Study on Mechanical Properties of Foamed Concrete Incorporating Palm Oil Fuel Ash and Mussel Shell as Partial Cement Replacement

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Abstract. Concept of sustainable construction has gradually become one of the concern issues in our construction industry in recent years. Concrete which acts as an important construction material has contributed to excessive consumption of natural resources. Simultaneously, tonnes of waste materials were produced from agricultural activity in form of palm oil fuel ash (POFA) while mussel shell from marine hatchery. Utilization of agricultural waste as cement replacement is an option to reduce the environmental impact from the construction industry. In this study, these waste materials were used as partial cement replacement to produce foamed concrete in wet density of 1800 kg/m³. The main purpose of this research is to study the workability and mechanical properties of foamed concrete which contain uniform 20% of POFA combined with 5% to 10% of mussel shell powder (MSP) and mussel shell ash (MSA) respectively. The cube specimens were cast in dimension 100 mm x 100 mm x100 mm to test the compressive strength at 7th and 28th. The cylinder specimens were cast in 100 mm diameter x 200 mm diameter for split tensile test to determine the tensile strength and compression test to determine modulus of elasticity at 28th day. The result showed workability of foamed concrete decreased as more cement was replaced by POFA combined with MSP and MSA. Foamed concrete mixture with 20% POFA and 5% MSP was selected as optimum percentage of cement replacement due to reduction less than 5% compromised performance in compressive strength at 16.52MPa while tensile strength at 1.83MPa.

1. Introduction
Foamed concrete is a type of lightweight concrete with different physical and mechanical properties compares to normal concrete. Foamed concrete can be designed ranging from 300 – 1850 kg/m³ as compared to normal concrete at 2400 kg/m³ [1]. The foamed concrete which also known as cellular concrete without coarse aggregates was created by void in form of small bubble that utilize air molecules [2]. Advantages of foamed concrete in construction works due to its lightweight density, fire resistance, thermal conductivity and acoustical properties [3]. Due to the presence of air bubbles and micro-structural cells in the concrete which make it porous in nature, the foamed concrete had shown unexpectedly good thermal insulation and sound absorbance [4]. The amount of waste produced by humans are increased significantly and many researchers integrated the waste materials into construction materials technology. Improvement in term of raw materials, manufacturing process, packaging and transportation are necessary to minimize environmental hazards of cement products that may help optimize reserved natural resources.
Meanwhile, palm oil fuel ash (POFA) and seashell are among those waste materials that can be used as partial cement replacement in the concrete production. These waste materials have caused land and air pollution and will become a threat for human life. In this project, combination of POFA and mussel shell were used as partial cement replacement in foamed concrete to determine the workability and mechanical properties of foamed concrete. POFA contains silica oxide content while mussel shell has high calcium oxide (CaO) content to be utilized as cement replacement materials. The silica oxide content in POFA will react with calcium hydroxide (Ca(OH)\textsubscript{2}) from the hydration process which was deteriorated to concrete and the pozzolanic reactions produce more calcium silicate hydrate (C-S-H) which was a gel compound which reduce the amount of calcium hydroxide. This property helped to produce stronger and denser concrete as well as enhanced the durability of concrete [5].

2. Materials

2.1. Fine Aggregate
Natural river sand accordance to the standards BS EN 12620 was used as fine aggregate. Fine aggregate was sieved passing 5mm mesh and clear from contaminant. The collected sand was stored damp area without free standing water to ensure materials kept in saturated surface dry condition.

2.2. Palm oil fuel ash (POFA)
Palm oil fuel ash was produced by burning of palm oil shell and husk in palm oil mill at 800 to 1000°C in order to use the steam produced to generate electricity in biomass thermal power plants [6]. There were two main physical properties of POFA which are specific gravity and grain size distribution. These two parameters were related with the fineness of POFA which affected the performance of concrete. Specific gravity of POFA was varying which depends on few factors such as treatment process and burning temperature, but according to many researchers, the specific gravity of POFA never exceeded 3.0.

Study conducted by Sata et al. [7] highlight that when the POFA particles size was finer, the specific gravity of POFA increased up to 2.78 due the reduction of porosity. In general, POFA had the median particle size range from 30.80 to 62.5μm with 34.80 to 70.00% by weight retained on a 45μm sieve [8]. The fineness of POFA can affect the pozzolanic nature of material and hydration rate. The pozzolanic reactivity increased due to the increase in fineness of POFA after the grinding process [9].

Table 1 shown the physical properties of POFA in Malaysia.

| Physical Properties | Central | North | South |
|---------------------|---------|-------|-------|
| Specific gravity    | 2.48    | 2.42-2.56 | 2.22-2.42 |
| % Passing through 45 μm sieve (%) | 95.0 | N.A | 90.00-95.02 |

POFA has been used as supplementary cementitious materials (SCM) by previous researchers [12-16] to determine POFA can be used to replace cement in concrete without affecting the strength of concrete produced. From the study of Awal et al [17], the researchers had observed that the compressive strength of concrete that contains 20% POFA was almost same with OPC concrete. According to study of Alhadooh et. al [18] which had used POFA as pozzolan in concrete with 10% to 50% of POFA, the results shown that the concrete mixture with 20% of POFA replacement had achieve the highest compressive strength of 35 MPa at the 28-days of curing process. In terms of workability, the study of Foti & Cavallo [19] stated that increase in percentage of POFA in concrete mixture had lowered the workability and decreased the slump value. On the other hand, the research of Mo et. al [20] had concluded that the using of ultra-fine POFA particles will increased the workability of concrete. Ultra-fine POFA had low carbon content and concrete which containing unburned carbon had caused decrease in workability.
2.3. Mussel shell
Mussel shell (bivalve mollusk) was one type of seashell which have triangular shape and elongates with round edges. Commercial fisheries industry in Malaysia had recorded more than 50 thousand tonnes metric of seashell class of seafood so does the waste produced. Shellfish farming had becoming one of the world’s fastest food sector and it had increased sharply going from 1 million tonnes in 1950 to about 14.6 million tonnes in 2010 [21]. The chemical composition of seashell contained higher than 90% of calcium carbonate (CaCO₃) by weight and this composition was similar to limestone powder which use to produce Portland-limestone cement (PLC).

Two physical properties, specific gravity and grain size distribution of any SCM are important as these have significant influence on the properties of concrete. According to the study of Skariah et. Al [22], the specific gravity of mussel shell powder was 2.86 with generic value does not exceed 3.0. Mussel shell primarily comprises CaCO₃ which means its specific gravity was closer with calcium carbonate. The mussel shell powder was obtained after crushing and grinding and the size of powder was varied as this depends on the grinding process. The average particle size of mussel shell powder was 29.87 μm and its Blaine surface area was determined as being 6186 cm²/g. According to Momeen et al. [23], the split tensile strength and modulus of elasticity (MOE) reduced in the range of 10 to 30% when seashell powder was added into the mixture at high portion. Previous study of Olivia et al. [24] shown by replacing 2, 4, 6 and 8% of seashell powder, tensile strength of concrete composed of OPC and seashell powder was higher than the normal concrete.

In this study, mussel shell was cleaned from residual organic then pulverised into small particles. Processed mussel shell was diversified into two forms which are mussel shell powder (MSP) that not subjected to heat treatment while mussel shell ash (MSA) was burned at 1000 °C for 1 hour in furnace.

2.4. Foaming agent
Foaming agent was prepared with water in the foam generator. Foaming agent Sika AER-50/50 used in the study with dilution ratio 1:20. The foam created microbubbles thus allowing air entrained subsequently reducing the density of concrete. Pre-foaming method as shown in figure 1 was produced stable foam before mixed with mortar to produce foamed concrete.

![Figure 1. Pre-foaming method using foaming generator.](image)

3. Methodology

3.1. Mix proportions
Design mixture is the calculation process to determine the right quantities of each raw materials to achieve desired properties. In this study, design for the foamed concrete materials calculation was referring to previous equation proposed by Kearsley et al. [25] as in equation 1.
Where;

\[ p_m = x (\frac{W}{c}) \times x (\frac{V}{c}) \times RD_f \times V_f \]  

(1)

\( p_m \) = target casting density, kg/m\(^3\)
\( x \) = cement content, kg
\( w/c \) = water/cement ratio
\( s/c \) = sand/cement ratio
\( RD_f \) = Relative density of foaming agent
\( V_f \) = volume of foam, m\(^3\)

Meanwhile, the foamed concrete wet density was selected at 1800 kg/m\(^3\) with controlled water/cement ratio at 0.50 respectively and fine aggregate content used twice quantity of cement. Table 2 summarized type of foamed concrete mix with respect to percentage of partial cement replacement.

| Types of concrete mixes (%) | Specific dimension |
|-----------------------------|-------------------|
|                             | Cube (Compressive) | Cylinder (Split tensile) | Cylinder (Modulus of elasticity) |
|                             | 100mm x 100mm x 100mm | 100mm dia. x 200mm height | 100mm dia. x 200mm height |
| Control                     | 6 nos.             | 3 nos.                    | 3 nos.                      |
| 20 POFA                     | 6 nos.             | 3 nos.                    | 3 nos.                      |
| 20 POFA + 5 MSP             | 6 nos.             | 3 nos.                    | 3 nos.                      |
| 20 POFA + 5 MSA             | 6 nos.             | 3 nos.                    | 3 nos.                      |
| 20 POFA + 10 MSP            | 6 nos.             | 3 nos.                    | 3 nos.                      |
| 20 POFA + 10 MSA            | 6 nos.             | 3 nos.                    | 3 nos.                      |

Foamed concrete mixture were fixed with 20% POFA and varies percentages of mussel shell type at 5% and 10% respectively. Specimens consists of cube with dimension 100mm x 100mm x 100mm for compressive strength test while cylinder with dimension 100 mm diameter x 200 mm height for split tensile strength test and modulus of elasticity.

3.2. Fabrication

Raw materials were dry mixed in a rotary mixer for 5 minutes to ensure consistency between each matrix and binder. Next, potable water was added into the dry materials and mixed for 1 minute. Specific volume of foam was measured and added into the wet mixture until uniform consistency with density of 1800 kg/m\(^3\) achieved. Finally, the fresh foamed concrete was ready to be poured into the mould. J-ring test with aided of a slump cone was carried out to determine workability of foamed concrete in accordance to ASTM C1621. Foamed concrete specimens were left for air curing with curing periods of 7 days and 28 days.

4. Result

4.1. Specific gravity

The physical properties of POFA and MSA were examined in the specific gravity test using Le Chatelier flask method. The density of POFA, MSP and MSA compared with ordinary Portland cement. The testing conducted according to the standard of specification BS 4550-3.4:1978 Standard Test Method for Density of Cement. Specific gravity of material is tabulated in table 3.
Table 3. Specific gravity of OPC, POFA, MSP and MSA.

| Material | Specific gravity |
|----------|-----------------|
| OPC      | 3.16            |
| POFA     | 1.96            |
| MSP      | 2.59            |
| MSA      | 2.54            |

Based on the result, OPC had the highest specific gravity value at 3.16 which in normal range between 3.0 and 3.20. POFA had the lowest specific gravity value at 1.96. This was associated to the fine size of POFA particles. Previous studies by [26] highlighted the value of specific gravity directly influenced by grinding process to increase contact surface area. Next, specific gravity value of MSP which is 2.59 and MSA 2.54. Heat treatment process on mussel shell particle slightly lower the specific gravity values by eliminating organic materials subjected to high temperature.

4.2. Grain size distribution

Figure 2 shows distribution of particles analysis OPC, POFA, MSP and MSA. Based on the result, POFA was observed has highest fineness percentage with D60 value 7.89µm. MSP shows better size distribution with recorded lowest 10.55µm and largest D60 value at 36.19µm. Value of D10, D30 and D60 of MSA were largest which were 10.55µm, 25.35µm and 36.19µm respectively.

4.3. Workability

Testing on workability of foamed concrete was conducted using J-ring flow test assisted by inverted slump cone. Based on the result in table 4, control sample had the highest workability which flow and spread fluently without any visible blocking. The J-ring flow value decreased as more cement was replaced by POFA and MSP and the variation of flow with respected on control sample was ranged between 14 to 16%. Addition of cement replacement materials mainly from POFA absorbs the water surrounding grain particles. The porous nature of POFA particles had led to high water demand and thus decreasing the concrete workability [27]. Combination of POFA and MSP reduced the flow to 372.5mm and 367.5mm as compared to control specimen of flow 435mm. On the other hand, mixture of POFA and MSA have resulted 375mm and 370mm which are slightly better than unburned mussel shell. Workability decreased as flow decreased due to the lower specific gravity and higher porosity of POFA and MSA as compared to OPC. The increased in porosity absorbed more water in the production of foamed concrete mix.
Table 4. Workability result of fresh foamed concrete.

| Mix Proportion | J-ring Flow (mm) | Variation of flow with respected on control sample (%) |
|----------------|------------------|-------------------------------------------------------|
| Control        | 435              | -                                                     |
| 20% POFA + 0% MSP | 377.5           | -14.1                                                 |
| 20% POFA + 5% MSP | 372.5           | -15.4                                                 |
| 20% POFA + 5% MSA | 375            | -14.8                                                 |
| 20% POFA + 10% MSP | 367.5           | -16.8                                                 |
| 20% POFA + 10% MSA | 370             | -16.1                                                 |

4.4. Compressive strength

General trend of decline can be observed in figure 3 when percentage of cement replacement materials increases. Foamed concrete specimens with combination of POFA+MSP and POFA+MSA show strength reduction to 10% than control mix. At 7\textsuperscript{th} day, mixture with 20POFA+5MSA has the highest compressive strength compared to other two mix proportion at 15.57 MPa which 3%% less than the control. Foamed concrete with 20POFA+10MSP had the lowest compressive strength at 14.74 MPa. However, the presence of MSP and MSA combined with POFA in foamed concrete shows potential in early development in compressive strength. due to high amount of silica dioxide (SiO\textsubscript{2}) in POFA and MSA which enhanced the pozzolanic reaction in concrete mix. Besides, MSA contains high amount of calcium oxide (CaO) which reduced the time of hydration process leading to reduction of strength at early age. Presence of mussel shell as calcium oxide contributed in tricalcium silicate (C\textsubscript{3}S) which is responsible for early strength development in cement matrix as a result of the increased lime content [28]

Figure 3. Compressive strength with various mix.

In term of 28 days compressive strength, mixture 20POFA+5MSA has the highest value at 16.52 MPa which 2% reduction than control. Heat treatment MSA provided better pozzolanic reactivity when combined with POFA as partial cement replacement. POFA, higher compressive strength was obtained in the long term, due to their pozzolanic reaction. Compressive strength reduction was observed in foamed concrete mixture 20POFA+10MSP and 20POFA+10MSA respectively. This result agrees with previous experimental studies conducted by other researchers [29,30] that partial cement materials up to 30% can reduce up to 20% the compressive strength of the concrete. This is mostly due to the high water absorption from cement replacement materials which distorted hydration process during C-S-H formation.
4.5. Split tensile strength

Split tensile test of foamed concrete specimen was conducted to determine the effect on tensile strength of POFA combined with MSP and MSA. Based on figure 4, similar trend of strength reduction was observed when the percentage of cement replacement increases. Optimum percentage was shown in mixture of 20POFA+5MSA at 1.83MPa with negligible difference as compared to control specimen. Similar tensile strength was also recorded with mixture 20POFA which suggest presence of 5% MSA will produce similar performance without reducing tensile capability of foamed concrete. However, both foamed concrete mixture at 20POFA+10MSP and 20POFA+10MSA show strength reduction to 11%. Foamed concrete mixture at 20POFA+10MSP has the lowest tensile strength at 1.65MPa. Variance of strength result was observed between two different types of mussel shell preparation. Unburned mussel shell contained residual organic materials originally attached to the prismatic layer that influence hydration process in foamed concrete.

![Figure 4. Split tensile strength with various mix.](image)

Additionally, high percentage of cement replacement materials distorted bonding at the interface between binder paste and fine aggregates which produce lower tensile strength concrete. Incorporation of POFA was not effective in improving the interfacial zone between aggregate and cement particle [31]. POFA combined with MSP and MSA mixes were observed not provide additional tensile strength but optimum proportion between both cement replacement materials can be considered with acceptable split tensile strength reduction.

4.6. Modulus of elasticity

Modulus of elasticity are the main mechanical properties will contribute to the flexural and shear stiffness of masonry structures. Data were obtained from the compression test of cylinder specimen with attached strain gauges were analyzed using stress-strain curve. Effect on modulus of elasticity due to combination of POFA with MSP and MSA as partial cement replacement in foamed concrete mixtures are shown figure 5.
Figure 5. Modulus of elasticity with various mix.

Based on the result, it was observed that foamed concrete with 20%POFA show less variance in term of modulus of elasticity when combined with 5% of MSA and MSP respectively. The trend of reduction in was similar within 8% which indicates addition of mussel shell materials as partial cement replacement will not enhance stiffness of foamed concrete specimen. Further reduction in modulus of elasticity was shown when the total percentage of cement replacement at 30% with value recorded at 18% lower than control specimen.

Previous researcher Lim et al. [32] highlighted cement replacement materials in foamed concrete simultaneously reduced their stiffness due to higher ductility than OPC. As the percentages of POFA and MSA increases, high water absorption from the fine particles disrupts reaction of C-S-H gel resulting lesser cylinder compressive strength which subsequently further reducing modulus of elasticity than normal foamed concrete.

5. Conclusion

This paper utilize combined matter on workability and mechanical properties of foamed concrete incorporating POFA combine with MSP and MSA. The combination of 20% POFA with 5% MSA shows potential as sustainable materials to be implemented as partial cement replacement in construction sector. Based on the data acquired, the findings of this study are summarized as follows:

i. Specific gravity of POFA has the lowest values which correspond to grain size distribution highest fineness percentage with D60 value 7.89µm.

ii. Workability of foamed concrete significantly reduced to 370mm for 20POFA+ 10MSA while 367.5mm for 20POFA+10MSP compared to control at 435mm. High water absorption from cement replacement materials directly lower the flow ability in foamed concrete.

iii. The compressive strength of foamed concrete mixture was reduced when the percentage of cement replacement increases. Presence of MSA combine with POFA has significance in term of early strength development. Mixture 20POFA+5MSA has potential due to slight compressive strength reduction as compared to control.

iv. Variance of strength result was observed between two different types of mussel shell preparation. Optimum percentage was shown in mixture of 20POFA+5MSA at 1.83MPa.

v. Reduction in modulus of elasticity was shown 18% lower than control specimen when the total percentage of cement replacement at 30%. Higher ductility from of foamed concrete resulting less stiffness produced by the binder materials.
6. References

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