Replacing Cement with POFA to Improve the Thermal Properties of Lightweight Foamed Concrete

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Abstract. The construction industry highly relies on the utilization of cement as the main binder material in concrete production. It is inevitable even though the cement manufacturing process responsible for the high energy consumption and the worldwide carbon dioxide (CO2) emission. One of the promising solutions is the application of lightweight foamed concrete in building construction that might be able to reduce the dead load of building, hence, shrink the foundation size and leads to minimize the cement demand and construction cost. Moreover, the long-term application of lightweight foamed concrete also contributes to the reduction of energy consumed by air conditioning system in order to achieve thermal comfort for occupants due to its excellent thermal insulation. To produce a decreased density for acceptable strength level, this study investigated the potential of palm oil fuel ash (POFA) to partially replace cement content at the levels of up to 60% in foamed concrete having a density of 900 kg/m3. At the 28-days curing age, foamed concrete with 20% POFA reveals a much higher compressive strength than the control specimen but still having an acceptable thermal conductivity value. The pozzolanic characteristic of POFA is believed in improving the applicable lightweight foamed concrete properties.

1. Introduction
The growth of population and human activities increases building demand which gives a huge contribution to the world global warming and climate change related to the issues of energy consumption and carbon dioxide (CO2) emission [1]. A tropical country like Malaysia which experiencing the warm and humid climate condition throughout the year facing the high intensity of solar radiation and high air temperature which affect the increasing indoor air temperature of a building [2]. This current situation leads people to rely on the cooling system to satisfy their thermal comfort. For cooling the indoor environment, Malaysian building consumed around 30-60% of the total energy used [3].

Moreover, the application of unsuitable building materials like concrete might be able to reduce indoor thermal comfort due to its high thermal conductivity. Concrete has an ability to absorb and keep the heat until transmitted through the building envelope into the building. The usage of the concrete based building also contributes to the embodied energy consumption and CO2 emission during cement production, increasing greenhouse gas at the atmosphere, hence, lead to the thicker thermal blanket and makes the environment heater [1]. This situation then increases people using air conditioning. To overcome the problem, architects and designers should consider the building envelope design and material used as the boundary of the thermodynamic system.

Utilization of lightweight foamed concrete is believed as one of the passive systems in improving the indoor thermal environment. Since the 1920s, foamed concrete has been used around the world. Even though the compressive strength is not high but foamed concrete still can be used in particular application [4]. Foamed concrete is a mixture of mortar and the stable foam, having advantages in high
flow-ability, low self-weight, minimal aggregate consumption and excellent thermal insulation properties [5]. In order to reduce cement content and improving the properties of foamed concrete, the use of agricultural waste materials is intensively studied currently. One of the industrial by-products that have a potential to be used as cement replacement is palm oil fuel ash (POFA).

POFA is a by-product obtained from the combustion of palm oil biomass including palm oil fiber and kernel shell as an alternative fuel to generate electricity in palm oil mill. The incineration of biomass produces 5% POFA by the weight of the solid waste [6], which usually disposed of around the mill. The uncontrolled disposal method was considered affecting environmental deterioration [7].

Utilization POFA as cement replacement material in concrete production has been studied by researchers since 1990s in normal concrete [8][9][10][11], high strength concrete [6][12][13][14][15], aerated concrete [16][17] and lightweight concrete including foamed concrete [18][19]. However, the application of POFA to replace cement in foamed concrete is still lacking.

In this study, the foamed concrete was cast having a density of 900 kg/m³ with cement to sand ratio of 1:1.5. POFA was used to partially replace cement in the replacement level varied of 20%, 30%, 40%, 50% and 60%. The potential of POFA as cement replacement and the characteristics of lightweight foamed concrete including mechanical and thermal properties are discussed in this paper.

2. Experimental process

2.1. Materials
The concrete mixtures produced by using two types binder material namely Portland composite cement which manufactured by YTL Cement as the main binder material and POFA collected from a palm oil mill in Penang, Malaysia. After taken from the mill, POFA undergo a series of processes before being used as the supplementary binder. As the fine aggregate, the river sand was dried to remove the moisture content and sieved until passing through a 600 µm sieve (figure-1) with a fineness modulus and specific gravity of 1.35 and 2.74, respectively. Stable foam with the density of 65kg/m³ was produced using a protein-based foaming agent which was diluted with the ratio of 1:30 and then aerated using a portafom machine before was then entrained into the slurry. To improve the workability and strength of foamed concrete, 1% polycarboxylate based superplasticiser and 5% silica fume were added by the weight of the binder.

2.2. POFA processing treatment and its characterization
The POFA collected from palm oil mill is a by-product of the third stage burning process of biomass which is burned at the temperature exceeding 1000°C. The high burning temperature can remove the POFA’s unburned carbon, which leads to the low percentage of LOI. After collected, the raw POFA was dried in the oven at the temperature of 105±5°C for 24h to remove the moisture content. The dried POFA was then sieved until passing 300µm sieve to discard the bigger particle and the remaining

![Figure-1: Fine sand grading curve](image-url)
unburned carbon content before being ground using ball mill machine to produce finer ashes. After undergoing the treatment process, the ground POFA having the median particle size \((d_{50})\) and specific gravity of 4.03µm and 2.47, respectively, smaller than cement (Table-1).

The chemical composition of cement and POFA was determined using XRF test as shown in Table-2. The results exhibit that the major chemical composition of POFA is silicon dioxide \((\text{SiO}_2)\) of 54.93\%, while the higher chemical composition of cement is calcium oxide \((\text{CaO})\). The total amount of \text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 of POFA is 62.16\% with 5.66\% LOI, which indicates that POFA can be classified as between class C and class F pozzolana. From the XRD pattern, it is shown that the \(\alpha\)-Quartz \((\text{SiO}_2)\) is the major crystalline phase of POFA (figure-2).

### Table-1: Physical properties of cement and POFA

| Materials | Median particle size \((d_{50})\) | Specific gravity |
|-----------|----------------------------------|-----------------|
| Cement    | 4.29                             | 3.01            |
| POFA      | 4.03                             | 2.47            |

### Table-2: Oxides composition of binder materials

| Oxides    | \text{SiO}_2 | \text{Al}_2\text{O}_3 | \text{Fe}_2\text{O}_3 | \text{CaO} | \text{MgO} | \text{SO}_3 | \text{Na}_2\text{O} | \text{K}_2\text{O} | \text{P}_2\text{O}_5 | SUM* | LOI |
|-----------|--------------|-----------------------|-----------------------|-----------|-----------|----------|------------------|----------------|----------------|-------|-----|
| Cement (\%) | 14.84       | 3.64                  | 2.44                  | 56.09     | 1.52      | 2.65     | 0.57            | 0.06           | -              | -     | -   |
| POFA (\%)  | 54.93       | 3.27                  | 3.96                  | 10.77     | 5.02      | 4.09     | 9.50            | 5.64           | 62.16         | 5.66  | -   |

* \text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3

** Below the limit of detection tools

![Figure-2: XRD patterns of POFA](image)

2.3. Mix proportion

Six concrete mixes having the same target density of 900kg/m\(^3\) and cement to sand ratio of 1:1.5 which the control mix was 100\% cement and five mixtures with different proportion of POFA were investigated in this research. POFA was used to replace cement content at the replacement level between 20 to 60\% by the weight of the binders. table-3 presents the mixture proportion of POFA foamed concrete.

### Table-3: Mixture Proportion

| Materials (kg/m\(^3\)) | C100 | LFC-20 | LFC-30 | LFC-40 | LFC-50 | LFC-60 |
|-------------------------|------|--------|--------|--------|--------|--------|
| Cement                  | 338.57 | 270.85 | 237.00 | 203.14 | 169.28 | 135.43 |
| POFA                    | 0    | 67.71  | 101.57 | 135.43 | 169.28 | 203.14 |
| Sand                    | 507.85 | 507.85 | 507.85 | 507.85 | 507.85 | 507.85 |
| Water                   | 192.17 | 158.13 | 159.66 | 161.59 | 171.59 | 284.51 |
| Foam                    | 0.066 | 0.064  | 0.063  | 0.061  | 0.060  | 0.054  |
| Silica Fume             | 16.93 | 16.93  | 16.93  | 16.93  | 16.93  | 16.93  |
| Superplasticiser        | 3.39  | 3.39   | 3.39   | 3.39   | 3.39   | 3.39   |
2.4. Casting, curing and testing procedure

The concrete mixes were produced with a laboratory mixer where all the dry materials including cement, POFA, sand and silica fume were blended together before water and superplasticiser were poured gradually into the mixer to get homogenous slurry. The workability test was conducted to investigate whether the spread reaches the required value, hence, additional water might be needed. After the stable foam was added and the target wet density was obtained, the specimens were cast in moulds and were not subjected to any compaction. The specimens were kept for 24 hours until demoulded and wrapped with plastic cling to prevent excessive loss of moisture from the concrete.

For each group, total of 15 samples of cubes specimens with the dimension of 100mm were prepared for the compressive strength test. The cylinder specimens with 50mm in height and 45mm in diameter were cast for porosity test. The testing procedures were conducted at the age of 7, 14, 28, 56 and 90 days. The result was the average of three specimens of every testing day. Small samples with the size of 30mm × 30mm and 15mm thickness were prepared from one sample of 28-days curing age to be used for thermal conductivity test.

3. Results and discussions

3.1. Workability

Workability of fresh concrete was represented by the correlation between the spread value achieved and water/solid (w/s) ratio when concrete was mixed before the stable foam added (Table-4). The control specimen with 100% cement content achieved the spread value of 180mm with w/s ratio of 0.227. When POFA replaced 20% cement content, the workability increases 22% than the control, even though the w/s ratio reduces to 0.187. This result can be attributed to the success of additional 1% superplasticiser that acted as the water reducer, hence, with the lower w/s ratio, the workability can still achieve. However, as the POFA replacing level increased, the workability of foamed concrete decreased. Concrete with up to 50% POFA reach the same spread value of 220mm but w/s ratio increases to 0.203. The increasing w/s ratio is because of the high porosity of POFA particle which tent to absorb more water, thus resulting in high water demand.

In the terms of foam quantity, increasing POFA replacement level in foamed concrete mixture reduces the amount of foam required. The amount of stable foam reduced from 0.066m³ for the control mix to 0.054m³ for foamed concrete containing 60% POFA. The reducing amount of foam is believed due to the lower specific gravity of POFA compared to cement which able to detract the actual mortar density, hence, demanded a lower amount of foam to achieve the targeted plastic density.

| Materials (kg/m³) | C100 | LFC-20 | LFC-30 | LFC-40 | LFC-50 | LFC-60 |
|------------------|------|--------|--------|--------|--------|--------|
| Spread (mm)      | 180  | 220    | 220    | 220    | 220    | 165    |
| w/s ratio*       | 0.227| 0.187  | 0.189  | 0.191  | 0.203  | 0.294  |

*water to solid ratio

3.2. Compressive strength

Table-5 shows the compressive strength of foamed concrete with POFA replacing level for the testing age between 7 days up to 90 days curing ages. Referring to the result, it can be seen that the compressive strength increases by the ages but decreases with the increasing POFA replacement level beyond 20%. Foamed concrete with up to 50% POFA obtained a higher compressive strength than the control specimen, where LFC-20 obtained the highest compressive strength of all mixtures of 3.21MPa (figure-3).

The pozzolanic reaction between calcium hydroxide (Ca(OH)₂) from cement hydration process and the silicon dioxide (SiO₂) in POFA is believed in producing more calcium silicate hydrate (C-S-H), which able to make the foamed concrete denser, hence give a higher compressive strength. Moreover, additional 5% silica fume in the mixtures also contributes to the stronger and denser foamed concrete. The fine particle size of silica fume is able to fill the water-filled pocket between cement particles [20].
The finer particles allow denser transition zone within cement paste and aggregates, improving the concrete microstructure and properties. Generally, the pozzolanic effect occurred not only due to the pozzolanic reaction but also the filler effect of the finer particle [21]. LFC-60 obtained the lowest strength of all the mixtures, which only gained 0.61MPa at 28 days of curing age. This might be caused by the increased water/solid ratio during mixing. The more POFA added, the more water required even though superplasticiser had been added, due to the natural behaviour of POFA in absorbing water.

| Mix   | % of POFA | Compressive strength (MPa) |
|-------|-----------|----------------------------|
|       |           | 7 days | 14 days | 28 days | 56 days | 90 days |
| C100  | 0         | 0.91   | 0.97   | 1.33    | 1.37    | 1.39    |
| LFC-20| 20        | 2.31   | 2.99   | 3.21    | 3.29    | 3.32    |
| LFC-30| 30        | 2.07   | 2.18   | 2.30    | 2.41    | 2.67    |
| LFC-40| 40        | 1.66   | 1.82   | 2.14    | 2.22    | 2.29    |
| LFC-50| 50        | 1.14   | 1.25   | 1.38    | 1.59    | 1.63    |
| LFC-60| 60        | 0.54   | 0.57   | 0.61    | 0.66    | 0.68    |

Figure-3: Compressive strength of foamed concrete incorporated POFA

3.3. Water absorption
Figure-4 shows the water absorption of foamed concrete containing up to 60% POFA at the curing age between 7 to 90 days. Replacing cement content with POFA tends to increase water absorption of foamed concrete proportionately, except for the LFC-20. Additional POFA beyond 30% in foamed concrete having more capability to absorb water compared to the control specimen. Water absorption reading of LFC-30, LFC-40, LFC-50 and LFC-60 were 22.48%, 27.96%, 31.66% and 46.88%, respectively. The values were higher than C100 which only gained 8.63%. The porous nature of POFA particle has the tendency to absorb water when submerged.
3.4. Porosity

The result reveals that foamed concrete with 100% cement obtained a higher percentage of porosity than that of the foamed concrete incorporated POFA (figure-5). Over time, porosity value was reduced but increase proportionally with increasing POFA replacement level. The reduction porosity during the curing ages is believed due to the C-S-H formed from the pozzolanic reaction between SiO₂ and Ca(OH)₂ which makes concrete denser. However, the increasing porosity by increasing percentage of POFA was occurred because of the natural behaviour of POFA particle which tends to absorb water.

3.5. Thermal conductivity

Table-6 shows that the thermal conductivity of foamed concrete incorporated POFA up to 50% achieved higher readings than control specimen with 100% cement. This happened related to the densification of microstructures of foamed concrete when POFA was added. The densification might be happened due to the pozzolanic reaction which enhanced the compressive strength and also increases its thermal conductivity. However, the increasing amount of POFA slightly reduces thermal conductivity as the reduction of densification which also affecting the reduction of strength. Eventually, when POFA was added at the level of 60%, thermal conductivity drops to 0.196 W/mK, lower than control specimen, which obtained 0.292 W/mK.

In this study, an anomaly trend result was gained by LFC-50 which having the highest thermal conductivity. This increasing result is believed due to the technical error while testing was conducted.
The random selection of specimen picked up a perforated sample which then affecting the heat source directly penetrated to the heat sensor or only passed through a thin layer of the specimen.

Table-6: 28-day thermal conductivity of foamed concrete

| Mix     | % of POFA | Thermal conductivity (W/mK) |
|---------|-----------|----------------------------|
| C100    | 0         | 0.292                      |
| LFC-20  | 20        | 0.316                      |
| LFC-30  | 30        | 0.313                      |
| LFC-40  | 40        | 0.306                      |
| LFC-50  | 50        | 0.320                      |
| LFC-60  | 60        | 0.196                      |

4. Conclusion

- This study revealed that foamed concrete incorporated up to 50% POFA as cement replacement obtained better strength than that of LFC with 100% cement.
- Foamed concrete containing 20% POFA obtained the highest compressive strength of 3.21 MPa, lowest porosity of 47.67% and gained thermal conductivity of 0.316 W/mK, a slightly higher than that of the control specimen which achieved 0.292 W/mK.
- The denser the concrete, the higher compressive strength and linearly and the higher thermal conductivity value.
- The increasing POFA replacement level might be able to reduce the properties of foamed concrete. Eventually, replacing cement with POFA beyond 50% tend to weaken the foamed concrete.

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