Development and mechanical properties of low fired bricks from drinking water sludge and fly ash

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Abstract. Demand for water and energy supply has dramatically increased the amount of drinking water sludge (DW) and fly ash (FA) annually. These wastes should be properly managed and disposed to protect any potential contamination to surrounding ecosystem. Both by-products can be potentially recycled as raw material for brick development. This study aimed to examine the influence of fly ash content on mechanical properties of drinking water sludge brick at low firing temperature of 500 °C. Different ratios of FA content were added to the DWS ranged between 0 and 45%. Brick sample was moulded in 215 mm x 102.5 mm x 65 mm dimension. Samples were air-dried prior to firing at 500 °C for 3 hours in a furnace. Basic characterization of DW and FA showed pH of 5.76 and 10.1 with organic contents of 8.42% and 1.14%, respectively. Clay and silt fractions were dominant in DWS while silt more apparent than sand and clay in FA. The volume changes and water absorption of the brick samples decreased with increasing FA content. For the water absorption of the brick increased back as 40% of FA content. The density and compressive strength dropped with the increasing amount of FA. The compressive strength of brick experienced with sulphate attack also decreased with increasing FA content. The results suggested that further study are needed to improve the compressive strength of the studied bricks.

Keywords: Sludge, fired brick, waste, compressive strength

Track Name: Advanced Technology and Renewable Energy

1. Introduction

Drinking water sludge is a waste product generated from drinking water treatment facility. Large amount of drinking water sludge has been produced annually as a result of highly demand of clean water for domestic and industrial usages. In Malaysia, it was recorded that around 0.5 million tons of waste was recorded in 2011 which involving 450 water treatment plants and its quantity is expected to rise every year [1]. Conventional treatment involves coagulation, flocculation, sedimentation, filtration and disinfection processes which ended up with large amount of residue which by-product generated during coagulation/flocculation processes [2]. Coagulation and flocculation processes by adding Al₂(SO₄)₃.14H₂O (alum) and poly-aluminium chloride (PAC), Al₂Cl(OH)₆ to separate suspended solids and the dose used depending of the quality and quantity of the raw water. It composes 1-3% of total volume of raw water during the treatment process [3]. Clean water is channelled to supply tanks while
residue is discharged into lagoons which is finally dumped in designated sites for dehydration and further biological stabilization. Coal supplied 29% of energy world-wide and is expected to increase by 30% by 2035 which actual amount of coal consumed per year will increase from 3840 million tons in 2015 to 4032 million tons in 2035 [4]. It is characterized of its powdery form as a result of burning of finely ground coal in a boiler which comprised dominantly of silica content. Both wastes should be contained and properly disposed to avoid potential damage to surrounding environments. Recycling of wastes is better alternative approach instead of sending them to the landfill.

Sludge from water treatment plant contains clay, silt and sand which can substitute raw material to clay-based products [5]. Attempts to study the potential usage of drinking water sludge in development of alternative brick [6][7][8][9]. Fly ash has been widely added in cement and can improve the properties of concrete that associated with pozolanic and hydraulic reactions [10]. Range between 15% and 25% of fly ash were added in concrete application and some cases higher fly ash content of more than 45% was used to achieve better mechanical property and higher durability [11]. Conventional brick is considered not eco-friendly building product as its footprint associated with high temperature firing for length period of up to 40 hours. Therefore, this study aimed to examine the effect of fly ash on the mechanical properties of drinking water sludge brick at lower firing temperature of 500 °C for 3 hours. The mechanical characteristics of the studied brick were examined in terms of volume change, density, water absorption and compressive strength. Compressive strength of brick exposed to sulphate attack were also tested in the laboratory.

2. Materials and Methods

2.1. Wastes materials

The drinking water sludge (DW) was collected from one of raw water treatment facility in Selangor while the fly ash (FA) was provided by coal-based power plant of Sultan Salahuddin Abdul Aziz located at Kapar Selangor. Bulk samples were collected and were stored in air-tight containers. For the DWS, it was slightly wet when collected from the disposed site while FA was almost dry and very fine-grained and dark grey in colour. In the laboratory, DWS was further dried under room temperature for several days and aggregates were broken down and sieved through 2 mm. Any coarse particles or plant matters was removed from the sieve. The basic characteristics of the used materials are shown in Table 1. DW was acidic of pH 5.76 and alkaline for FA (pH 10.1). The values of specific gravity were less than 2.0. The organic content for DW higher than FA as stated by LOI test. DW displayed higher fraction of silt and clay than sand while FA was dominantly contained of silt fraction, approximately of 77%. Compaction test was performed on DW sample and resulted with maximum dry density and optimum moisture of 1.32 gcm $^{-3}$ and 29%. XRD analysist showed the presence of silica and kaolinite in DW and silica, mullite and aluminium calcite in FA.

| Parameters                  | Drinking Water Sludge (DW) | Fly Ash (FA) |
|-----------------------------|-----------------------------|--------------|
| pH                          | 5.76                        | 10.1         |
| Specific gravity            | 1.99                        | 1.82         |
| Loss of ignition (LOI), %   | 8.42                        | 1.14         |
| Clay, %                     | 36.31                       | 18.05        |
| Silt, %                     | 48.44                       | 76.97        |
| Sand, %                     | 15.25                       | 2.11         |
| Max. dry density, gcm $^{-3}$ | 1.32                     | -            |
| Opt. moisture ct., %        | 29.00                       | -            |
| XRD analysist               | Quartz, SiO$_2$             | Quartz, SiO$_2$ |
|                            | Kaolinite, Al$_2$SO$_4$(OH)$_4$ | Mullite, 3Al$_2$O$_3$.2SiO$_2$ |
|                            |                             | Aluminium calcite |

Table 1. Characteristics of the wastes used for making the studied bricks.
2.2. Compaction tests

Compaction test was carried out to establish the value of maximum dry density, $\rho_{\text{max}}$, and optimum moisture content, $w_{\text{opt}}$, of the mixture of the wastes at different ratios. The ratio between the base material of DW over FA is shown in Table 2. The results from the test would be used to estimate the amount of water added to the mixture of wastes to achieve a workable mixture during preparation of brick samples. It suggested that the optimum moisture content dropped from 29.0% to approximately 26.0% for 15, 30 and 45% of FA contents.

| Brick sample | Ratio of mixture (DW:FA) | $\rho_{\text{max}}$ (kg/m$^3$) | Opt. Moisture Content $w_{\text{opt}}$ (%) |
|--------------|--------------------------|-------------------------------|----------------------------------|
| DW100        | 100:0                    | 1.32                          | 29.0                             |
| DW85         | 85:15                    | 1.20                          | 26.1                             |
| DW70         | 75:25                    | 1.25                          | 26.4                             |
| DW55         | 55:45                    | 1.26                          | 26.1                             |

2.3. Preparation of Brick Samples

Fired brick samples were prepared by dried mixing of DW and FA. The ratio of added FA was based on 0, 15, 30 and 45% of the dry mass of the DW sludge. Once the FA was added, the mixture was mixed thoroughly in the container. Then, water was added 5% higher than optimum moisture content to produce workable mixture. The mixture was transferred into mould of 215 mm x 65 mm x 102.5 mm. A total of three layers and each layer received 27 blows by compaction hammer. The samples were left dried under room temperature for 4 days. The samples were removed from the moulds before carefully transferred into furnace for 24 hours at temperature of 105°C. Then the temperature was set up to 500 °C at increment of 30 °C/minute. At this stage, the firing process would take 3 hours and then the samples were kept inside for overnight cooling down before taking out of the furnace the next day.

2.4. Testing Procedures

The brick samples were examined for linear shrinkage, density, water absorption and compressive strength. The linear shrinkage of the bricks involved measurement of each final dimension after firing process. A total of 10 samples were used and each dimension was measured at three different positions. A vernier calliper was used to measure each dimension of individual brick. The linear shrinkage, $\Delta L$ was calculated according to the following equation:

$$\Delta L = \frac{L_o - L_f}{L_o} \times 100\%$$

where $L_o$ – measurement each dimension before firing, mm; $L_f$ – measurement of dimension after firing, mm. The volume change of brick, $\Delta V$ was calculated from the readings from the measurement of each dimension as shown by the following equation:

$$\Delta V = \frac{(V_o - V_f)}{V_o} \times 100\%$$

where $V_o$ – volume before drying and/or firing, mm$^3$; $V_f$ – volume after drying and/or firing, mm$^3$. The density tests of the bricks were performed according to Archimedes’ buoyancy principal [12]. The same bricks tested earlier were weighed, $m_i$ and marked with waterproof in for labelling purpose. Samples were immersed in a tank of water for 2 hours before taking out and let to drain quickly (less than a minute). Any excess water was wiped out from the surface of the brick and its mass was recorded, $m_1$. Then the brick was put on the apparatus to measure its submerged mass, $m_2$. This apparatus consists of
a steel cage to place the sample which connected to a digital weight indicator. These steps were repeated for all the bricks and the volume, $V$ is calculated based on the following equation:

$$ V = (m_1 - m_2) \times 1000 $$

where: $V$ – volume, mm$^3$; $m_1$ – mass of wet sample (gram); $m_2$ – mass of submerged sample (gram).

Hence, the density, $D$ can be calculated from:

$$ D = \frac{m_d}{V} \times 1000000 $$

where: $D$ – density of sample (kgm$^{-3}$); $m_d$ – mass of dry sample in gram; $V$ – volume of sample, mm$^3$.

The same bricks were also used to determine the water absorption. All the bricks were placed in a tank of water for 24 hours. Then the saturated mass was recorded, $m_w$, and water absorption, $w$ was calculated based on the following equation:

$$ w\% = \frac{m_w - m_d}{m_d} \times 100 $$

where: $w$ – percentage of water absorption; $m_d$ – dry mass (gram); $m_w$ – saturated mass (gram). The compressive strength test was performed by using Autocon 2000 Universal Testing Machine with 2000 kN maximum capacity. The brick sample was cleaned and a piece of hard wood was positioned on bed part of the brick. The brick was shearing by applying load at rate of 7.0 kN/s. Maximum load at failure ($N_f$) was recorded and would be used to determined its compressive strength, $\tau$. Three bricks were used in this test and the compressive strength was calculated from the following equation:

$$ Compressive~strength = \frac{Maximum~load~at~failure~(N_f)}{Area~(m^2)} $$

Determination of water absorption and compressive strength were carried out according to the BS 3921: 1985 [13]. Meanwhile, for the assessment of the resistance of the brick against sulphate attack, the samples were exposed to 10% of potassium sulphate (K$_2$SO$_4$) by daily spraying for a minute up to 28 days. Then, the samples were tested for their compressive strength.

### 3. Results and Discussion

#### 3.1. Linear shrinkage

After drying and firing processes, brick normally changes in its dimension and the change should be small. Change in dimension will end up with the overall volume of the final brick. The average and linear shrinkage of length $L_P$, width $L_W$ and height $L_H$ of the brick dimension are shown in Table 3. The linear shrinkage of each dimension dropped as FA content was increased. However, at 30% of FA content, brick showed apparent decrease of $L_P$, $L_W$ and $L_H$ represented by 28%, 45% and 66%, respectively. The shrinkage patterns in terms of volume change of the fired bricks are shown in Figure 1. As shown in Figure 1, significant change in volume was seen at 30% of FA content.

| FA content (%) | Length, $L_P$ (mm) | $L_P$ (%) | Width, $L_W$ (mm) | $L_W$ (%) | Height, $L_H$ (mm) | $L_H$ (%) |
|---------------|-------------------|-----------|-----------------|-----------|-------------------|-----------|
| 0             | 204.0±0.8         | 5.1       | 98.0±0.8        | 4.4       | 63.7±0.9          | 2.1       |
| 15            | 204.3±0.9         | 5.0       | 98.0±0.8        | 4.4       | 64.0±0.8          | 1.5       |
| 30            | 207.0±0.5         | 3.6       | 100.0±0.8       | 2.4       | 64.7±0.5          | 0.5       |
| 45            | 209.0±0.5         | 2.6       | 100.7±0.5       | 1.8       | 65.0±1.6          | 0.0       |
3.2. Density
The results of density of the fired bricks are shown in Figure 2. The value of the density gradually changed with slightly increased as FA contents were added. Increasing of the FA content has not contributed significant change in density of the fired brick. In terms of specific gravity, FA and DWS had very close value of 1.82 and 1.99, respectively (Table 2). Thus, alteration of the ratio of brick’s mixture from the addition of FA has insignificant effect on the density of the studied fired brick.

3.3. Water Absorption
Bricks should have very small water absorption capacity and this characteristic can enhance their mechanical strength. The result of water absorption test is shown in Figure 3. The fired brick displayed a decreasing trend up to 30 % of FA content. At FA content of 45 %, the water absorption increased to
40%. It was not very clear why the increase in water absorption occurred at this FA content. Therefore, it can be suggested that the optimum content of FA should be limited at lower than 45% for this type of brick with similar thermal treatment.

![Figure 3. Water absorption of the fired bricks.](image)

### 3.4. Compressive Strength

Brick is always used to support load and its load-bearing capacity is measured by the compressive strength value. Different ranges of compressive strength will be intended for different engineering applications [14]. The result of compressive strength of the studied bricks is shown in Figure 4. The studied bricks displayed a gradual decreasing trend as the FA contents were increased up to 30%. However, at FA content of 45%, a significant drop was observed from 1.83 MPa to 0.88 MPa representing a 57.4% loss in strength. It was found that the compressive strength is limited by the amount of FA contents. Previous studies also experienced similar findings from different base materials that being added with various ranges of FA contents [15],[16].

![Figure 4. Compressive strength of the fired bricks.](image)
3.5. Acid Sulphate Attack
The resistance of acid sulphate attack on the studied fired brick was accessed by the compressive strength tests. Bricks should withstand from the sulphate attack which can decay in their mechanical strength. Hot and humid nature of Malaysia pose a significant threat to brick and other masonry materials [17]. The result of compressive strength of the studied bricks against the sulphate attack is shown in Figure 5. As the content of FA increased, the compressive strength dropped from 1.91 MPa to 0.45 MPa. Similar trend was also seen where significant decreased at FA content of 45%.

![Figure 5. Compressive strength of the fired bricks against sulphate attack.](image)

4. Conclusions
This study managed to determine the mechanical characteristics of the studied brick fired at lower temperature of 500 °C with different ratios of drinking water sludge and fly ash contents between 0% and 45% of dry weight of drinking water sludge as base material. The linear shrinkage of each dimension apparently dropped at 30% of FA content which also agreed with the volume change of the fired brick. Density of the brick was not significantly change as FA content was added the brick. For the water absorption tests, brick displayed initial decreased up to 30% of FA content which later increased as FA was 40%. The compressive strength exhibited gradual drop as FA increased to 30% and experienced drastic decrease at 45% of FA content. This trend also observed for the assessment of the compressive strength against the sulphate attack where apparently drop was seen at similar FA content. Therefore, optimum FA content was important to be known prior mixing of brick’s raw materials otherwise it could deteriorate the quality of particular brick. In this study, with studied material and firing condition, it is suggested to limit the FA content of 30%.

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