Effect of POFA Foamed Concrete Block on Indoor Air Temperatures

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Abstract. Palm oil ash fuel (POFA) is a by-product produced from the combustion of biomass, including palm oil fibre and kernel shell; it is commonly used as an alternative fuel to generate electricity in palm oil mills. The disposal of this ash around the mill is usually uncontrolled, causing environmental problems. To reduce the ash’s negative impact on the environment, several studies have sought to incorporate this waste into the production of concrete, mortar and paste. Incorporation of POFA can enhance the mechanical, material and thermal properties of foamed concrete. This study examines the effect of replacing cement with POFA in a lightweight foamed concrete mix with a density of 900 kg/m³ and cement-to-sand ratio of 1:1.5 on indoor air temperatures. The POFA foamed concrete was cast to produce blocks measuring 100 mm × 200 mm × 500 mm. A single-storey building with a floor area of 20 m² and height of 3 m was built and tested, and an actual test of indoor and outdoor temperatures was conducted. Comparison of actual and simulated data using simulation software showed that the indoor air temperature of the POFA foamed concrete block is lower than the outdoor air temperature. Using POFA foamed concrete blocks as a wall material decreased the indoor air temperature by up to 5.69 °C. The average indoor air temperature of a building with POFA foamed concrete blocks was 29.11 °C, which is close to that of a building with clay brick (29.12 °C). These temperatures are lower than those of buildings with normal concrete walls.

1. Introduction
Unlike traditional Malayan houses, which are built using low-thermal mass materials, such as timber, modern buildings are mostly built using concrete or other non-permeable and high-thermal-mass materials. Due to the high demand for building construction and the increasing value of land, the use of concrete as a primary building material has grown over time.

Utilisation of concrete in building structures in urban areas increases the indoor air temperature by approximately 3 °C during the day. Hot and humid air is trapped in the structure because the excessive heat transmitted through the building envelope is stored in concrete walls or the floor slab [1].

To reduce the indoor air temperature and maintain thermal comfort, air conditioning systems are necessary. Approximately 75% of all Malaysians rely on air conditioning systems to maintain a comfortable environment [2]. However, air conditioning systems consume approximately 30%–60% of the total electricity consumption of a building [3,4]. The Malaysia Energy Information Hub (2018) found that 54% of the total 11.375 ktoe electricity consumption in 2015 came from the building sector. Moreover, air conditioning systems also contribute to urban heat islands by increasing the outside air
temperature by approximately 0.5–2 °C due to heat discharge [6].

To reduce the indoor air temperature and improve the energy efficiency of a building, the passive energy strategy can be implemented. Improving the opaque envelope material may also be attempted. Walls are the largest parts of the building envelope and exposed to external environmental conditions, including solar radiation, outside air temperature, wind and precipitation. In this case, instead of using concrete or other heavy weight material, the walling system can be changed using lightweight materials. One type of lightweight material with potential use as building envelope is lightweight foamed concrete.

Foamed concrete has been used around the world since the 1920s [7]. This material is generally known for its many advantages, including high flowability, low self-weight, minimal consumption of aggregate, controlled strength and excellent thermal insulation properties [8]. However, due to its low density, foamed concrete tends to have low strength. Hence, several additional waste materials, such as fly ash, rice husk ash and bottom ash, have been introduced to improve the properties of foamed concrete. In particular, the applications of palm oil fuel ash (POFA) as an additive to foamed concrete have been investigated.

POFA is an agro-waste ash obtained from the combustion of palm oil biomass, including palm oil fibre and kernel shell. Biomass combustion produces 5% POFA by weight, which is equal to 0.1 MT/per year [9]. Approximately 2.6 MT of POFA is produced in Malaysia annually [10]. Due to the massive amounts of POFA produced, the waste is disposed in open grounds around palm oil mills, often leading to deterioration of the environment [11].

POFA has high potential as a pozzolanic material when it is ground to a fine particle size. Replacement of the cement content with 10% and 20% POFA can increase the compressive strength of the resulting concrete by approximately 100% and 99%, respectively [12]. POFA can improve the resistance of concrete to chloride penetration [13], reduce heat development and increase resistance to acidic environments [14]. POFA can also reduce 15%–50% of the thermal conductivity of concrete [15].

To enhance the findings of previous research, this develops an optimum design of foamed concrete containing POFA. The optimum design is employed to fabricate a block applicable to large-scale production, and the block is implemented in a real-scale model house to investigate the performance of POFA foamed concrete in decreasing indoor air temperatures.

2. Experimental

2.1. Materials

The constituent materials used to produce the foamed concrete in this study consisted of Portland composite cement, POFA, fine aggregate, silica fume, superplasticiser, water and stable foam. Dried fine sand passed through a 600 µm sieve with a fineness modulus and specific gravity of 1.35 and 2.74, respectively, was used as the fine aggregate. To produce stable foam, a protein-based foaming agent with a dilution ratio of 1:30 was aerated using a portafoam machine. The foam had a density of 65 kg/m³. To improve the workability and strength of the foamed concrete, 1% polycarboxylate-based superplasticiser (SP) and 5% silica fume based on the weight of the binder were added.

The POFA used in this study was the by-product of biomass containing palm oil fibre and kernel shell burned at temperatures above 1,000 °C. POFA was collected from a palm oil mill in Penang, Malaysia. Due to its disposal in open air, the collected raw POFA was dried in an oven at 105 ± 5 °C for 24 hours to remove its moisture content. The POFA was then sieved through a 300 µm sieve to remove unwanted particles, including unburned shell and fibres. After sieving, the POFA was dried using a ball mill machine to produce ash particles finer than that of cement. Table 1 shows the physical properties of the cement and ground POFA.
Table 1. Physical properties of POFA and cement

| 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 the cement and POFA are shown in Table 2. POFA consisted of 54.93% SiO$_2$, 62.16% SiO$_2$ + Al$_2$O$_3$ + Fe$_2$O$_3$ and 5.66% LOI. Considering its chemical composition, this POFA can be classified as class C–F pozzolana, which complies with ASTM C618.

Table 2. Chemical composition of POFA and cement

| Chemical compositions | Cement (%) | POFA (%) |
|-----------------------|------------|----------|
| Silicon dioxide (SiO$_2$) | 14.84     | 54.93    |
| Aluminium Oxide (Al$_2$O$_3$) | 3.64     | 3.27    |
| Ferric Oxide (Fe$_2$O$_3$) | 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$_2$O) | bdl$^a$   | 0.40     |
| Potassium Oxide (K$_2$O) | 0.57      | 9.50     |
| Phosphorus Oxide (P$_2$O$_5$) | 0.06    | 5.64     |
| SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$ | -       | 62.16    |
| LOI | -         | 5.66     |

$^a$ Below the limit of the detection instruments

2.2. Mixing proportions and casting

The mixing proportions of foamed concrete are summarised in Table 3. Six foamed concrete mixes were cast, and the final foamed concrete mixes had a density of 900 kg/m$^3$ and cement-to-sand ratio of 1:1.5. The control mixture (C100) was the foamed concrete containing only Portland composite cement as the cementitious material. Mixtures LFC-20, -30, -40, -50 and -60 were foamed concretes containing 20%, 30%, 40%, 50% and 60% POFA, respectively, by weight of the cementitious material.

After 24 hours, the foamed concrete specimens were removed from their moulds, wrapped with plastic film and stored until the testing date. The compressive strength of cube specimens measuring 100 mm × 100 mm × 100 mm were determined, and the porosity of foamed concrete was recorded using a vacuum saturation apparatus. The compressive strength and porosity tests were conducted on specimens aged 7, 14, 28, 56, 90 and 180 days. The thermal conductivity of the foamed concrete was also investigated using a thermal constant analyser at the age of 28 days.

Table 3. Mixing proportions of the foamed concrete (kg/m$^3$)

| Mix   | POFA (%) | Cement | POFA | Sand | Foam (m$^3$) | SP | Silica fume | W/S ratio$^a$ |
|-------|----------|--------|------|------|-------------|----|-------------|---------------|
| C100  | 0        | 338.57 | 0    | 507.85 | 0.066     | 0  | 0           | 0.227         |
| LFC-20| 20       | 270.85 | 67.71| 507.85 | 0.064     | 3.39| 16.93       | 0.187         |
| LFC-30| 30       | 237.00 | 101.57| 507.85 | 0.063     | 3.39| 16.93       | 0.189         |
| LFC-40| 40       | 203.14 | 135.43| 507.85 | 0.061     | 3.39| 16.93       | 0.191         |
| LFC-50| 50       | 169.28 | 169.28| 507.85 | 0.060     | 3.39| 16.93       | 0.203         |
| LFC-60| 60       | 135.43 | 203.14| 507.85 | 0.054     | 3.39| 16.93       | 0.294         |

$^a$Water-to-solid ratio
3. Foamed concrete properties

3.1. Compressive strength

Compressive strength development in the foamed concrete is presented in Figure 1. Amongst those of all samples tested, the compressive strength of LFC-20, at 3.21 MPa, was the highest on day 28. The foamed concrete containing up to 50% POFA showed a compressive strength higher than that of the control specimen. On day 28, LFC-20, -30, -40 and -50 revealed compressive strengths that were 141%, 73%, 61% and 4% higher than that of C100 (1.33 MPa), respectively.

The high compressive strength of foamed concrete with up to 50% POFA content can be attributed to the high silica (SiO$_2$) content and fineness of ground POFA, both of which promote reactions with Ca(OH)$_2$ to produce an additional calcium silicate hydrate (C--S--H) through the pozzolanic reaction and improve the compressive strength of the foamed concrete [9,16]. The fine particles of POFA can fill up voids and increase the densification of POFA foamed concrete [12,17].

Additional silica fumes in the foamed concrete mixtures also enhance their compressive strength. The fine particles of silica fumes can fill the transition zone within the cement paste and aggregate, thereby improving the densification of foamed concrete [18,19]. However, the compressive strength of foamed concrete decreased with continued increases in POFA content beyond 50%. Amongst the samples, LFC-60 showed the lowest compressive strength.

![Figure 1. Compressive strength development of the foamed concretes](image)

3.2. Porosity

Introducing up to 50% POFA to foamed concrete resulted in lower porosity compared with that of the control specimen, C100. Figure 2 presents the porosities of the foamed concretes including POFA. On day 28, the respective porosities of LFC-20, -30, -40 and -50 were 45.54%, 46.96%, 47.02% and 51.43% or approximately 15.4%, 12.8%, 12.7% and 4.5% lower than that of C100.

The porosity of foamed concrete decreased over time due to the densification of its structure. This phenomenon can be linked to the pozzolanic reaction between silica in POFA and Ca(OH)$_2$ from the cement hydration process, which produces additional C--S--H compounds. The high fineness of the POFA particles endows good filler effects to reduce voids in the cement paste and improve the density of the blended cement paste [18]. However, increasing the quantity of POFA added to foamed concrete increased its porosity because the material has a natural tendency to absorb large amounts of water.
3.3. Thermal conductivity

Figure 3 shows the correlation between thermal conductivity and the POFA content of the foamed concretes. Foamed concrete samples with 20%–40% POFA revealed higher thermal conductivities compared with that of the control specimen. LFC-20, -30 and -40 showed thermal conductivities of 0.316 W/mK, 0.313 W/mK and 0.306 W/mK respectively, all of which are higher than that of the control specimen (0.292 W/mK). This phenomenon may be related to the densification of the microstructures of the foamed concrete after POFA addition. The densification of microstructures in foamed concrete specimens is due to the pozzolanic reaction between SiO2 in POFA and Ca(OH)2, which not only enhances the composite strength but also increases its thermal conductivity.

Increasing amounts of POFA slightly reduced the thermal conductivity of the final samples. When 60% POFA was added to the concrete, for example, the thermal conductivity of the sample dropped to 0.196 W/mK, which is lower than that of the control specimen. Figure 4 shows the relationship between thermal conductivity and the compressive strength of the foamed concretes.
4. Fieldwork study

4.1. Model description

Based on the tests conducted on the properties of the foamed concretes, amongst the specimens fabricated, LFC-20 with 20% POFA as a partial cement replacement was the most ideal. Therefore, LFC-20 was chosen to fabricate a block measuring 100 mm × 500 mm × 200 mm. The blocks were installed as a partition wall in a single-storey building with a floor area of 20 m² and height of 3 m. The building is located at the School of Housing, Building and Planning in the main campus of Universiti Sains Malaysia (USM), Penang (5°2ʹN latitude and 100°2ʹE longitude) (Figure 5). The building did not receive any outdoor shade, such as that provided by trees. The building was elongated in the north-eastern and south-eastern parts; this orientation is considered the worst in the tropics because buildings oriented in this manner receive direct solar radiation in the morning and afternoon.

4.2. Description of the building

The building in Figure 5 had a concrete floor slab, plastered block wall (100 mm-thick block finished with 2 mm plaster), a 30° pitched roof (made of a 25 mm-thick concrete composite roof and a ceiling made of plaster boards) and two operable louver windows with dimensions of 1 m × 1 m (Figure 6).
The fieldwork study was conducted to investigate the thermal performance of POFA foamed concrete under actual hot and sunny climatic conditions. This study focused on the indoor air temperature and the indoor and outdoor temperature difference.

4.2. Experimental setup
To measure the indoor air temperature, LSI-LASTEM probes were placed at the level of occupants inside the building (Figure 7a). For outside air temperature measurements, the sensor was placed inside a Stevenson screen to protect it from direct exposure to solar radiation and precipitation (Figure 7b). The data were recorded using an environment data logger (BABUC/A) and subsequently transferred to a computer for analysis. Considering that the building was set in closed conditions, no readings for indoor air movement were obtained. This condition was set as aforementioned so that there are no other factors affecting the measurement of indoor temperature except the POFA block as external wall material.

Figure 7. Setup of the thermal measurement tools for the empirical study

5. Thermal performance of the foamed concrete block
The graph in Figure 8 shows the indoor and outdoor temperatures on the selected days in June 2018. The thermal behaviours of the indoor and outdoor air temperatures were typical for every testing day. The indoor air temperature became warmer than the outdoor temperature at 6.00 pm for all 6 days and remained this way until 8.00 am the next day (±14 hours).

This phenomenon is expected because, during the day, the building material stores heat when exposed to the sun for approximately 8–9 hours. As the sun begins to set, the outdoor air temperature gradually cools. Considering that ventilation was absent in the building, the indoor air temperature lasted for approximately 14 hours. The thermal behaviours of the indoor and outdoor temperatures are similar to previous results [20].

Figure 8. Indoor and outdoor air temperature
The indoor part of the building requires a longer time to reach the maximum temperature compared to the outside of the building. The time lag between the outside and inside of the building to gain the maximum temperature can be calculated using the following equation:

\[ \phi = t_{\text{in(max)}} - t_{\text{out(max)}} \]  

where \( \phi \) is the time lag and \( t_{\text{in(max)}} \) and \( t_{\text{out(max)}} \) are the times of the day when the inside and outside temperatures are at maximum levels.

Calculations revealed that the indoor air temperature requires 1.3 (1st day), 0.9 (2nd day), 1 (3rd day), 1.9 (4th day) and 3 (5th and 6th days) hours to peak. The indoor air temperature was reduced by up to 5.69 °C when the outdoor temperature was 39.1 °C at the hottest time on the 4th day, as shown in Table 4.

| Testing day | Time   | Max. Outdoor Temp. (°C) | Indoor Temp. (°C) | Temp. Difference (°C) |
|-------------|--------|-------------------------|-------------------|-----------------------|
| Day 1       | 3:00 pm| 36.9                    | 32.62             | 4.28                  |
| Day 2       | 4:00 pm| 35                      | 33.36             | 1.64                  |
| Day 3       | 4:00 pm| 34.5                    | 32.98             | 1.52                  |
| Day 4       | 3:00 pm| 39.1                    | 33.41             | 5.69                  |
| Day 5       | 2:00 pm| 36.5                    | 33.32             | 3.18                  |

Simulation software, namely, IES-VE, was used to compare the indoor air temperatures of buildings using POFA foamed concrete blocks, clay brick and normal concrete. The results are presented in Figure 9. During the day, normal concrete yielded the highest indoor air temperatures, followed by the POFA foamed concrete and the red clay brick. However, when the outdoor air temperature decreased at 6.00 pm, the indoor air temperature produced by the POFA foamed concrete blocks became lower than those obtained from the two other materials. This phenomenon can be attributed to the thermal mass characteristics of each material.
The thermal mass of a building material affects the indoor air temperature. Normal concrete, which has a high thermal mass, absorbs heat from solar radiation at a slow rate and is very effective in countering rapid heat transfer; however, normal concrete also requires some time to release heat. Red clay brick, which is also categorised as a high-thermal-mass material, has insulation ability and can absorb and release heat slowly. However, the utilisation of clay brick as a wall material is not usually recommended. Excessive digging for clay leads to soil depletion and, eventually, land degradation and environmental pollution [21,22]. POFA foamed concrete blocks feature a low thermal mass and can absorb and release heat faster than clay brick does because of its low density and porous structure.

In this study, the average indoor air temperature of the building with POFA foamed concrete blocks was 29.11 °C, which is lower than those of buildings with red clay brick (29.12 °C) and normal concrete (30.33 °C).

6. Conclusions
This study revealed that addition of 20% POFA as a cement replacement to foamed concrete yields an ideal concrete mixture. This mixture had a maximum strength of 3.21 MPa and minimum porosity of 15.4%, which is lower than that of the control specimen. The utilisation of POFA foamed concrete blocks as a wall partition material lowers the indoor air temperature compared with the outdoor air temperature for approximately 10 hours a day, starting from 8:00 am until 6:00 pm. The temperature was reduced by up to 5.69 °C at the peak outdoor temperature on the hottest testing day. POFA foamed concrete blocks also produced the lowest mean indoor air temperatures compared with those achieved by red clay brick and normal concrete. Considering the ability of POFA foamed concrete blocks to reduce indoor air temperatures, it can indirectly reduce energy consumption by minimising the need for air conditioning systems.

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