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CONTRIBUTION OF POFA-FOAMED CONCRETE BLOCKS TO THE REDUCTION OF ENERGY CONSUMPTION IN BUILDINGS

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Abstract

The high indoor air temperature of buildings located in tropical countries such as Malaysia forces people to rely on indoor air conditioning systems (AC). Despite reducing indoor air temperature, the utilization of AC systems consumes a large amount of energy and has a negative impact on the thermal environment. Therefore, the use of lightweight concrete with high thermal insulation properties has become a necessity for overcoming such problems. This study aimed to investigate the reduction of the indoor air temperature inside a building using foamed concrete blocks containing palm oil fuel ash (POFA), a by-product of the combustion of palm oil biomass, including palm oil fibres and kernel shells. Foamed concrete blocks with a density of 900 kg/m^3 were cast using 20% POFA as a cement replacement. The blocks were installed as the external partition wall in a single-floor building with a total area of 20 m^2. Measurements of the indoor and outdoor air temperatures of the building were conducted. A simulation study also was conducted using an IES-VE software simulation to assess the electricity consumption of the building. The experimental result showed that the application of POFA-foamed concrete blocks could reduce the indoor air temperature by as much as 5.69ºC during peak periods. The electricity consumption using POFA-foamed concrete was found to be 32.8% less than that of normal concrete. Owing to its excellent characteristics in reducing the indoor air temperature, POFA-foamed concrete blocks can be used to provide high insulation in building partitions.

Keywords: Blocks, Energy consumption, Foamed concrete, Indoor air temperature; POFA.

1. Introduction

Energy consumption has been the most controversial issue in countries around the world in the past few decades. Global energy consumption has grown exponentially. The increase in global energy demand mostly comes from developing countries, where there is an increase in building demand due to strong economic growth and increase in population. The energy demand from developing countries is forecasted to increase by 71% from 2012 to 2040 [1]. Of the total global energy consumption, approximately 40% is consumed by the construction sector [2]. Malaysia is one of the countries that experienced a massive population increase in the past three decades. Its population has increased substantially every year. Approximately 32.0 million people were living in Malaysia in 2017, 1.1% higher than in 2016 [3]. Large populations lead to increasing construction demands. Because of the high demand for building construction, increase in land value, and the scarcity of materials resources, alternatives are increasingly being used to replace wood and bamboo as the primary traditional building materials. Modernization brought by the Chinese and Europeans during the colonial era caused people to adopt new building materials such as clay bricks, concrete, iron, steel, glass, and metal, which are commonly used in western cold-climate countries [4, 5]. Clay brick and concrete have become the most popular wall materials in the last fifty years, and this growth will be unavoidable over time [5]. However, owing to the excessive excavation of clay, which causes soil depletion, the utilization of clay bricks is no longer recommended. Therefore, concrete has become the most common basic building material that is currently produced.

Concrete has several advantages in building construction. For example, it can be produced to the desired strength, can be formed as desired, withstands high temperatures and is resistant to wind and water. However, the use of concrete materials proved unsuitable as it has high thermal conductivity, which is undesirable in the hot climate of Malaysia [4]. The utilisation of concrete as the basic material for construction increases the environmental temperature and urban heat island intensity, which contribute to global warming and climate change [6]. These harmful effects are driven mainly by the characteristics of concrete, including its easy absorption of solar radiation, storage of heat, and transfer of absorbed heat into buildings [5, 7]. According to Davis et al [8], the concrete buildings in urban areas overheat by approximately 3°C in a day. The hot and humid air trapped inside these structures can increase the indoor air temperature because the excessive heat transmitted through the building envelope is stored in the concrete walls and floor slabs.

Because of high indoor air temperatures, people often use air conditioning (AC) systems to maintain their comfort. As stated by Al-Yavouby et al. [9], approximately 75% of Malaysians rely on AC to maintain a comfortable indoor environment. Despite its ability to reduce indoor air temperatures, AC systems increase electricity consumption in the building sector, a sector that consumes approximately 40% of energy resources around the world [10]. The increase in the use of electricity generated using fossil fuels can increase greenhouse emissions [11]. In addition, the heat released from AC systems contributes to increasing the outside temperature by 0.5 to 2ºC at night (7 pm to 2 am) [12].

The usage of concrete-based building materials also contributes to the embodied energy consumption and CO_2 emission released during the production of cement.

CO_2 is the most important greenhouse gas (GHG), the proportion of which is increasing in the atmosphere. Cement production contributes approximately 70% to the greenhouse effect, which can lead to a thicker thermal blanket, thus affecting the earth's atmosphere by retaining excessive heat [13, 14]. The global emissions of CO_2 have increased by almost 50% since 1990 and grew more quickly between 2000 and 2010 than in each of the previous three decades [15]. To reduce indoor air temperatures with lower energy consumption, as well as reduce CO_2 emission, the application of passive elements in building envelopes is necessary. One of the methods is the implementation of lightweight foamed concrete to replace the use of normal-weight concrete as a wall material.

Lightweight foamed concrete, also known as foamed concrete, is a mixture of cement paste, consisting of cement, sand, and water, with a stable foam produced from a surfactant [16]. This type of lightweight concrete has a wide density ranging from 300 to 1800 kg/m^3 [17]. Foamed concrete has the advantages of low density, high flowability, and excellent thermal insulation owing to its cellular microstructure [18]. The thermal conductivity of foamed concrete is 5% to 30% lower than that of normal-weight concrete. Owing to its lower thermal conductivity, the use of lightweight foamed concrete in structural and non-structural building envelopes has become a valuable method for reducing the heat transfer into a building [19]. The thermophysical properties of construction materials greatly influence the energy required to cool a building and achieve thermal comfort [20].

The application of lightweight foamed concrete materials to building envelopes can provide a solution to reduce indoor air temperature, which leads to the reduction in energy consumption for air conditioners and dependence on the use of cement. Another approach to reducing greenhouse emissions is to produce lightweight foamed concrete that incorporates pozzolanic materials such as palm oil fuel ash (POFA) as a substitute for cement. This type of ash is a by-product of the combustion of palm oil biomass, including palm oil fibres and kernel shells. In palm oil mills, biomass is used as an alternative fuel to generate the power required by the plant. The combustion of biomass produces 5% POFA by weight of solid waste [21]. In practice, this ash is usually disposed of around the mills. Because it is left in the open, it is difficult to prevent POFA from spreading into the groundwater and being blown by the wind on a hot and humid day, causing environmental pollution [22].

Although the use of POFA as a cement replacement has been investigated extensively in normal-weight concrete production, as studied by Tay [23], Sata et al. [24] and Johari et al. [25], the use of these ashes in lightweight foamed concrete is still limited. Moreover, POFA is suggested to be used in the production of foamed concrete because Malaysia as one of the biggest palm oil producers has been facing challenges to manage the waste to reduce environmental problems. This paper investigates the effect of POFA on foamed concrete's thermo-physical properties. The optimum mixture, established by a laboratory experiment, was cast into blocks and applied as an external wall in a real-scale building. The effect of the blocks on the indoor air temperature of the building was then measured. This report elaborates not only on the ability of POFA as a building material, based on laboratory-tested properties, but also on its performance in reducing the indoor air temperature of the building.

2. Experimental Programme

This section is divided into three stages, namely laboratory experiment, field experiment, and simulation. The laboratory experiment was conducted to investigate the properties of foamed concrete with the inclusion of 20% POFA as the cement replacement and normal foamed concrete with 100% cement. The properties of foamed concrete such as compressive strength, porosity, and thermal conductivity were investigated. Foamed concrete blocks were produced with a size of 500 × 200 × 100 mm. The blocks were applied as the partition wall of a model building, in which the indoor air temperature measurement was conducted. An in-depth investigation was also carried out using an IES-VE software simulation to compare the indoor air temperature and annual electricity consumption of a building with POFA-foamed concrete, clay brick, and normal concrete walls

2.1. Laboratory experiment

2.1.1. Materials

The foamed concrete was cast using Portland composite cement as the basic cementitious material and POFA as the cement replacement. The cement used as the main binder was supplied by a single brand manufactured by YTL Cement Sdn. Bhd. which conforming to MS EN 197-1:2014 [26], CEM II/B-L 32.5N. Whereas POFA as the supplementary cement material was collected from a palm oil mill located in Nibong Tebal, Penang, Malaysia. The dry fine sand from a local riverbed passing through a 600-µm sieve was used. The sand had a fineness modulus and specific gravity of 1.35 and 2.74, respectively. The stable foam was produced using a protein-based foaming agent, which was diluted with water at a ratio of 1:30 and then aerated using a Porta Foam machine to obtain a density of 65 kg/m^3 before being entrained into the slurry. Clean tap water was added to the mixture according to BS EN 1008 [27].

Previously, the authors conducted preliminary research, which found that the presence of POFA in foamed concrete tends to increase water demand and indirectly reduce its strength caused by the angular and irregular shape and porous nature of POFA particles [28]. Therefore, in this study, a polycarboxylate-based superplasticizer (SP) and silica fume were used as chemical admixtures with fixed doses of 1% and 5% of the binder weight to improve the workability and strength of foamed concrete containing POFA, respectively. The addition of the chemical mixture is compensation in terms of the reuse of waste materials. Meanwhile, there were no chemical additives in the control specimen.

The raw POFA collected from a palm oil mill was a by-product of the combustion process of biomass, including palm oil fibre and kernel shells, which were burned at temperatures exceeding 1000°C. Before being used, this ash underwent a series of treatment processes: drying, sieving, and grinding. Because the POFA was stored in the open air around the mill, this ash was oven dried for 24 hours at a temperature of 105 ± 5°C to reduce its moisture content. The ash was then passed through a 300-µm sieve to remove any unburned fibres and shells, as well as other large particles. Then, it was subjected to a grinding process using a ball mill machine to produce finer ash particles. After the grinding process, the POFA had a median particle size (d_{50}) and specific gravity of 4.03 µm and 2.47, respectively. This was finer than cement, as shown in Table 1.

Table 1. Physical properties of cement and POFA.

Physical properties	Cement	POFA
Median particle size d_{50} (μm)	4.92	4.03
Specific gravity	3.01	2.47
Loose bulk density (kg/m^3)	1058	1006

The chemical compositions of cement and POFA were determined using an x-ray fluorescence analysis method, and the results were tabulated in Table 2. The results exhibit that the major chemical composition of the POFA was 54.93% silicon dioxide (SiO_2). The total chemical composition of the pozzolanic essential compound, namely silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), and ferric oxide (Fe_2O_3) was 62.16%. The loss on ignition (LOI) and SO_3 were 5.66% and 4.09%, respectively. This indicates that POFA used in this study can be classified as between class C and class F pozzolana following ASTM C618 [29].

Table 2. Chemical composition of cement and POFA.

Chemical compositions	Cement (%)	POFA (%)
Silicon dioxide (SiO_2)	14.84	54.93
Aluminium oxide (Al_2O_3)	3.64	3.27
Ferric oxide (Fe_2O_3)	2.44	3.96
Calcium oxide (CaO)	56.09	10.77
Magnesium oxide (MgO)	1.52	5.02
Sulphur oxide (SO_3)	2.65	4.09
Sodium oxide (Na_2O)	Bdl*	0.40
Potassium oxide (K_2O)	0.57	9.50
Phosphorus oxide (P_2O_5)	0.06	5.64
$SiO_2 + Al_2O_3 + Fe_2O_3$	-	62.16
LOI	-	5.66

* Below the limit of detection tools

2.1.2. Mix design, curing and sample preparation

Based on the pilot test, the replacement level of POFA was set at 20% [30]. Foamed concrete with a design density of 900 kg/m^3, a filler-to-binder ratio of 1.5 and a water-to-cement ratio of 0.45 was prepared. The control mixture (C100) was cast using 100% cement as the comparator. The mixture proportions are shown in Table 3.

Table 3. Calculated mix constituents (kg/m^3).

Mixtures	Cement	POFA	Sand	Water	Foam (m^3)	SP	Silica fume
C100	338.6	0	507.6	152.36	0.066	0	0
LFC-20	270.6	67.71	507.6	152.36	0.064	3.39	16.93

The dry materials were blended using a rotary concrete mixer. The water and superplasticizer were added gradually into the mixer until a homogenous mixture and the required spread value (220 to 240 mm) were obtained. To achieve the required spread value, additional water might have been added. The stable foam was added to the slurry to obtain the targeted fresh density. After obtaining the homogenous mixture, the fresh concrete was placed into greased moulds and left for 24 hours until it hardened. After de-moulding, the samples were wrapped in plastic cling wrap and stored at room temperature until the testing date, which was 28 days after casting.

A compressive strength test was carried out using a 100-mm cube specimen. It was measured using a GOTECH GT-7001BS300 compression machine with a compressive capacity of 3000 kN, in compliance with BS EN 12390-3 [31]. The porosity was measured using concrete cylinders with a diameter of 45 mm and a height of 50 mm. The porosity reading was determined using the vacuum saturation approach [32]. The thermal conductivity was measured using a hot disc thermal constant analyser following ASTM C518 [33].

2.2. Field experiment

2.2.1. Block production and building construction

POFA-foamed concrete blocks with a size of 100 × 500 × 200 mm were produced for the field experiment (Fig. 1). The blocks were installed as a partition wall in a single-floor building located at the School of Housing, Building, and Planning, on the main campus of Universiti Sains Malaysia, Penang (5°2´N and 100°2´E), as shown in Fig. 2. The building had a total area of 20 m^2 and a height of 3 m.

It had a concrete floor slab and plastered block walls (100-mm-thick block finished with 2-mm of plaster and painted white). The roof was made of a 25-mm-thick concrete composite tile with a 30° pitched roof as a suitable roof angle in the tropics [34]. A plasterboard ceiling and two 1 × 1 m operable louvered windows (Fig. 3). The windows of the building were installed on the north and south-facing walls, respectively to allowed direct radiation inside the building through the windows.

Both windows were set in closed condition during the measurement; therefore, the POFA-foamed concrete blocks were the only factor affecting the indoor air temperature. Figure 4 illustrates the building construction process.

Fig. 1. POFA-foamed concrete blocks production.

Fig. 2. Location of the field experiment.

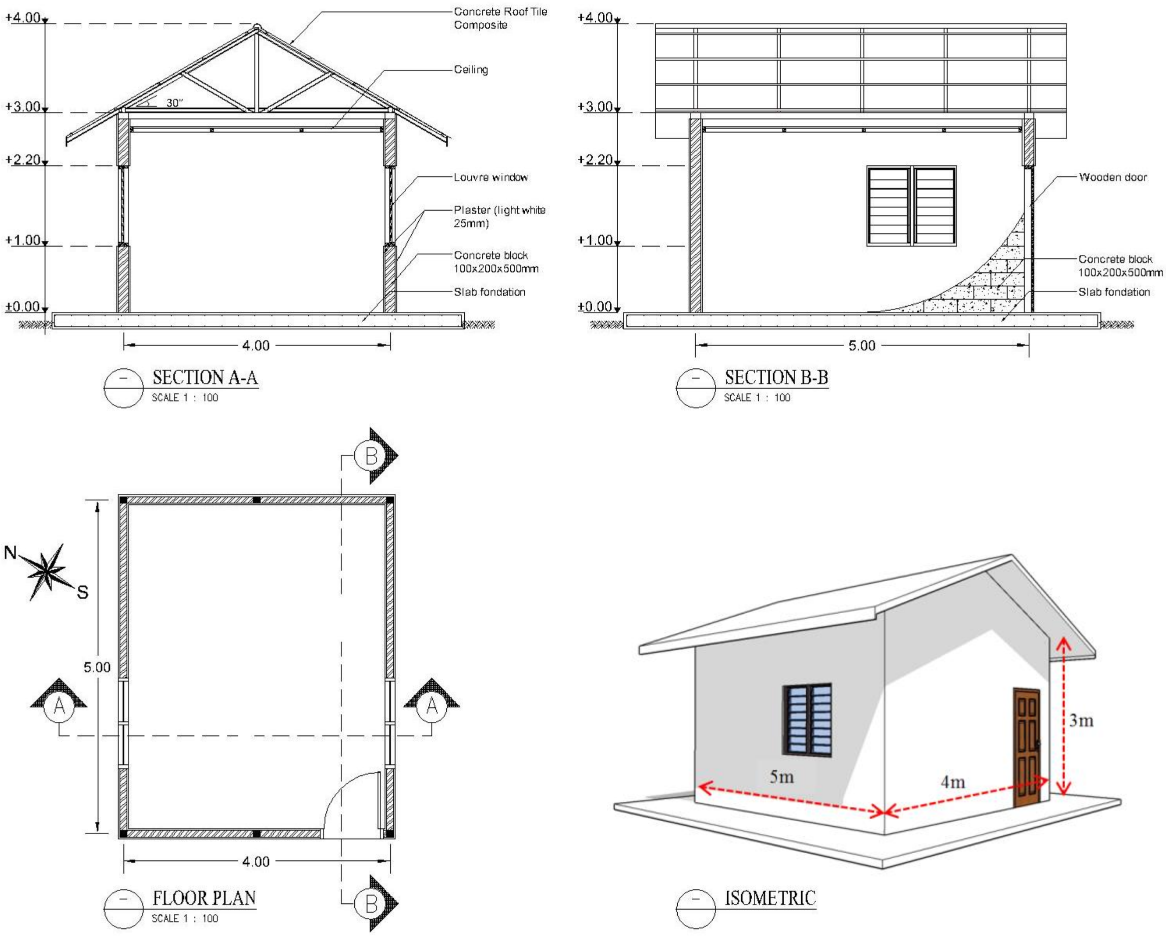


Fig. 3. Dimensioned drawing and isometric view of the building.

Fig. 4. Building construction process [35].

2.2.2. Block production and building construction

The indoor air temperature was measured using a data logger (BABUC A, LSI-LASTEM), which included a black globe thermometer probe to calculate the mean radiant temperature and a psychrometer to measure the air temperature and relative humidity. The devices were located in the middle of the room at a height 1.25 m above the floor, according to the ASHRAE Standard 55 [36] and as illustrated in Fig. 5. To measure the outdoor air temperature, a thermometer was placed inside a Stevenson screen to protect the sensor from direct exposure to solar radiation and precipitation. The field experiment was conducted 24 hours per day over six consecutive days in June 2018. Measurements were taken at 10-minute intervals. The test day was chosen at random, considering that global warming and current climate change have increased global temperatures and intense heat waves, as well as because this area has relatively stable average humidity throughout the year.

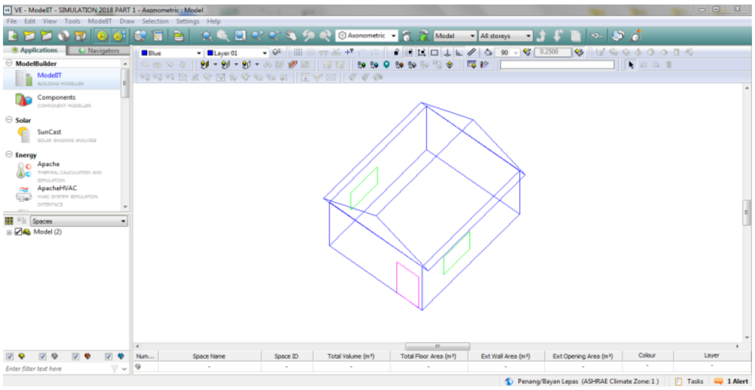
Fig. 5. Positions of sensors and data logger.

2.3. Software simulation

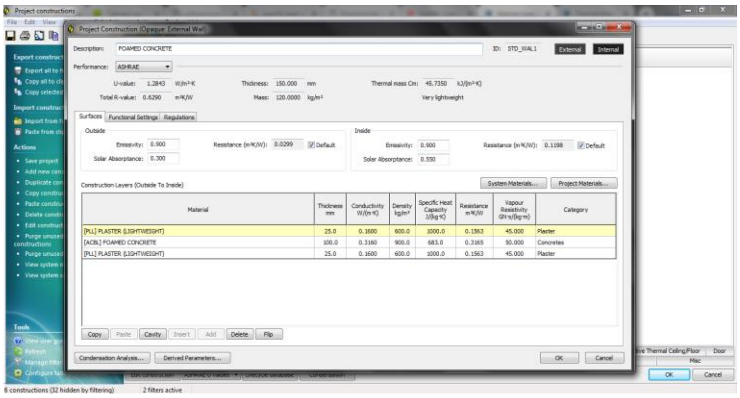
To investigate the performance of POFA-foamed concrete walls on indoor air temperature using various wall materials, a software simulation was conducted using the Integrated Environmental Solution-Virtual Environment (IES-VE), version 2017, which is a software tool for designing and operating energy-efficient buildings. This software meets the requirements of ASHRAE Standard 140 for building envelopes and fabric loads and for the performance of space cooling equipment simulations. The IES-VE software was validated, the percentage difference between the computer simulation result and the field experiment result being 13.3%, which is in the range of acceptable percentage difference as stated by Maamari et al. [37].

The building model was created based on the actual size and location of the field experiment. The IES-VE simulated the building in two conditions: air-conditioned and not air-conditioned. The simulation with the non-air-conditioned room was conducted to investigate the indoor air temperature of a building with various wall materials, whereas the air-conditioned room was simulated to investigate the annual electricity consumption for the AC system. The actual data for the POFA-foamed concrete including thermal conductivity, specific heat, and density from the laboratory experiment were loaded into the simulation program (Fig. 6). These data were used to generate ready-to-use wall specifications for the POFA-foamed concrete building.

For comparison purposes, two types of wall materials such as clay brick and normal concrete were selected, representing the common wall materials used in current buildings. The specifications of clay brick and normal concrete were generated from the software database. All of the building models had the same wall thickness (150 mm). The model for every simulation was created to have the same conditions with the same material specifications, except for the walls. The specifications of the wall materials are presented in Table 4.



(a) Building model for IES-VE simulation



(b) Material setup

Fig. 6. Building model and material setup for IES-VE simulation.

Table 4. Specifications of wall materials.

Specifications	POFA-Foamed Concrete	Clay Brick	Normal Concrete
Thickness (mm)	150	150	150
Conductivity (W/m²·K)	0.316	0.727	1.600
Density (kg/m^3)	900	1922	2200
Specific heat capacity (J/(kg K))	683	837	1050
U-Value (W/m²·K)	1.2843	1.6674	1.9059
R-Value (m^{2}K/W)	0.6290	0.4501	0.3750
Thermal mass (kJ/(m^{2}K))	45.7350	95.4357	130.5000

3. Results and Discussion

3.1. Properties of foamed concrete

From the laboratory experiment, it was found that the foamed concrete containing 20% POFA (LFC-20) had a compressive strength of 3.21 MPa that was 141% higher than that of the control specimen C100 (1.33 MPa). The higher silica (SiO_2) content and higher fineness of the POFA and silica fume particle size, was believed to be attributable to the enhanced geo-polymerization of the binders, which increased the compressive strength. The SiO_2 content in POFA and silica fume enhanced the pozzolanic reaction between the calcium hydroxide ($Ca(OH)_2$) from the cement hydration process and the SiO_2 from the POFA and silica fume. The pozzolanic reaction increased the production of calcium silicate hydrate (C-S-H), which produced a denser POFA-foamed concrete. This reaction product can fill internal voids; therefore, it increased the strength as well as reduced the porosity. Hence, unlike the compressive strength, the porosity value of LFC-20 was 15.4% lower than that that of the C100. This is confirmed by Sata et al. [21] and [38].

A reduction in porosity produces a quality improvement and vice versa. This explains why the LFC-20, which had a lower porosity value, obtained a higher compressive strength. However, a decrease in porosity value also causes an increase in thermal conductivity. The POFA-foamed concrete also had a thermal conductivity value of 0.316 W/m.K, which was approximately 8.22% higher than that of the control specimen (0.292 W/m.K). This is because materials in the gas phase have the lowest thermal conductivity, whereas those in the solid phase have the highest. Therefore, foamed concrete, which has many pores filled with air, has a lower thermal conductivity.

The compressive strength, porosity, and thermal conductivity of foamed concrete are also significantly related to the amount of water used to achieve the spread value during the mixing process. The high amount of water in a foamed concrete mixture increases the evaporable water. During the hardening process, the water content evaporates, leaving empty pores in the foamed concrete specimens. Because the LFC-20 was mixed with an additional 1% SP, the water content was reduced significantly. The LFC-20 had a water-to-solid ratio of 0.183, which was about 19.38% lower than that of the C100. Therefore, the LFC-20 had a lower porosity value. A summary of the compressive strength, porosity, and thermal conductivity of the foamed concrete is provided in Table 5.

The results of the compressive strength test show that the replacement of 20% POFA in foamed concrete production fulfils the requirements for non-structural masonry, which is 2.9 MPa, according to MS 2282-4 [39]. Given their larger size, the foamed concrete blocks had an average compressive strength of 2.20 N/mm_2, lower than the cubic specimen but still able to fulfil the requirements for autoclaved, aerated concrete, which is 1.5-8.0 N/mm^3 following BS EN 771-4 [40].

Table 5. Properties of foamed concrete.

Mixtures	Compressive Strength (MPa)	Porosity (%)	Thermal Conductivity (W/m.K)
C100	1.33	53.85	0.292
LFC-20	3.21	45.54	0.316

3.2. Effect of the blocks on air temperature

Figure 7 shows a comparison of the outdoor and indoor air temperatures for the six testing days. The six consecutive days selected for the measurement were clear; therefore, the readings of indoor and outdoor air temperature show little fluctuation. The air temperature gradually increased from 8:00 am to 12:00 pm. The outdoor environment showed a maximum temperature of 39.10°C, an average of 30.82°C, and a minimum of 26.80°C. Meanwhile, the inside of the building had a maximum temperature of 34.36°C, an average of 30.56°C and a minimum of 27.34°C. It is undesirable that the use of a composite concrete tile roof with a thermal conductivity of 0.647 also contributes to a decrease in indoor air temperature. This may be better when compared to normal tile roofs with a thermal conductivity of 0.840 W/m^2 K [41].

The outdoor temperature started increasing at 8:00 am when the sun started to rise. After reaching its maximum between 2:00 pm and 4:00 pm, the outdoor temperature cooled down until the next morning. When the solar radiation hit the surface of the outer wall, heat travelled through the wall material until it finally propagated to the surface of the inner wall by heat transfer, i.e. from a high-temperature place to a low-temperature place. This process required a certain period. Therefore, the indoor air temperature of the building was found to be cooler than the outdoor temperature during the day when the measurements were being conducted.

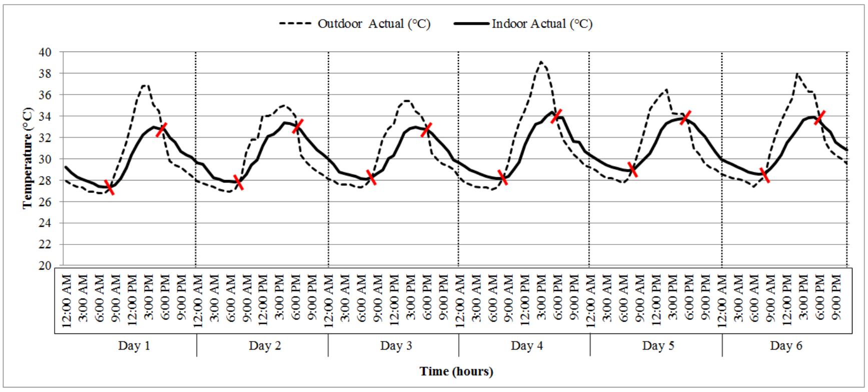


Fig. 7. Outdoor and indoor air temperatures of a building with POFA-foamed concrete blocks [35].

Aside from the time needed for heat propagation, the low thermal conductivity of the POFA-foamed concrete blocks also contributed to reducing the indoor air temperature. As illustrated by the graph in Fig. 8, the temperature of the indoor air was cooler than that of the outdoor air during the day for approximately 10 hours from 8:00 am to 6:00 pm. The diurnal maximum indoor air temperature reduction recorded was 4.59°C at 2:00 pm (Day 1), 2.78°C at 12:00 pm (Day 2), 3.15°C at 1:00 pm (Day 3), 5.69°C at 3:00 pm (Day 4), 4.18°C at 11:00 am (Day 5) and 5.18°C at 2:00 pm (Day 6).

However, the heat from solar radiation, which was trapped in the wall structure during the day, was released at night when the outside air temperature decreased. Under similar conditions, the heat from inside the building also needed time to be released to the outside environment, which made the indoor air temperature hotter during the night, starting at 6:00 pm until 8:00 am the next day. The diurnal maximum of the indoor air temperature increment was 2.19°C at 8:00 pm (Day 1), 2.41°C at 7:00 pm (Day 2), 1.96°C at 8:00 pm (Day 3), 2.01°C at 7:00 pm (Day 4), 2.49°C at 9:00 am (Day 5) and 1.72°C at 8:00 pm (Day 6). The differences between the outdoor and indoor temperatures for 24 hours are illustrated in Fig. 8.

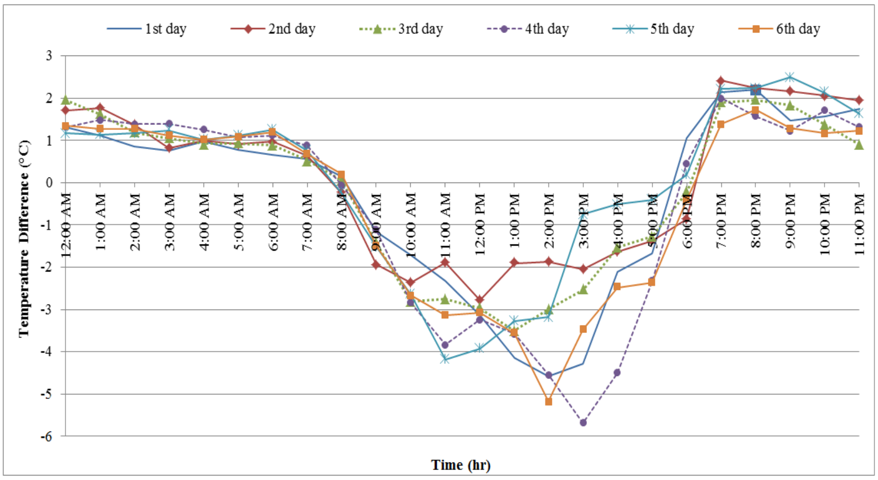


Fig. 8. Differences between outdoor and indoor temperatures.

3.3. Indoor air temperature and electricity consumption

Figure 9 illustrates the indoor air temperature of the building with various wall materials. The readings of indoor air temperature show that it was nearly stable. This result shows that the building with normal concrete walls achieved the highest maximum indoor air temperature (34.29°C) during the day, followed by the POFA-foamed concrete and clay brick walls, which reach 34.17°C and 33.32°C, respectively. However, when the outdoor air temperature decreased at 6:00 pm, the POFA-foamed concrete building reached the lowest indoor air temperature, whereas the building made of normal concrete did not show a significant drop in indoor air temperature. Table 6 presents the maximum, average, and minimum indoor air temperatures of the building with the various wall materials.

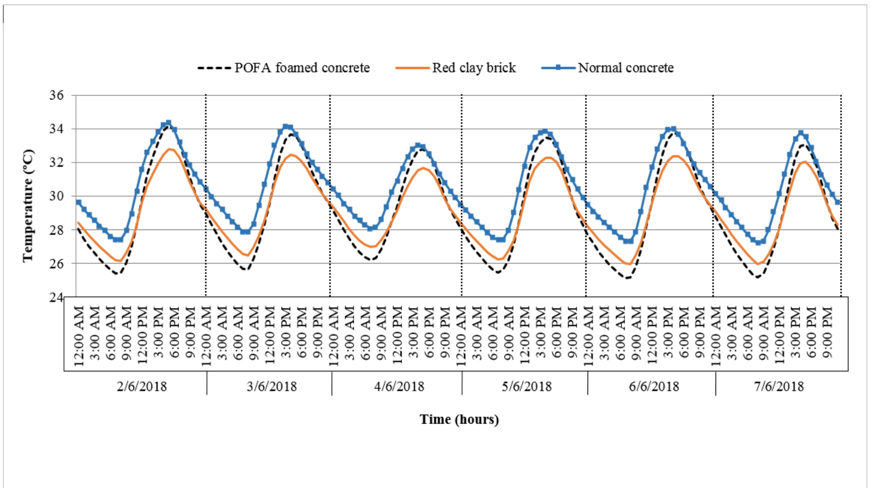


Fig. 9. Indoor air temperature of POFA-foamed concrete, clay brick, and normal concrete building using IES-VE software simulation [42].

Table 6. Maximum, average, and minimum air temperatures (°C)

Wall Materials	**Air Temperature (°C)**		
	Min	Mean	Max
POFA-Foamed Concrete	25.14	29.11	34.17
Red Clay Brick	25.60	29.12	33.32
Normal Concrete	26.97	30.33	34.29

When considering the building materials, the highest value of indoor air temperature can be related to their thermal conductivity, specific heat and density, which influence the thermal mass characteristic of each material [43]. Because of higher thermal mass, more heat is stored and less heat is transmitted to the inner surface of the wall [44]. Heavyweight building materials, including cement blocks, bricks, concrete, and other solid materials that are categorized as having high thermal mass, absorb heat from solar radiation at a slower rate but take a longer time to release it [45]. This explains why the building made from normal concrete, which had the highest thermal conductivity of 1.6 $W/m^2 \cdot K$, specific heat of 1,050 J/(kg.K) and a density of 2,200 kg/m^3 obtained the highest indoor air temperature at night. The higher the thermal conductivity of the materials, the more rapidly the heat will be transferred [46].

On the other hand, lightweight materials including foamed concrete are known as low thermal mass materials, which easily absorb heat. In addition to its rapid heat absorption, foamed concrete is known to release heat much faster than clay brick. This is because foamed concrete has a low density and low thermal conductivity owing to its porous structure. Materials with high porosity tend to have high insulation because of their air content, which makes them very poor thermal conductors [47]. The interconnections in the microstructure have an impact on the thermal conductivity of building materials [48]. Figure 10 shows a micrograph of LFC-20, featuring its porous structure.

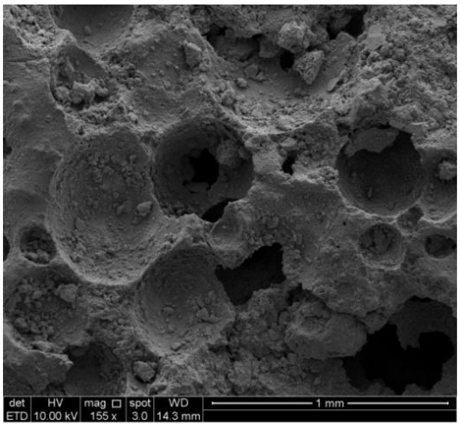


Fig. 10. SEM micrograph (155× magnification) of LFC-20.

Considering that the temperatures on the surfaces of building elements and its adjacent environment are different, the heat transfer through porous building elements is affected not only by conductivity but also by other heat transfer mechanisms, i.e. convection and radiation. Convection is a heat transfer mechanism that occurs through the molecular movement induced by differential temperature variations, whereas radiation occurs through electromagnetic energy [46]. Therefore, in a porous material, heat is propagated by thermal conduction through the solid and fluid (air) phases, radiation occurs between solid particles and convection occurs in the fluid phase [49]. Figure 11 shows a sketch of the heat transfer mechanisms through a wall material.

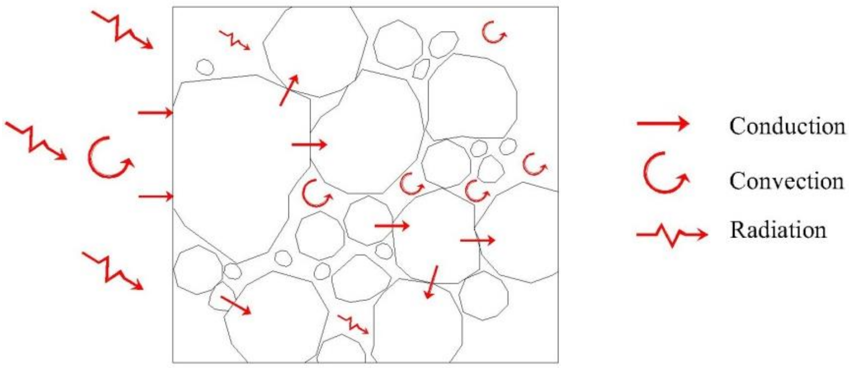


Fig. 11. Heat transfer mechanisms through a wall material. Source: Modified from Balaji et al. [43].

Heat transfer occurs from a place with a higher temperature to a place with a lower temperature. Therefore, when the outside air temperature dropped during the night, POFA-foamed concrete rapidly released the heat from the inside the building to the outside, resulting in the lowest indoor air temperature of 25.14°C. Meanwhile, a building that was made from clay or normal concrete achieved indoor air temperatures of 25.60°C and 26.97°C, respectively. In contrast to the air temperature, buildings with POFA-foamed concrete blocks as walls have a relative humidity of 48.78%, slightly higher than normal concrete (48.27%), while clay bricks have the highest relative humidity value of 49.42%.

The pattern of an indoor air temperature the relative humidity of the building also affected the amount of electricity consumed when the AC system was activated. From the recorded data, POFA showed the lowest total annual electricity consumption, which was 3,164.90 kWh, around 18.97% lower than clay brick and 32.8% lower than normal concrete, which had annual electricity consumption levels of 3,905.90 kWh and 4,709.80 kWh, respectively.

The monthly electricity consumption of buildings with various wall materials showed similar patterns. The electricity consumption of all the buildings decreased from January to February but increased in March, which is known to be the hottest period in Malaysia [50]. The energy required for cooling gradually decreased and reached its lowest level in October. After that, it increased again (Fig. 12).

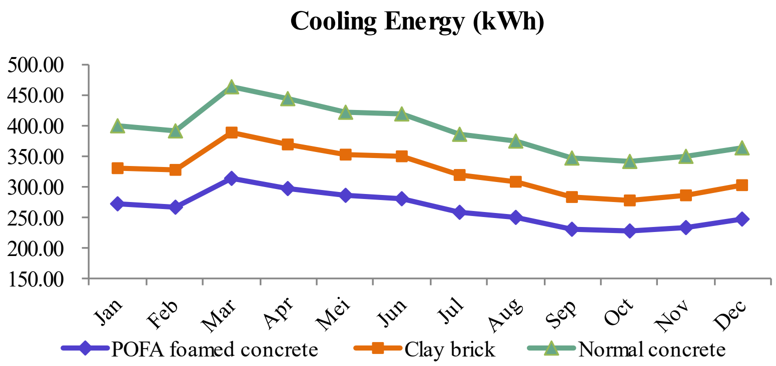


Fig. 12. Annual cooling energy consumption.

4. Conclusions

This paper demonstrated the performance of foamed concrete blocks with the inclusion of 20% POFA as a cement replacement in reducing the indoor air temperature. The POFA-foamed concrete blocks were able to reduce the daytime indoor air temperature by as much as 5.69ºC. A comparison between the indoor air temperature of a building with POFA-foamed concrete and other materials using the IES-VE software simulation showed that the POFA-foamed concrete wall achieved the lowest average indoor air temperature. The application of POFA-foamed concrete blocks reduced the annual cooling electricity consumption in the building by around 18.97% more than clay brick and 32.8% more than normal concrete. Recycling POFA from waste materials into cement substitutes also contributes to a reduction in environmental deterioration. Because it is used as an external wall that is exposed to temperature changes throughout the year, the future study can be conducted to investigate the effects of humidity and rainfall on POFA-foamed concrete blocks, especially in the rainy season.

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