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~~Masonry Blocks from Palm Oil Fuel Ash~~

Performance of Masonry Blocks Incorporating Palm Oil Fuel Ash

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Abstract

This paper presents an experimental study on the development of masonry block with Palm Oil Fuel Ash (POFA) as a partial replacement to cement whilst maintaining satisfactory properties of masonry block. The dosages of POFA are limited to 0%, 20%, 40% and 60% by mass of the total cementitious material in the masonry block. The experiments on masonry block investigate the compressive strength and the breaking load for mechanical properties and water absorption and efflorescence for its durability. The compressive strength and the breaking load of the masonry blocks reduce with increasing percentage of POFA replacement. However, it satisfies the requirements of Class 1 and Class 2 load-bearing masonry block according to Malaysian Standard MS76:1972. In terms of durability of the masonry block, water absorption for all the masonry blocks satisfies the requirement of ASTM C55-11 and there is no any sign of efflorescence on all the masonry blocks. POFA based masonry block are also found to be cheaper than the cement sand masonry blocks. The experimental studies indicate that POFA based masonry block has a significant potential for application in the construction industry.

Keywords: Masonry Block, Waste Material, Palm Oil Fuel Ash.

1. Introduction

Masonry blocks are one of the earliest and strongest building units. Masonry blocks such as bricks are well known to be one of the very old and strongest building materials. The oldest brick is the sun dried brick made from mud which was found to be around 9000 years old from Jericho, dated around 7000 BC. Later on, fired bricks were discovered around the 5th century BC in the city of Babylon. Other traces of bricks were also found in China, Rome and Europe. One of the obvious usages of bricks in China can be seen through the Great Wall of China which dated around the 3rd century BC. In Rome, bricks can be seen through the Herculaneum gate of Pompeii and the Baths of Caracalla [1].

Even now, masonry blocks are extremely popular for a very wide range of construction around the world and are considered as a demanding construction material. Developing countries like Malaysia are undergoing very significant infrastructural change and the related demand for masonry blocks is thus very high. The ingredients of masonry block used in Malaysia are sand, cement and water. The cement production industries are liable for approximately 7% of the world's carbon dioxide emission. Consequently, the environmental impact including the carbon footprint of masonry block is significant.

Parallel to the infrastructure boom, Malaysia's agricultural sector has also been developing over time. Malaysia is one of the world's largest producers and exporter of palm oil in the world. As a result, a very significant amount of biomass including empty fruit branch, oil palm shell and palm oil fuel ash (POFA) are generated every year and it is anticipated to generate about 100 million dry tonnes of solid biomass by 2020 [2]. POFA is a by-product of palm oil industry and is generated from the combustion of empty fruit branch and shell of palm. It is a contributor to air, river, sea and groundwater pollution. Reuse of POFA in masonry block attempts to address a part of the environmental problems related to POFA.

An increasing focus of the society towards sustainability, along with support from government policies, has led to a significant increase in the use of different types of waste materials including rice husk ash (RHA), POFA, rubber tire, Oil Palm Shell (OPS) and fly ash (FA). The reuse of POFA in masonry block is also an attempt to address a part of these problems by introducing sustainable materials in the construction industry. Many researchers have carried out study on masonry blocks using waste materials. Ling & Teo [3] reported on the potential use of waste rice husk ash (RHA) and expanded polystyrene (EPS) beads in producing lightweight concrete bricks and found that the properties of the bricks are mainly influenced by the content of EPS and RHA in the mix and also the curing condition. Muntohar & Rahman [4] presented the use of oil palm shell waste as masonry block material and found that the maximum strength was obtained by mixing proportion of 1 C: 1 sand: 1 OPS. Cicek & Tanrıverdi [5], Chindaprasirt & Pimraksa [6] reported that it is possible to produce good quality bricks from fly ash due to pozzolanic properties of fly ash. Shakir et al. [7] investigated bricks incorporating fly ash, quarry dust, and billet scale and summarised that bricks can be made using these waste materials. Fernández-Pereira [8] studied bricks made from gasification ash and compared with typical values for commercial bricks and concluded that the bricks could be used commercially. Turgut [9] used limestone powder, class C fly ash, silica fume and water in masonry brick production and found that the compressive and flexural strengths of the samples containing silica fume were found to increase significantly when the silica fume content in the mixtures was increased. Gorhan & Osman [10] investigated the effects of rice husk on the porosity and thermal conductivity properties of fired clay bricks and found that samples with coarse rice husk have lower thermal conductivity than samples with ground rice husk.

Rahman et al. [11] made bricks from clay-sand mixes with different percentages of rice husk ash burnt in a furnace at different firing times and concluded that light weight bricks could be

made from rice husk ash without compromising the quality of the bricks. Malhotra & Tehri [12] carried out study on granulated blast furnace slag based bricks and found that good quality bricks can be produced from a slag-lime mixture and sand. Bilgin et al. [13] investigated the application of waste marble dust as an additive material in industrial brick and found that the marble dust as an additive had positive effect on the physical, chemical and mechanical strength of the produced industrial brick. Weng et al. [14] investigated bricks made from dried sludge collected from an industrial wastewater treatment plant and found that brick shrinkage, water absorption, and compressive strength decreased with increasing of the sludge content. Faria et al. [15] reported that recycled sugarcane bagasse ash waste could be used as filler in clay bricks. Gencel et al. [16] investigated bricks made from clay with ferrochromium slag and natural zeolite and found that the mechanical strengths of bricks were increased and thermal conductivity of samples was decreased than control bricks.
Ismail et al. [17] carried out study on disposed paper sludge and POFA based masonry block. The dosages of paper sludge and POFA were 0%, 5%, 10%, 15%, 20% & 25%. It was found that paper sludge-POFA brick made with 60% cement, 20% sludge and 20% POFA satisfied the strength requirements of BS 6073 Part 2: 2008 and that the amount of copper as well as lead resulting from leaching were within the acceptable limits of 'Malaysia Environmental Waste Disposal Act'.

Some studies exist on POFA based self compacting concrete (SCC) and normal vibrating concrete. Fresh concrete properties of POFA based SCC have been investigated [18] where the dosage of POFA was limited to 15% by mass of the total cementitious material. It was found that the filling ability and passing ability decreased and sieve segregation resistance increased with increasing POFA content. Strength, modulus of elasticity and shrinkage of concrete incorporating POFA have also been studied by researchers [19]. Laboratory test data based on short-term investigation revealed that the modulus of elasticity of POFA concrete in association with its compressive strength was somewhat lower than that of OPC concrete and the shrinkage strain of POFA concrete was higher than that of OPC concrete. Some investigations into strength increase through the use of POFA in concrete have been studied [20] and it was found that the compressive strength of the concrete increased with the fineness of POFA. Laboratory tests were conducted to evaluate the performance of palm oil fuel ash in concrete and it was found that POFA has a potential in suppressing expansion due to alkali-silica reaction [21], controlling heat of hydration of concrete [22], and increased durability and sulphate resistance [23]. Additionally, the strength & durability properties of high-strength green concrete (HSGC) containing up to 60% of ultrafine POFA have been studied and it was found that ultrafine POFA has the potential to produce HSGC [24].

It is observed from existing literature that significant research work exist on masonry block incorporating different types of waste material based ash including limestone powder, fly ash, silica fume, RHA, quarry dust, gasification ash, and sugarcane bagasse ash. Different parameters have been determined in these investigations but compressive strength and water absorption have been determined by most researchers. Although different types of waste material have been used to produce brick for research purposes, commercial production and application is still limited due to lack of standard guidelines. Further research and development are needed to develop guidelines for masonry block incorporating waste material [25]. It can also be seen from the literature review that there are significant research work have been conducted on SCC and normal vibrating concrete incorporating POFA due to their pozzolanic properties. However, according to the author's best knowledge, there is no research work carried out so far on masonry block incorporating only POFA. These studies confirm that there is a definite possibility of creating masonry block using POFA conforming to various standards of adequacy.

This paper experimentally studies POFA based masonry blocks by examining their mechanical and durability properties. The experiments on masonry block investigate the compressive strength, density and the breaking load for its mechanical properties and water absorption and efflorescence for its durability. The compressive strength and the breaking load test are also conducted under soaked or unsoaked condition. Additionally cost analyses of masonry block and carbon footprint discussion are also presented.

2. Experimental Program

2.1 Materials

The materials used for the production of masonry blocks are cement, POFA and river sand. Tap water was used for mixing of cement, POFA and sand. All materials are available locally and POFA is a free of cost.

2.1.1 Ordinary Portland Cement (OPC)

Ordinary Portland Cement (OPC) grade 42.5 based on ASTM: C150 / C150M - 12 was used in concrete as cementitious material. The particle density of the cement is 2950 kg/m3 and specific gravity of 3.14. The Blaine specific surface area was 3510 cm^2/g.

2.1.2 Palm Oil Fuel Ash (POFA)

POFA was obtained from a nearby palm oil mill at Lambir, Miri, Sarawak, Malaysia. The POFA obtained was sieved to 75µm in the laboratory to remove coarse particles. This is to ensure that only small particle sized POFA were used to obtain a better control over manufacturing masonry blocks. The sieving process also acts as a filter to remove incomplete combusted materials. The sieved POFA was stored in a clean, dry and air tight in a humidity controlled room.

2.1.3 Local River Sand

The sand used for the masonry block is local river sand. A sieve analysis was carried out to determine if this local river sand complies with the AS 2758.1 [26]. The fineness modulus of the local river sand was calculated to be 1.34. Fig. 1 shows the local river sand grading curve from the analysis and it is observed that 100% sand passed through 600 μm, indicating that the maximum size the particles is 600 μm. The particle size distribution curve is also steeper as the particle size range is smaller which describes a poorly graded sand. From Fig. 1, it can also be seen that most part of the sample curve falls within the upper limit and lower limit as required by the AS 2758.1 [26]. Using the tolerance given in this standard, the sample curve is considered to be acceptable. Consequently, the local river sand was deemed appropriate for use in the production of the masonry blocks.

2.2 Masonry block Mix Design

Four batches of masonry blocks were made where the OPC was partially replaced with 0%, 20%, 40% and 60% POFA by binder weight. The dimension of each masonry block was 200mm long, 100mm wide and 70mm thick. Tables 1 and 2 show the masonry block mix ratio and testing regime. The masonry blocks were tested at the end of 28 days since the cement paste takes 28 days of curing to reach around 80% of its total strength. The cement paste hardens over time, initially setting and becoming rigid and gaining strength over time starting from a relatively weak condition. The masonry blocks were also tested at the end of 56 days to determine the relatively long term effects. Compressive strength test, breaking load test, water absorption test and efflorescence test were carried out. These tests were based on the ASTM C55-11, a normative document on standard test methods for sampling and testing masonry blocks and structural clay tiles.

2.3 Preparation of Masonry blocks

The method of production for the masonry blocks in this project was through simple blending and compressing. It did not involve heating and thus carbon emission was not present. First, cement and sand were measured and blended using a Hobart A200 mixer in order to obtain a homogenous mixture. Next, the POFA was measured and added into the mixture to be blended. While blending, water was constantly added into the mixture until a homogenous mixture was obtained. The entire mixing process takes approximately 15 to 20 minutes. Upon obtaining the homogenous mixtures, they were placed into 200mm x 100mm x 70mm timber masonry block moulds. The samples were tamped manually by hand compaction. To further compact the masonry blocks, the mixtures in the mould were compacted using a compaction machine (Fig. 2). The specimens were dismantled from the mould and were cured. Once made, the masonry blocks were kept in controlled rooms (Fig. 3) for either 28 days or 56 days, where they were wrapped with plastic.

2.4 Testing Methods

The testing method was divided into two categories corresponding to the soaked and unsoaked condition of the masonry blocks. The difference between the two categories is that the soaked masonry blocks were subjected to water absorption test. For the soaked masonry blocks, the experimental program started with the water absorption test once the masonry blocks reached the required age, at the end of 28 days or 56 days. Once the water absorption rate was obtained, the masonry blocks were tested accordingly for compressive strength or breaking load.

2.4.1 Compression Test

The compressive strengths of the masonry blocks at the age of 28 days and 56 days were measured. The test was carried out using a Universal Testing Machine (UTM). The masonry block specimens were placed so that the load applied is perpendicular to the surface bed of the masonry block. A constant loading rate of 1.25mm/min was applied to conduct the test and the load was applied to the masonry block until the failure of the specimen. The failure load for the specimen was recorded and all pertinent details regarding the failure were observed. Compressive strength of each specimen was calculated in MPa (N/mm^2) as

$$C = W/A \tag{1}$$

where C is the compressive strength, W is the maximum load indicated by the universal testing machine and A is the average gross area of the upper and lower bearing surface of the specimen.

2.4.2 Breaking Load Test

The breaking load of the masonry blocks at the age of 28 days and 56 days were obtained. The test was also carried out using the Universal Testing Machine where the masonry block specimen was placed so that the load applied was perpendicular to the bed surface of the masonry block. The specimen was supported with solid steel rods at the underside while the load was applied at the mid span of the masonry block. A constant loading rate of 1.27mm/min was set to the testing machine. The load was applied to the masonry block through a steel bearing plate until the failure of the specimen. The failure load for the specimen was recorded and all pertinent details regarding the failure were observed. The breaking load of each specimen was calculated in terms of N/mm as

$$p = P/w \tag{2}$$

Where p is the breaking load per width, P is the transverse breaking load obtained from the machine and w is the width of the masonry block specimen.

2.4.3 Water Absorption Test

The water absorption rate was determined before being tested for compression, breaking load or efflorescence. The masonry block specimens were weighed and the weight was recorded as W_i. The specimen was then dried in a ventilated oven at 110°C for at least 24 hours. The weight of the specimen was then recorded as W_d. After drying, the specimen was cooled in a drying room at 25°C with relative humidity of 30% to 70%. The specimens were then stored to be free from air draft and were unstacked and separately placed for 4 hours until the surface temperature was approximately 28°C, which was equal to that of the drying room. The specimen was then submerged in clean water at 30°C for 24 hrs.

The surface water of the specimens was wiped off with a damp cloth and the weights of the specimens were again weighed and recorded as W_s after removing the specimen from the submerged condition. The water absorption of each specimen in percentage was computed as

$$\text{Absorption, \%}=100(W_s-W_d)/W_d \quad (3)$$

2.4.4 Efflorescence Test

Efflorescence test was carried out to determine if efflorescence occurs at the surface of the masonry blocks at the ages of 28 days and 56 days . The first test masonry block specimen was partially immersed in a tray with distilled water to a depth of approximately 25mm for 7 d in the drying room. The second test masonry block specimen was stored in the drying room without contact with water for 7 days. At the end of 7 days, both specimens were inspected before oven drying for 24 hrs. All observations were recorded.

The efflorescence effect of each specimen were observed on all faces from a distance of 3m under an illumination of not less than 50 foot candles by an observer with normal vision. Under these circumstances if no difference is noted, the specimen is considered not to have effloresced. On the contrary, if perceptible differences due to efflorescence were noted, the specimen is recorded as effloresced.

3. Results and Discussions

3.1 Density

A higher density of a masonry block is indicative of closely packed particles. Fig. 4 shows the average densities of masonry block. It can be seen in the Fig. 4 that the density decreases with increasing POFA contents as POFA has a lower density. The decrease in dry density with 20%, 40% and 60% POFA are 5.4%, 5.8% and 8% indicating that by adding POFA it would be possible to produce lighter weighing masonry blocks. In compliance with ASTM C55-11, batch 1 (B1), batch 3 (B3) and batch 4 (B4) masonry blocks are considered as normal weight masonry blocks as they are all above 2000 kg/m^3. Only batch 2 (B2) is considered as medium weight masonry block as the density is within 1680 - 2000 kg/m^3.Overall, POFA masonry blocks are found to be lighter than cement sand masonry blocks.

3.2 Compressive Strength

The compressive strength of the masonry blocks are shown in Fig. 5 and Fig. 6. The graphs show that the compressive strength of the masonry blocks is affected by the POFA replacement, aging and immersion.

3.2.1 Effect of Aging

The results of 28 days and 56 days compressive strength are shown in Fig. 5. The age of the masonry block plays an important role for the compressive strength as a higher age corresponds to a higher compressive strength. Fig. 5 shows that the strength of 56 days masonry blocks is higher than those of 28 days. The reason can be attributed to the slow pozzolanic activity of the POFA [27]. Additionally, the cement also continuously react with time producing more CSH gel, which gives more strength to the masonry block. The pozzolanic activity slowly diminishes the calcium hydroxide content from the hydration process though reaction with silicon dioxide from the POFA [28] and produces more CSH gel. As a result the compressive strength also increases with the increasing of time.

3.2.2 Effect of POFA Replacement

The compressive strength results with different percentages of POFA are presented in Fig 6. In terms of POFA replacement, generally the compressive strength of the control masonry blocks is higher than those partially replaced with POFA, which are batch 2 (60%), batch 3 (40%) and batch 4 (20%). The reason most likely behind this occurrence is due to the fineness of the POFA particles. The raw POFA used was sieved to 75 μm, which is coarser than ground POFA and hence can be associated with lower compressive strength. The fineness of POFA is related to its micro-filling ability that fills micro-voids between cement particles and eventually contributes to an increase in the compressive strength [29].

The coarseness of raw POFA for this project resulted in larger voids that led to lower compressive strengths [4]. Larger particle sizes have higher porosity that increases the actual water/binder ratio and thus resulting in lower compressive strength [27]. Additionally, finer particles have higher surface area, which affects the pozzolanic activity [29] and hence, the compressive strength. Likewise, the use of larger particles led to more voids, resulting in lower compressive strength. Another possibility contributing to lower strength is due to insufficient chemical constituent from the cement that is needed to form the bonding.

3.2.3 Effect of Immersion

In terms of soaked and unsoaked masonry blocks, Fig. 6 also shows that unsoaked masonry blocks produced higher compressive strength than the soaked masonry blocks. The low compressive strength of the soaked masonry blocks might be due to loss of strength during submersion through water absorption which softens the matrix.

3.3 Breaking Load

The breaking load of the masonry blocks is as shown in Fig. 7. The trend observed from the Fig. 7 is comparable to those for compressive strength whereby breaking load is also affected by POFA replacement and immersion. In general, unsoaked masonry blocks has higher breaking load than soaked masonry blocks. Secondly, as POFA content increases, the breaking load decreases.

3.3.1 Effect of Immersion

Similar to the compressive strength, the lower breaking load of the soaked masonry blocks may be due to loss of strength during submersion through water absorption that softens the matrix. Softened matrix results in weaker bonding thus causing a weaker masonry block that can only resist low loads.

3.3.2 Effect of POFA Replacement

The breaking load of a masonry block is governed by the tensile crack which is dependent on the bonding between the POFA, cement and aggregate. For compressive strength, it was discussed in the previous section that a higher POFA replacement was related to a weaker bonding in the masonry blocks due to possible limitations in chemical constituent in cement. A similar reasoning may also be applied here as the breaking load decreases with the increase in POFA content. Cracks or failure for breaking load happens at a location of weakest bond. Therefore, the mixing process for masonry block production is very important to ensure proper blending between the POFA, cement and aggregate. Unbalanced spread of these materials will result in weak spots which could lead to cracking and consequently, a lower breaking load.

3.4 Water Absorption

The water absorption results are presentation in Fig. 8. It can be seen that all water absorption values were below the maximum water absorption capacity, which is 208 kg/m^3 for normal weight masonry block, 240 kg/m^3 for medium weight masonry block and 320 kg/m^3 for light weight masonry block in accordance with ASTM C55-11. This shows that the masonry blocks fulfill ASTM C55-11 requirement for normal, medium or light weighted masonry blocks in terms of water absorption. Comparing between the POFA masonry blocks and the control masonry blocks, the water absorption of POFA masonry blocks are observed to be slightly higher (0.1%). The reason behind this is due to the greater porosity of POFA which tend to favor water absorption [27].

3.5 Efflorescence

Efflorescence is the formation of salt deposits on the masonry block surfaces due to leaching of lime compounds. This is found when water percolates through poorly compacted masonry blocks and when evaporation takes place at the surface of the masonry blocks. The reaction starts with the absorption of CO_2 into the masonry block. If water is presence in the masonry block, the dissolved CO_2 react with lime form $CaCO_3$ which is the visible white salt. The efflorescence typically occurrs when cool, wet weather is followed by a dry and hot spell [30, 31].

The efflorescence results are presented in Table 3. It can be seen from the Table 3 that there is no efflorescence. This is due to the pozzolanic properties of POFA. One of the primary factors affecting efflorescence is cement, where a greater cement content tends to increase the likelihood of efflorescence effects [32]. Therefore, a higher percentage of POFA replacement leads to a lower chance of efflorescence in the masonry blocks. Most of the soluble salts and free lime needed for efflorescence are provided by cement. The main chemical constituents in POFA are SiO_2, Al_2O_3, Fe_2O_3, CaO, and MgO. The SiO_2 from POFA reacts with free lime released by the hydration of Portland cement and generates Calcium Silicate Hydrate (CSH) as a gel. The CSH gel is the main binder that holds together the aggregates reduces permeability. Thus the lower the cement content and higher the POFA, the lower is the possibility of efflorescence.

3.6 Cost of Masonry Block

The cost of masonry block varies depending on the material cost. The material costs used for comparison purposes are shown in Table 4. From Table 4, it can be seen that the factor that changes the cost of the masonry blocks is the cement. Comparing to the normal cement sand masonry block, POFA masonry blocks are found to be cheaper since POFA is a free waste material. Consequently, less cement is usedas shown in Table 5. The higher the percentage of replacement of cement, the cheaper the cost of the masonry block produced. Fig. 9 shows the cost comparison of the masonry blocks where the cement sand masonry block cost is set as the benchmark.

3.7 Comment on Materials & Carbon Footprint

Significant amount of virgin materials, including limestone and clay, besides energy, are consumed to produce cement and 1.5 ton of virgin materials are needed to produce one ton of cement [33]. Cement production industries are liable for more or less 7% of the world's carbon dioxide discharge and to produce one tone of cement approximately one ton of CO_2 is released in the atmosphere [33, 34]. POFA is a by-product of palm oil industry which can be abundantly found in Malaysia, Indonesia and Thailand and is a contributor to air, river, sea and groundwater pollution. This study shows that POFA has good potential as a cement replacement up to 60% in masonry block production. Every year significant amount POFA is produced by Malaysia, Indonesia and Thailand. The reuse of waste materials in masonry block is an attempt to address a part of these problems by introducing sustainable materials in the construction industry and consequently reduce carbon footprint.

4. Conclusions

POFA seems to have a good potential for cement replacement in masonry block production. The blocks can eventually be used for construction of low-cost housing projects. Simultaneously, the use of POFA also reduces waste materials. The following observations and conclusions can be made on the basis of the current experimental results.

i. The compressive strength of POFA masonry block decreases as the percentage of cement replacement increases. Compressive strength of POFA masonry block also increases through time but decreases when submerged into water. In addition, POFA masonry block has lower compressive strength compared to cement sand masonry block. However, it satisfies the requirements of Class 1 and Class 2 load-bearing masonry block according to Malaysian Standard MS76:1972 [35].

ii. The breaking load of POFA masonry block possessed a similar pattern as compared to the compressive strength. The breaking load also decreases with the increase of cement replacement percentage and when submerged into water. POFA masonry block also has lower breaking load compared to cement sand masonry block.

iii. POFA masonry blocks have water absorption less than the limit stated in ASTM C55-11 which is 208 kg/m^3. Even so, POFA masonry block has a slightly higher water absorption rate than cement sand masonry block.

iv. In terms of efflorescence effects, POFA masonry block and cement sand masonry block do not show any white salt formation on any of its surfaces and thus no efflorescence effect is present.

v. Based on density, cement sand masonry block along with 20% and 40% POFA replacement masonry block falls under normal weight masonry block according to ASTM C55-11. However, a 60% POFA replacement masonry block is categorized as medium weight masonry block. Therefore, higher replacement of cement with POFA results in lighter weight of masonry block.

vi. The unit cost of POFA masonry block is cheaper than cement sand masonry block as it is made of free waste material.

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