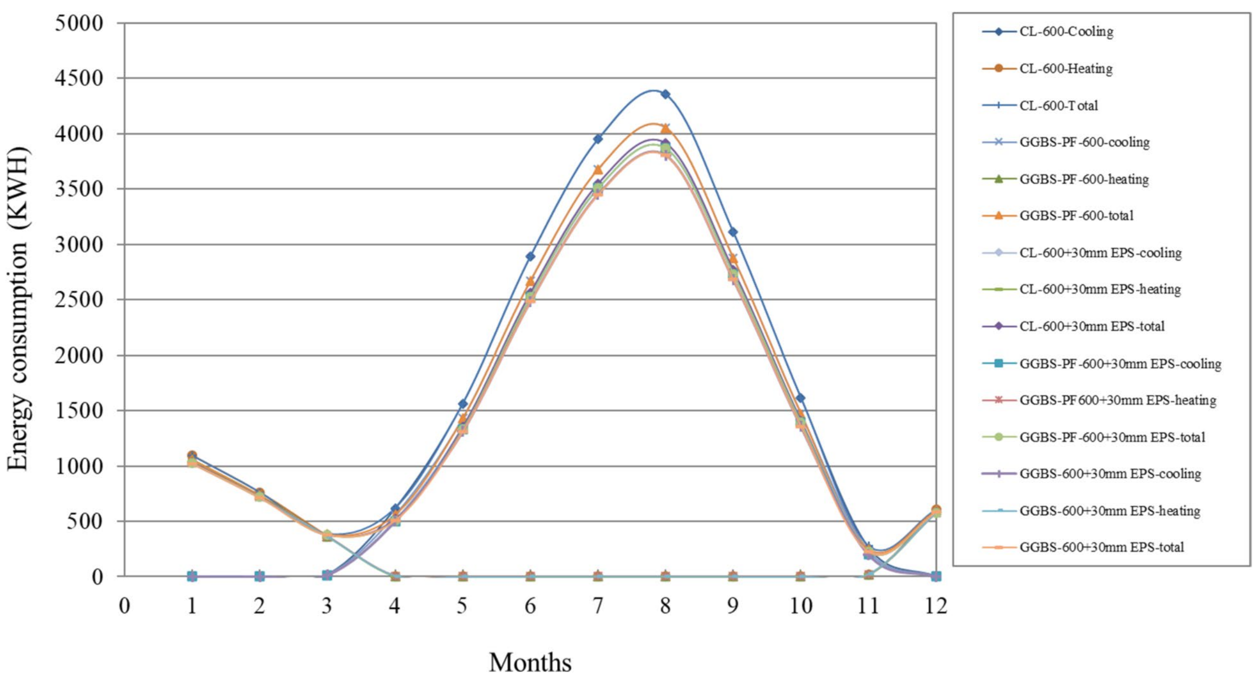

Fig. 11 Average monthly energy consumption using HVAC system for wall thickness 600 mm

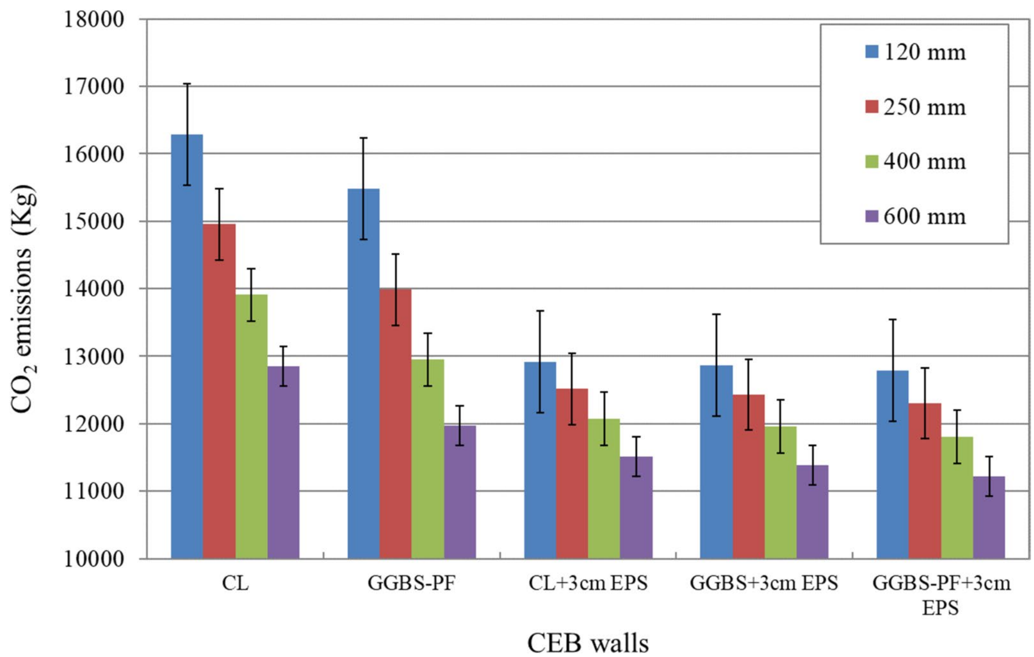

Fig. 12 CO_2 emissions using HVAC system

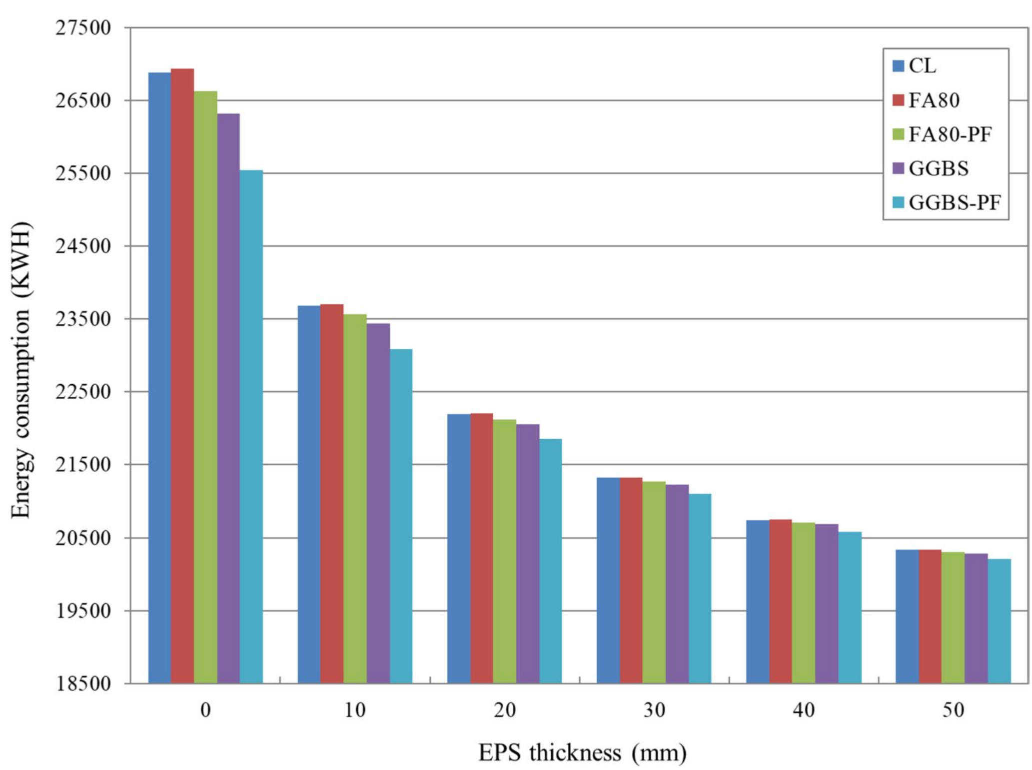

Fig. 13 Effect of EPS thicknesses on energy consumption of CEB walls of thickness 120 mm

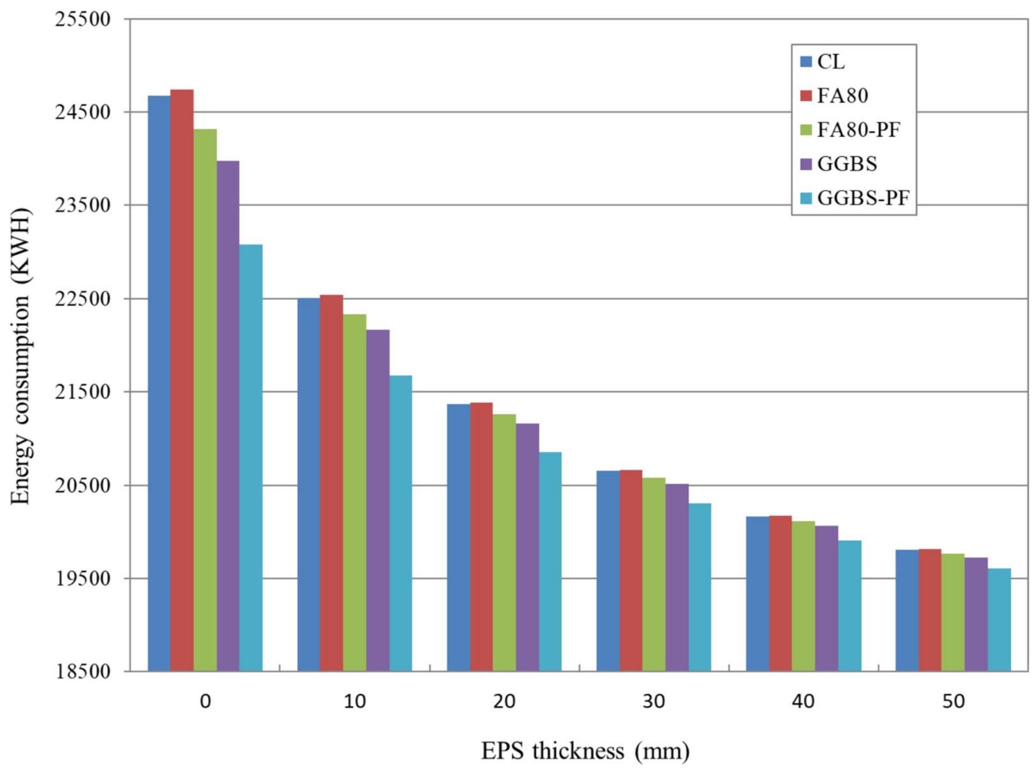

Fig. 14 Effect of EPS thicknesses on energy consumption of CEB walls of thickness 250 mm

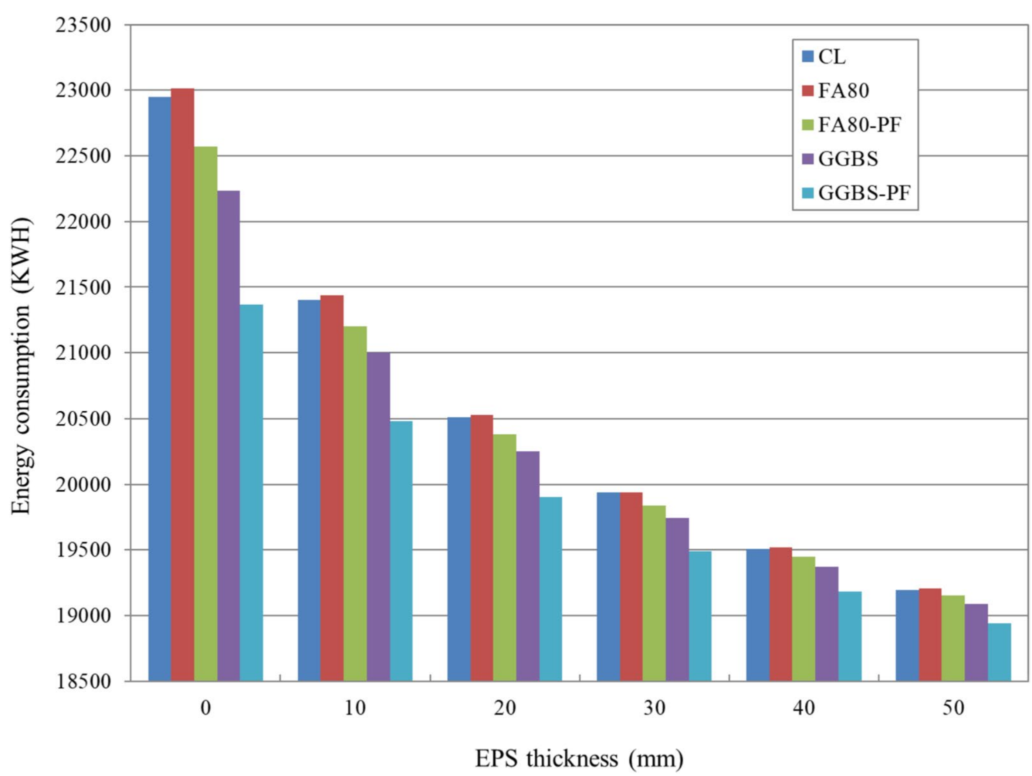

Fig. 15 Effect of EPS thicknesses on energy consumption of CEB walls of thickness 400 mm

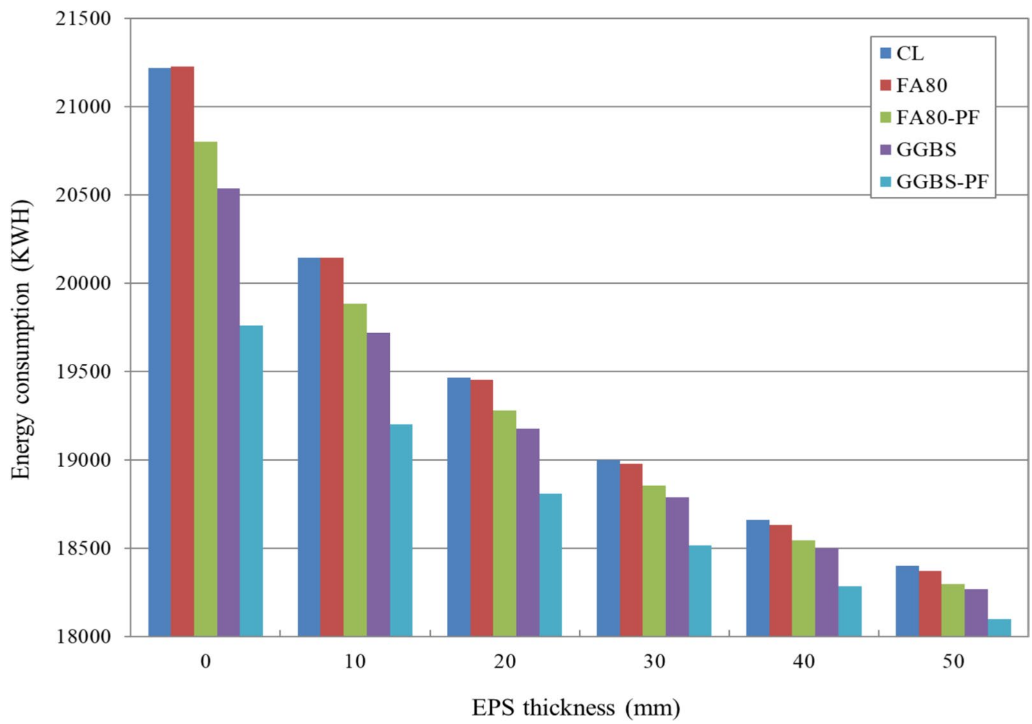

Fig. 16 Effect of EPS thicknesses on energy consumption of CEB walls of thickness 600 mm

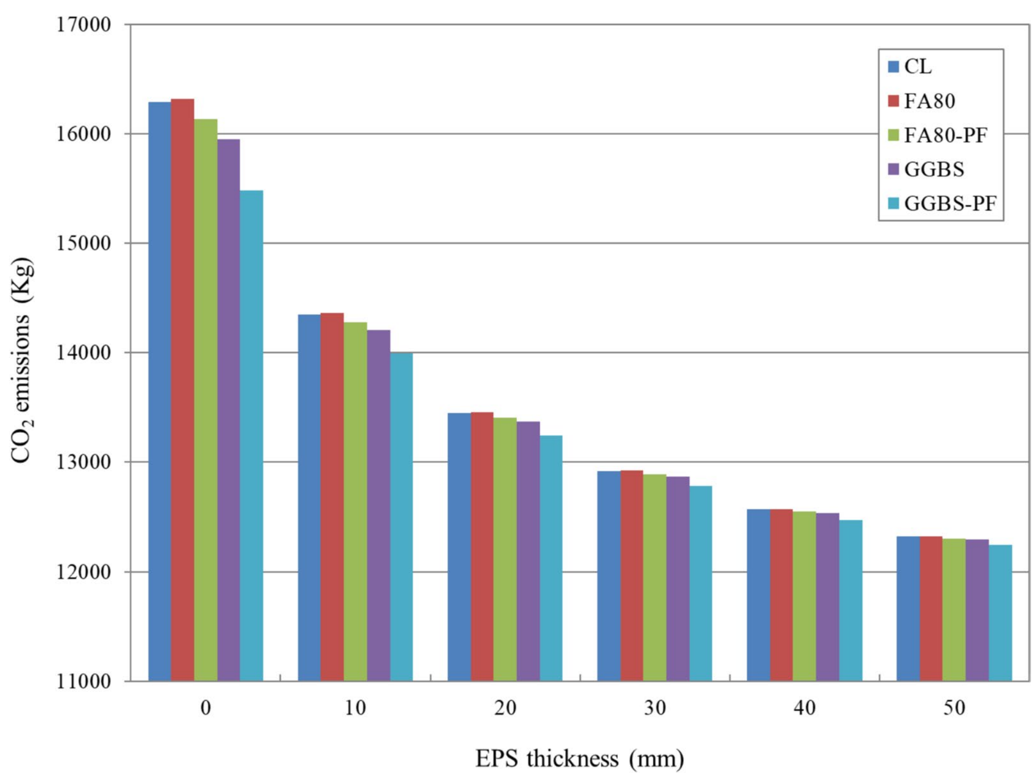

Fig. 17 Effect of EPS thicknesses on CO_2 emissions of CEB walls of thickness 120 mm

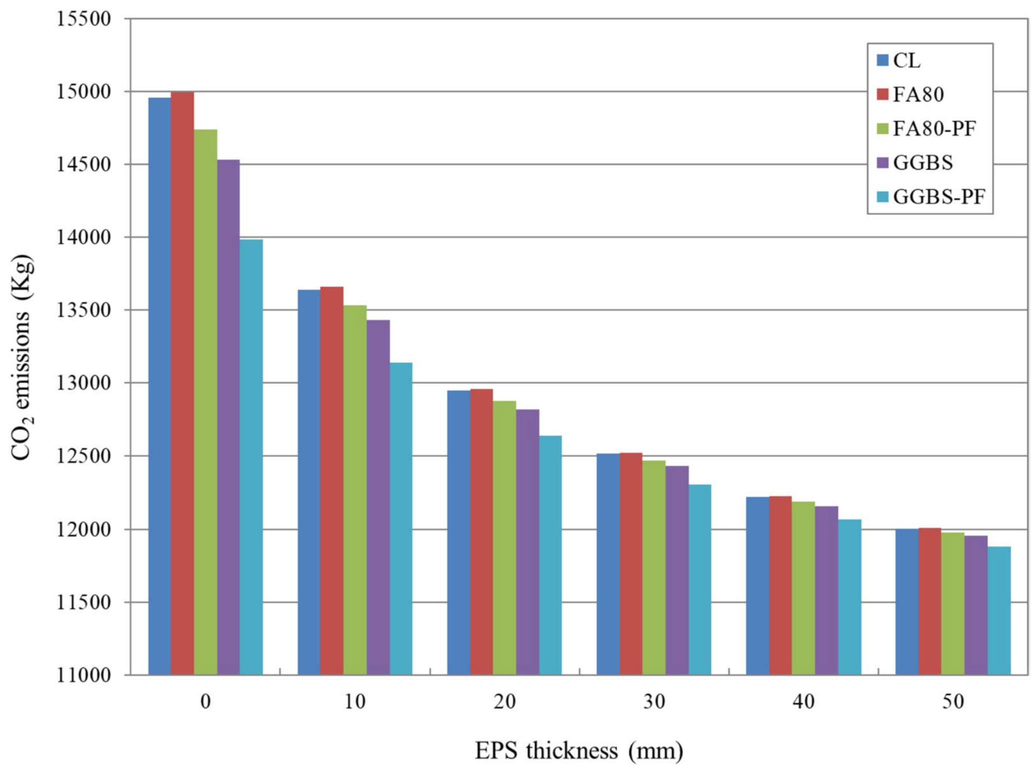

Fig. 18 Effect of EPS thicknesses on CO_2 emissions of CEB walls of thickness 250 mm

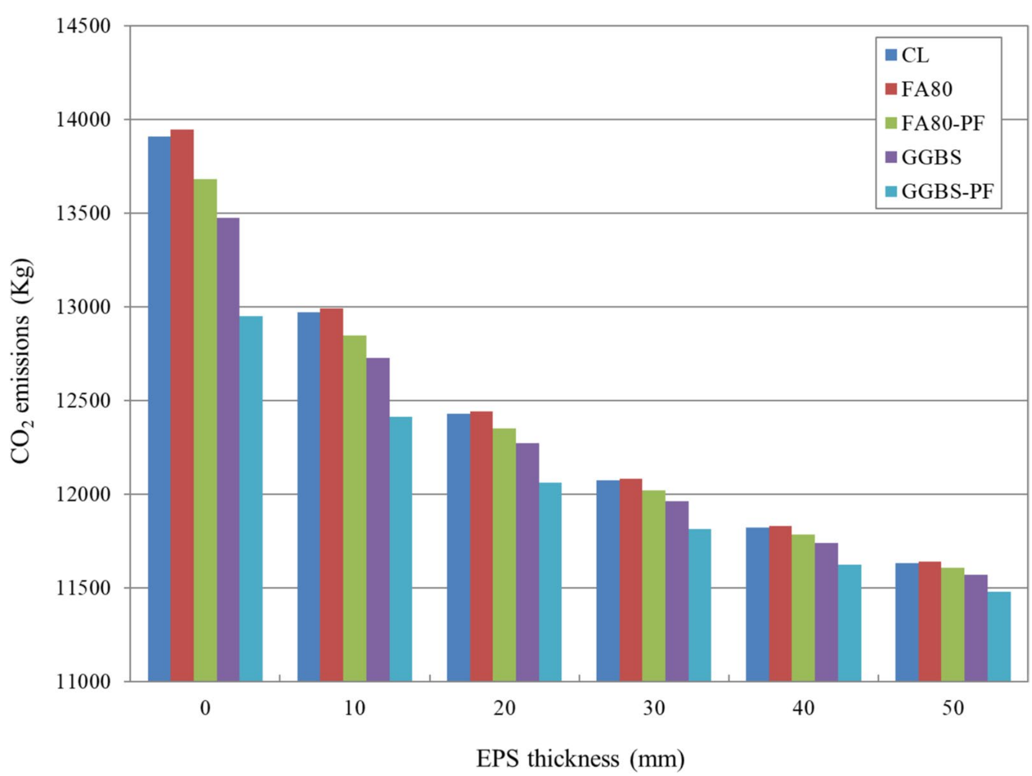

Fig. 19 Effect of EPS thicknesses on CO_2 emissions of CEB walls of thickness 400 mm

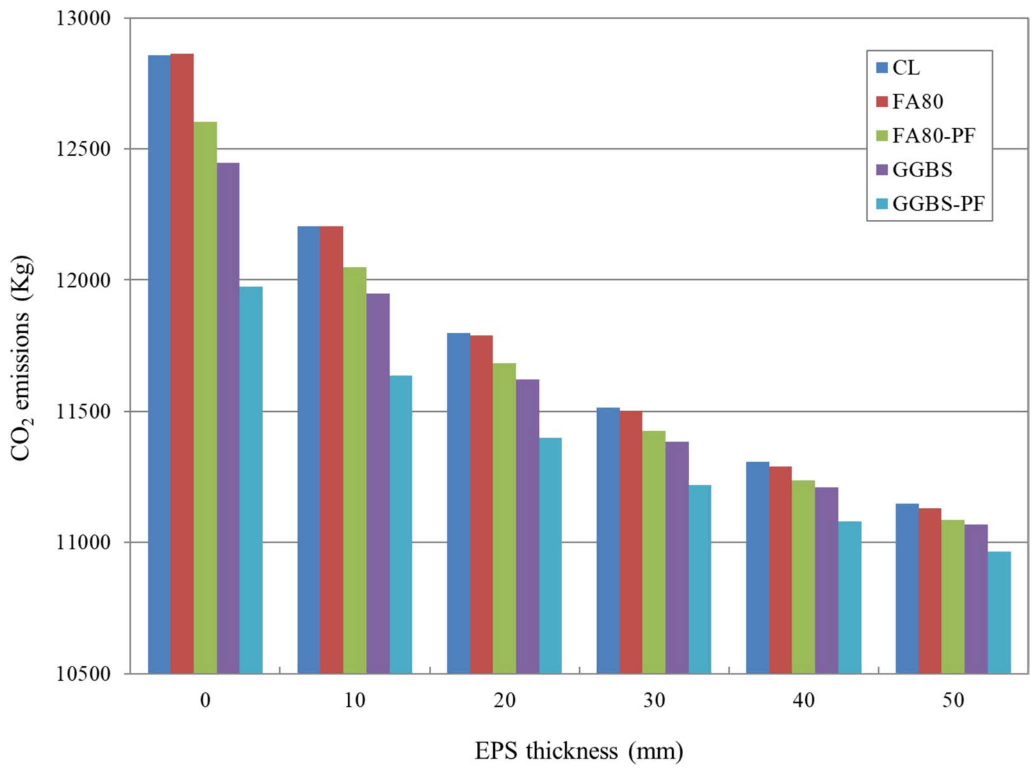

Fig. 20 Effect of EPS thicknesses on CO_2 emissions of CEB walls of thickness 600 mm

consumption previously determined, because the evaluation of annual average CO_2 emissions in the software is based on the total energy consumption.

5 Effect of EPS Thickness on the Total Energy Consumption and CO_2 Emissions

Design Builder software was employed to investigate the effect of EPS thickness on the total energy consumption and CO_2 emissions for CEB walls. The utilized CEB materials were CL, FA80, FA80–PF, GGBS, GGBS–PF.

The effect of using EPS insulating layer with different thickness on the total energy consumption and CO_2 emissions is illustrated in Figs. 13, 14, 15, 16, 17, 18, 19 and 20. The presence of EPS insulating layer has a vital role in reducing both the total energy consumption and CO_2 emissions regardless the wall type. It was expected that the dominant factor was the thickness of EPS due to its very low thermal conductivity which is about 0.04 W/m K.

It was noticed from Figs. 13, 14, 15, 16, 17, 18, 19 and 20 that the increase in EPS thicknesses from 10 to 50 mm in CEB walls with thickness of 120 mm led to a remarkable reduction in total energy consumption and CO_2 emissions of these walls. This reduction was from 11.9% to 24.3% for CL wall and from 10.9% to 22.9% for GGBS wall, whereas the reduction was observed to be from 9.6% to 20.8% for GGBS–PF wall and from 11.5% to 23.7% for FA80–PF wall. In addition, it was observed that for FA80 wall nearly the same reduction percentages as that for CL wall were obtained. This is due to that the thermal conductivity of both walls are nearly the same. However, when 50 mm glass wool insulation blanket was inserted between two layers of bricks of thickness 120 mm each by An-Naggar et al. (2017), the reduction in energy consumption and CO_2 emissions were about 40% and 30%, respectively.

Moreover, Figs. 13, 14, 15, 16, 17, 18, 19 and 20 show that the effect of EPS thickness in reducing the total energy consumption and CO_2 emissions declines when the CEB wall thickness increases. It was observed that the increase in EPS thicknesses from 10 to 50 mm in CEB walls with thickness of 600 mm led to lower reduction percentages than that for 120 mm walls. The reduction of total energy consumption and CO_2 emissions in wall thickness 600 mm was observed to reach 13.3%, 11.1%, 8.5%, 13.5%, and 12% for CL, GGBS, GGBS–PF, FA80 and FA80–PF walls, respectively, when EPS thicknesses increased up to 50 mm compared to the same walls without EPS.

It was also revealed that as the EPS thickness increases, the rate of reducing the total energy consumption and

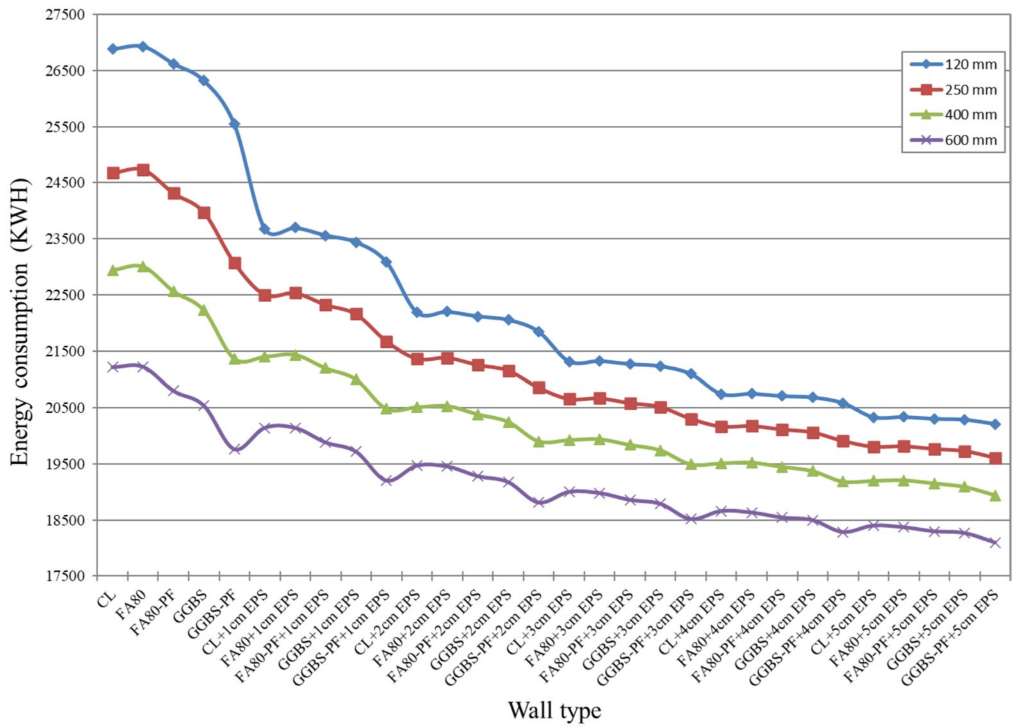

Fig. 21 Energy consumption for different CEB wall types

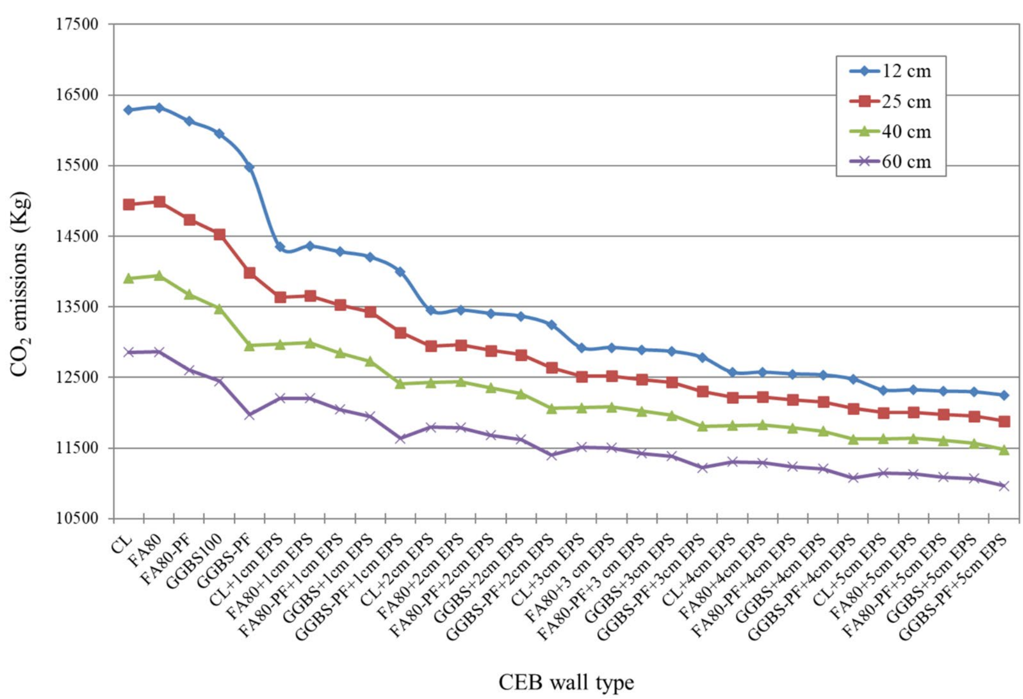

Fig. 22 CO_2 emissions for different CEB wall types

CO_2 emissions declines. For example, for wall thickness 120 mm, the total energy consumption and CO_2 emissions for CL wall decreased by about 5.3% when EPS thickness increased from 10 to 20 mm. While, when EPS thickness increased from 40 to 50 mm, the total energy consumption and CO_2 emissions decreased by 1.9%.

It was observed that as the EPS thickness increases, the effect of wall thickness and type is marginal in reducing the total energy consumption and CO_2 emissions.

The selection of EPS thickness to achieve certain design criteria requirements regarding the total energy consumption and CO_2 emissions can be estimated using Figs. 21 and 22 for the different wall types and wall thicknesses. It was observed that as the EPS thickness increases, the effect of wall thickness and type is marginal in reducing the total energy consumption and CO_2 emissions.

6 Conclusions

Based on the results of this study it can be concluded that:

- Walls of compressed earth bricks (CEB) made by alkali-activated ground granulated blast furnace slag (GGBS) as soil stabilizer with full replacement of cement is promising for sustainable built environment compared to those stabilized by cement, whereas those walls have good mechanical and thermal properties in addition to decreasing the total energy consumption and CO_2 emissions.
- The cooling load represents almost 87% of the total energy consumption due to the hot weather in Egypt that leads to turning on the HVAC for cooling.
- The effect of wall types was not significant in determining the indoor air temperature, because it is controlled by HVAC system. The average maximum absolute PMV value for the different walls when using HVAC system was 0.80, which lies between "slightly cool" to "slightly warm" according to the seven sensation scales of PMV.
- Energy consumption and CO_2 emissions decrease as CEB wall thickness increases. The reduction in energy consumption and CO_2 emissions reached about 22% when CEB thickness increased from 120 to 600 mm for GGBS walls incorporating 0.25% polystyrene foam.
- The use of expanded polystyrene (EPS) insulation layer with 30 mm thickness showed improvement in thermal behavior of CEB walls. It is preferred to use EPS layer in GGBS CEB walls rather than those incorporating 0.25% polystyrene foam, since the difference in energy consumption and CO_2 emissions between both types is about 0.5% only for wall thickness 120 mm.
- The presence of EPS insulating layer has a vital role in reducing both the total energy consumption and CO_2 emissions of CEB walls. In addition, as the thickness of EPS layer increases, the effect of CEB wall thickness on the total energy consumption and CO_2 emissions decreases and the rate of decrease in the total energy consumption and CO_2 emissions declines.

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Author contributions
Engy Hany: writing—review and editing. Nabil Fouad: supervision and visualization. Mona Abdel-Wahab: conceptualization, methodology, and visualization. Ehab Fawzy: data curation, writing—original draft, and investigation. Sherif Mahmoud: simulation a building.

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Availability of data and materials
The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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