Absorption and strength properties of lightweight foamed concrete with egg shell powder as partial replacement material of cement

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Abstract. Around 85 thousand tonnes of egg shell waste were yield in Malaysia at 2017, and when its utilization rate is low and not treated and disposed properly, it might result in environmental problem. By partially replacing cement with egg shell powder, the waste can be reduced and meanwhile reduce cement production that results in depletion of natural limestone and emission of carbon dioxide. Therefore, this study was carried out by aiming to mitigate the environmental issue by reducing eggshell wastes and pure cement production, and meanwhile, to promote the application of lightweight foamed concrete. The objective of this study is to investigate the effects on spread diameter, stability water absorption, initial surface absorption, sorptivity, and compressive strength of lightweight foamed concrete with fresh and hardened density of 1000 ± 50 kg/m³ and 1400 ± 50 kg/m³ when the cement is partially replaced by egg shell powder at replacement levels of 0%, 2.5%, 5%, 7.5%, and 10% by mass. The results showed that with incorporation of egg shell powder at all levels, the water absorption, initial surface absorption, sorptivity were improved, but spread diameter was reduced. Besides, stability of foam and compressive strength were improved in overall at replacement level of up to 7.5%. Therefore, it is feasible to use up to 7.5% egg shell powder as partial cement replacement material.

1. Introduction
This study focuses on absorption properties namely water absorption, initial surface absorption (ISAT), and sorptivity of 1000 kg/m³ and 1400 kg/m³ medium density lightweight foamed concrete (LFC) that contain egg shell powder (ESP) as partial replacement material of cement; however, other properties such as spread diameter, stability, and compressive strength were also evaluated.

LFC is generally mixture of base mix mortar and stable foam, that can be applied widely and have numerous advantages due to its low density and good thermal and sound insulation properties, and many researchers have studied its engineering properties in detail [1-9]. However, application of LFC is still considered unpopular in Malaysia.

Durability of concrete is mainly dependent on the permeability of concrete, which is capacity of fluid to penetrate and flow through the concrete, and it depends on volume and size of interconnected pores [10]. Also, sorptivity has recently been recognized as an important index of concrete durability [11]. And it was reported that higher surface water absorption represents lower compressive strength, high permeability, and low resistance to sulphate attack at linear correlation, and represents higher chloride ion diffusion at exponent correlation whereas chloride ion diffusion increased at decreasing rate [10].

Penetration of moisture to LFC and its consequences have also attracted increasing attention, and it was found that the compressive strength of 550kg/m³ LFC is decreased linearly with increased...
moisture content, whereas every 10% of moisture content increment in volume, the compressive strength is reduced by 5.9% [2].

Egg shell (ES) contains up to 94% of calcium carbonate [12-13], and it was reported that calcium carbonate will act as inert filler to decrease porosity and increase strength of concrete [14]. It was also reported that calcium carbonate can accelerate the hydration of tricalcium silicate (C₃S) of cement and increase the strength of mortar that containing not more than 10% of it [15].

ESP was found able to improve water absorption properties of normal concrete when it replace the cement at 5% by mass, whereas, the absorption (rate of water ingress to submerged oven-dried concrete specimen) and sorptivity were reduced while water absorption (termed as “permeable void” in referred paper) was maintained; however, when replacement level was 10% and above, these properties were deteriorated [16]. In 1200kg/m³ LFC, sorptivity was also improved when ES replacement level (RL) was increased from 0% to 10%, however, there was no observable improvement on water absorption [5].

It was also found that ESP is able to improve compressive strength of both normal concrete and LFC when it replaces cement at replacement level of 5%, however, higher replacement level will reduce the compressive strength [5,16-17].

ES is more likely to be classified as waste due to its cumbersome and expensive processing [18]. However, disposal of ES waste is causing environmental issue such as land usage issue and pollutions due to its mass amount and its protein-rich membrane that cause pollutions and unpleasant condition such as attracting rats and other vermin [18-19]. Furthermore, ES waste is being produced increasingly and as abundant as around 7.2 million tonnes globally at 2010 and 85.6 thousand tonnes in Malaysia at 2017, which calculated based on mass of egg and ES at 60g and 7g respectively [20], global population and egg consumption of 6916 million and 8.9kg/person/year respectively at 2010 [21], and Malaysia egg consumption of 734 thousand tonnes at 2017 [22].

On the other hand, every 1 ton of cement production results in 0.89 ton of carbon dioxide emission as at 2006 in Malaysia [23] and 1.27 ton of natural limestone consumption [24]; and the production of cement is as huge as 17.5 million tonnes at 2018 in Malaysia [25] and 4.65 billion tonnes at 2016 globally [26].

Hence, this study was carried out by aiming to promote the application of ESP as partial replacement material of cement in the local construction industry to reduce environmental issue caused by disposal of ES and production of cement, and meanwhile promote the application of LFC. The objectives of this study are to investigate spread diameter that represent workability, stability, amount of water absorbed form hardened stage to saturated surface dry (SSD) stage, amount of water evaporated from SSD stage to oven-dried (OD) stage, water absorption, initial surface absorption, sorptivity, and compressive strength of the LFC with fresh and hardened density of 1000 ± 50 kg/m³ and 1400 ± 50 kg/m³ that contain ESP to replace cement at RL of 0%, 2.5%, 5%, 7.5%, and 10%.

2. Experimental procedures

2.1. Materials

Raw materials namely cement, egg shell powder (ESP), sand, water, and foam agent were used for this study. The cement is 52.5N "Orang Kuat" branded Ordinary Portland Cement (OPC) complying with Type I Portland Cement in accordance with ASTM C 150 [27] and MS EN 197-1 [28], and was sieved through 300 μm to remove all lumps [29] and stored in moisture-proof container; the egg shell was washed, oven-dried, ground, sieve through 63μm and stored in moisture-proof container; the sand was oven-dried and sieve through 0.6mm; its gradation is shown in Fig. 1; the water used is tap water from the municipal water supply in accordance with ASTM 1602 [30]; while the foam agent used is blend of synthetic surfactants and polymer.
The foam used is pre-formed dry foam that is normally very stable and has size of smaller than 1mm [3]. It was produced by forcing the foaming agent solution, mixture of water and foam agent at ratio of 1:20 in volume, through a series of high-density restrictions by compressed air at pressure of 0.5 MPa [5].

2.2. Testing methods
Testing method included density measurement, inverted slump test, water absorption (WA) test, initial surface absorption test (ISAT), sorptivity test, and compressive strength test were carried out in this study. The specimens were demoulded at 18 to 24 hours after casting, water cured until one day before testing, subjected to oven-drying of 24 hours at temperature of 105 ± 5 °C, and allowed cooling down before testing. The mass of the specimen was measured after demoulding, after 1 hour air-dried after water curing, and after oven-drying to obtain hardened density (HD), saturated surface dry density (SSDD), and oven-dried density (ODD).

Inverted slump test was performed as per ASTM C 1611 [31] to determine spread diameter that represents workability of the LFC. Water absorption was tested as per BS 1881-122 [32] by using 100 mm cubical specimen to determine the total amount of water that can be absorb by the LFC. It was calculated by difference of SSDD and ODD divided by ODD.

Sorptivity test was conducted as per ASTM C 1585 [33] by using 100mm diameter and 50mm height cut cylindrical specimen. It is to determine the rate of absorption (sorptivity) of water that caused by capillary action. The cut surface of specimen was placed on a steel rod and allowed 1 – 3 mm immersed in water. The mass was then recorded at 5, 10, 15, 30, 60, 90, 120, and 150 minutes.

Initial surface absorption test was conducted as per BS 1881- Part 208 [34] by using 100mm cubical specimens. It is to determine flow rate of water into a concrete surface that subjected to water pressure head of 200 mm. The measurement is carried out at 10, 30, 60, and 120 minutes after the surface is exposed to water, whereas, time taken for water to flow for certain number of divisions in capillary tube was recorded, then the calculation can be carried out accordingly to obtain the flow rate.

Compressive test was conducted as per BS EN 12390-3 [35] by using 100mm cubical specimens at loading rate of 2 kN/s to obtain compressive strength.

2.3. Mix proportions and screening
The LFC screening mix proportions are shown in Table 1 while screening results are shown in Table 2. Few water to cement ratios (w/c) were tried to obtain the optimal w/c that achieve highest compressive strength.
Table 1. Mix proportions of lightweight foamed concrete without egg shell for screening.

| Mixture Reference Name | Mix Proportions (per m³) | Foam Content (kg) |
|------------------------|---------------------------|-------------------|
|                        | Cement (kg) | Egg Shell (ES, kg) | Sand (kg) | Water (kg) | Required amount⁴ | Actual added |
| LFC-1400-0%ES-0.56     | 547         | 0                 | 547       | 306        | 14.1            | 21.6         |
| LFC-1400-0%ES-0.6      | 538         | 0                 | 538       | 323        | 13.6            | 18.4         |
| LFC-1400-0%ES-0.64     | 530         | 0                 | 530       | 339        | 13.1            | 17.9         |
| LFC-1000-0%ES-0.56     | 391         | 0                 | 391       | 219        | 22.9            | 28.4         |
| LFC-1000-0%ES-0.6      | 385         | 0                 | 385       | 231        | 22.6            | 26.6         |
| LFC-1000-0%ES-0.64     | 379         | 0                 | 379       | 242        | 22.2            | 26.5         |
| LFC-1000-0%ES-0.68     | 373         | 0                 | 373       | 254        | 21.9            | 29.7         |

Note: ¹density in kg/m³; ²ES replacement level in percentage of cement mass; ³w/c ratio; ⁴calculated based on foam density of 45 kg/m³.

The spread diameter results showed that increment of foam volume to reduce density had reduced the workability. Similar result was also found in previous study [4]. Based on the compressive strength results, optimal w/c of 0.6 for 1400 kg/m³ LFC and optimal w/c of 0.64 for 1000 kg/m³ LFC were obtained and spread diameter of the LFC at optimal w/c is near to a same value of 700mm. It shows that in order to obtain optimal strength of LFC at certain density, w/c have to be selected by which the LFC obtain certain level of workability so that the foam is more stable. It is because bursting of foam and interconnected foam could result in irregular microstructure in LFC and deteriorate the strength and other properties.

Based on the water absorption results, optimal w/c for 1000 kg/m³ LFC is 0.64 as well and further increment or decrement of w/c has deteriorated water absorption significantly. It might also due to stability of the foam, whereas, when the LFC is too wet or too dry to hold the foam, the foam bubbles start to burst and connect with each other and produce interconnected pore structure [6]. It can also be observed from the difference between required foam and actual foam added, which is the amount of foam burst, as shown in Table 1, the difference is smaller at w/c of 0.6 and 0.64 as compared to w/c of 0.56 and 0.68.

Table 2. Screening result of the lightweight foamed concrete.

| Mixture Reference Name | Spread Diameter (mm) | Hardened Density (kg/m³) | Stability¹ | Water Absorption (%) | Compressive Strength (MPa) |
|------------------------|----------------------|--------------------------|------------|----------------------|----------------------------|
| LFC-1400-0%ES-0.56     | 600                  | 1402                     | 1.02       | 23.73                | 7.68                       |
| LFC-1400-0%ES-0.6      | 705                  | 1415                     | 1.01       | 23.79                | 8.52                       |
| LFC-1400-0%ES-0.64     | 780                  | 1434                     | 1.00       | 22.68                | 7.67                       |
| LFC-1000-0%ES-0.56     | 560                  | 1038                     | 1.00       | 39.91                | 1.37                       |
| LFC-1000-0%ES-0.6      | 575                  | 1015                     | 1.02       | 36.81                | 1.85                       |
| LFC-1000-0%ES-0.64     | 690                  | 1021                     | 1.02       | 31.45                | 2.16                       |
| LFC-1000-0%ES-0.68     | 710                  | 1001                     | 1.01       | 37.62                | 2.07                       |

Note: ¹Stability = proportion of measured fresh density to measured hardened density [8].

For 1400 kg/m³ LFC, optimal w/c to achieve lowest WA is 0.64, but w/c has very small effect on WA result as compared to 1000 kg/m³ LFC, therefore, the optimal w/c of 1400 kg/m³ LFC was selected at 0.6 based on compressive strength result.
Table 3. Mix proportions of lightweight foamed concrete with various egg shell content.

| Mixture Reference Name | Mix Proportions (per m³) | Foam Content (kg) |
|------------------------|--------------------------|-------------------|
|                        | Cement (kg) | Egg Shell (ES, kg) | Sand (kg) | Water (kg) | Required amount | Actual added |
| LFC-1400°-0%ES-0.6³    | 538         | 0                  | 538       | 323        | 13.6            | 16.7         |
| LFC-1400-2.5%ES-0.6    | 525         | 13.5               | 538       | 323        | 13.6            | 16.2         |
| LFC-1400-5%ES-0.6      | 512         | 26.9               | 538       | 323        | 13.6            | 14.0         |
| LFC-1400-7.5%ES-0.6    | 498         | 40.4               | 538       | 323        | 13.6            | 14.8         |
| LFC-1400-10%ES-0.6     | 485         | 53.8               | 538       | 323        | 13.6            | 16.7         |
| LFC-1000-0%ES-0.64     | 379         | 0                  | 379       | 242        | 22.2            | 27.0         |
| LFC-1000-2.5%ES-0.64   | 369         | 9.5                | 379       | 242        | 22.2            | 28.1         |
| LFC-1000-5%ES-0.64     | 360         | 18.9               | 379       | 242        | 22.2            | 26.1         |
| LFC-1000-7.5%ES-0.64   | 350         | 28.4               | 379       | 242        | 22.2            | 27.0         |
| LFC-1000-10%ES-0.64    | 341         | 37.9               | 379       | 242        | 22.2            | 26.9         |

Note: ¹density in kg/m³; ²ES replacement level in percentage of cement mass; ³w/c ratio

3. Results and discussion

3.1. Spread diameter, stability, and water absorption

Testing results including spread diameter, fresh density, hardened density (HD), saturated surface dry density (SSDD), oven-dried density (ODD), stability, and water absorption of the lightweight foamed concrete (LFC) with various replacement levels at testing age of 28-day are presented in Table 4.

The results showed that increment of egg shell (ES) replacement level (RL) has decreased the workability of the LFC. It might due to porosity of egg shell powder (ESP), whereas ES absorbs more water than cement.

As shown in Tables 2 and 4, compared to targeted range of LFC fresh and hardened density at 1350 - 1450 kg/m³ and 950 - 1050 kg/m³ respectively, the achieved fresh and hardened densities were well controlled at the range of 1400 - 1438 kg/m³ and 1000 - 1045 kg/m³ respectively. Besides, the stability was ranged from 0.99 to 1.02 that is nearly to unity, which means that there is no significant different between the both fresh and hardened densities and the foam is quite stable and no significant bursting and deformation during hardened process. Therefore, ES has no adverse effect on the stability.

As shown in Table 4, the water absorption (WA) has narrow improvement when ES RL increased from 0% to 10%. The difference of WA between both densities is large as the WA is calculated by mass, however, if refer to the difference between SSDD and ODD (SSDD-ODD), which is the potential amount of water to be absorbed by the LFC, the result of both densities is comparable, and the lower density LFC even has lower SSDD-ODD.

The difference between SSDD and HD (SSDD-HD), which is the total water absorbed by the specimen from placement into until taken out from curing water, was reduced significantly as compared to SSDD-ODD. It reveals that the resistance of the LFC to absorption of water at immersion is improved with increased ES RL. These improvements might due to packing effect of egg shell, where it serves as inert filler to reduce the pores in the LFC.
Table 4. Workability, densities, stability, and water absorption of the lightweight foamed concrete.

| Mixture Reference Name | Spread Diameter (mm) | Fresh Density (kg/m³) | HD (kg/m³) | Stability | SSDD (kg/m³) | ODD (kg/m³) | WA (%) | SSDD - HD (kg/m³) | SSDD - ODD (kg/m³) |
|------------------------|----------------------|-----------------------|-----------|-----------|--------------|-------------|--------|-------------------|-------------------|
| LFC-1400-0%ES-0.6      | 705                  | 1414                  | 1409      | 1.00      | 1497         | 1251        | 19.6   | 87                | 246               |
| LFC-1400-2.5%ES-0.6    | 650                  | 1418                  | 1421      | 1.00      | 1498         | 1260        | 18.9   | 77                | 238               |
| LFC-1400-5%ES-0.6      | 620                  | 1408                  | 1400      | 1.01      | 1469         | 1236        | 18.8   | 68                | 233               |
| LFC-1400-7.5%ES-0.6    | 615                  | 1407                  | 1402      | 1.00      | 1470         | 1240        | 18.6   | 68                | 230               |
| LFC-1400-10%ES-0.6     | 605                  | 1405                  | 1400      | 1.00      | 1463         | 1231        | 18.8   | 63                | 231               |
| LFC-1000-0%ES-0.64     | 690                  | 1035                  | 1045      | 0.99      | 1172         | 938         | 24.9   | 127               | 234               |
| LFC-1000-2.5%ES-0.64   | 660                  | 1029                  | 1020      | 1.01      | 1113         | 890         | 25.1   | 93                | 223               |
| LFC-1000-5%ES-0.64     | 660                  | 1033                  | 1023      | 1.01      | 1110         | 893         | 24.3   | 88                | 217               |
| LFC-1000-7.5%ES-0.64   | 650                  | 1013                  | 1000      | 1.01      | 1084         | 874         | 24.1   | 84                | 210               |
| LFC-1000-10%ES-0.64    | 600                  | 1033                  | 1040      | 0.99      | 1114         | 900         | 23.8   | 74                | 214               |

Note: HD: Hardened Density; SSDD: Saturated Surface Dry Density; ODD: Oven-Dried Density

3.2. Initial surface absorption
Testing results of initial surface absorption test (ISAT) of the LFC with various RL at testing age of 28-day are presented in Fig. 2. Initial surface absorption rate is the rate of water ingress through surface of concrete that subjected to a water pressure, it is generally reduced with time at decreasing rate as shown in Fig. 2 as the specimen was slowly filled with water, and it is mainly induced by the interconnected capillary and non-capillary pores that connected to the surface.

The results showed that initial surface absorption of the LFC were reduced at increased ES RL of up to 5%, and generally maintain or slightly increase when ES RL further increased to 10%. Improvement of initial surface absorption represents reduced interconnected pores. Therefore, ESP might be able to act as inert filler to reduce the porosity or to disconnect the path of the interconnected pores in the LFC and improve the resistance to surface absorption under water pressure head. Besides, reduction of burst foam amount as shown in Table 3 when ES RL increased from 0% to 5% might contribute to lesser interconnected pores, it might be one of the reasons that initial surface absorption has better improvement at initial increment of ES RL of up to 5%.
3.3. Sorptivity
Sorptivity results of the lightweight foamed concrete with various replacement levels at testing age of 28-day are shown in Fig. 3. The results showed a fluctuation at ES RL of 2.5% but generally the sorptivity is improved at higher ES RL of 5% to 10%. It reflects that the ESP might act as inert filler to reduce the interconnected capillary pore in concrete.

Besides, the results showed that sorptivity of 1400 kg/m³ and 1000 kg/m³ are at comparable value, and improvement of ESP on sorptivity is more significant on 1000 kg/m³ LFC. Therefore, it can be concluded that ESP shows better improvement on sorptivity on LFC with lower density of 1000 kg/m³ as compared to 1400 kg/m³.

It was reported that the sorptivity shall be less than 6 mm/hr⁰.⁵, which is equivalent to 0.774 mm/min⁰.⁵, for laboratory concrete in order to fulfil the acceptable limits for durability index [5, 36-37]. The sorptivity results shown in Fig.3 are ranged from 0.21 to 0.35 mm/min⁰.⁵, which have fulfilled the limit of 0.774 mm/min⁰.⁵.

3.4. Compressive strength
Compressive strength results of the lightweight foamed concrete with various replacement levels at testing age of 28-day are shown in Fig. 4.
Figure 4. Compressive strength of the lightweight foamed concrete at testing age of 28 days.

The results showed that the compressive strength of the LFC was improved with increased ES RL of up to 5%; besides, the compressive strength of LFC with 7.5% ES RL was comparable to the LFC without ES; and further increment of ES RL has caused deterioration of compressive strength. The initial improvement of compressive strength might be caused by acceleration of hydration caused by ESP [15] or packing effect of ESP, i.e., the ESP act as inert filler to reduced porosity and improved the compressive strength [14], or improved stability of foam. The later deterioration of compressive strength might be caused by reduction of cement content, whereas, the improvement of strength by ESP is insufficient to compensate the decrement of strength caused by reduction of cement content.

In addition, the compressive strength of the 1400 kg/m³ LFC specimens at 0% to 10% ES RL and the 1000 kg/m³ LFC specimens at 5% ES RL has fulfilled the strength requirement of 2.8 MPa as normal block as accordance to MS 76: 1972 [38].

4. Conclusion
Some conclusion can be drawn as below for this study:
1. Incorporation of egg shell decreases the workability or spread diameter, however, shows no significant effect on stability of the lightweight foamed concrete.
2. Egg shell powder improves stability of foam at replacement level of up to 5%.
3. Egg shell powder improves water absorption, initial surface absorption and sorptivity of the lightweight foamed concrete.
4. Egg shell powder improves compressive strength of the lightweight foamed concrete at replacement level of up to 5%, despite that, the compressive strength is on par at 7.5% replacement level and is deteriorated at 10% replacement level.

Based on the results, it is feasible to replace partial cement with egg shell powder at up to 7.5% replacement level for Type II composite cement production.

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