UTILIZATION OF PULVERIZED FUEL ASH AS A CEMENT REPLACEMENT FOR SOIL-CEMENT BRICKS

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ABSTRACT

In Malaysia, coal is one of the energy resources. The requirements was predicted to be more than 22.5 million tons of coal utilized in 2010, which resulted in a large volumes of coal ash are produced as waste material. The utilization of Pulverized Fuel Ash (PFA) as a cement replacement in concert mixes has found high attention through the last few years. This study is based on laboratory works including determination of the optimum mix design which will lead to optimum compressive strength, water absorption and initial rate of suction of soil-cement bricks enhanced with (PFA).The replacement of some of the Portland cement offers greater potential as a method of reducing environmental impact. The experimental results showed that the Initial Rate of Suction of the bricks increases as the amount of the PFA increases till a certain limit and then start decreasing, that limit is when brick became durable because all the pores inside the brick are filled with PFA hence it will decrease the penetration of the water. According to the results of the 0%, 10%, 20% and 30% PFA the average compressive strength of soil-cement interlocking bricks with mortar fill was around 13.52, 9.42, 9.86 and 7.81 N/mm2 respectively, which illustrates that based on BS 3921 the interlocking brick unit, all can be classified as load bearing bricks class 1. It is found that soil-cement interlocking bricks containing up to 20% PFA is viable to be used as load bearing wall.

KEYWARDS: Pulverized Fly Ash (PFA), Interlocking Brick, PFA Soil-Cement Brick, Load Bearing Brick.

1- INTRODUCTION

Pulverized Fly Ash (PFA) is the ash resulting from the burning of pulverized bituminous, hard coals in power station furnaces. The furnaces are used to generate steam for the production of electricity with a typical temperature of >1400 ^{o}C. The resulting material is a siliceous ash consisting of oxides of silica, aluminum and iron, and containing < 10% calcium oxide. Many countries categorize siliceous fly ash as a construction material class F.

Coal is a readily available source of energy which consists of carbon and a mixture of various minerals (Shale, clays, sulfides and carbonates). Coal, a mineral substances of fossil origin and may be of one of four types: Anthracite (>90% carbon), Bituminous or Hard coal (~80% carbon), Lignite and brown Coal (<70% Carbon). Coal is delivered to the power stations in lumps of about 50 mm diameter or lesser. It is stored in heaps where it is compacted to prevent any un-controlled combustion or oxidation. The coal is recovered and placed in bunkers that supply the power station's coal mills which grinds the coal to a size 70% passing 75 μm. This finely ground coals is transported in a current of a heated air to the burners, where it is blown into the boiler. The pulverized coal is injected into the furnace in a stream of hot air. The coal burns in a multistage process suspended in the combustion air in the boiler, reaching a peak temperature of some 1450 ± 200 ^{o}C. This temperature is above the melting point of most of the minerals present, which undergo various chemical and physical changes. For example, clay forms glass spheres of complex silicates; pyrites is converted into oxides of sulfur and iron, including spherical particles of magnetite; and aluminum oxidizes.

The exact nature of the fly ash depends on a variety of factors including the temperature, the type and fineness of the coal, and the length of time the minerals are retained in the furnace. Approximately 80-85% of the ash carried out of the furnace by the exhaust gases is subsequently extracted by mechanical and electrostatic precipitators. The remaining 15-20%condenses on the boiler tubes and subsequently falls to the bottom of the furnace where it sinters to form furnace bottom ash (FBA). In the UK, FBA is flushed from the bottom of the furnace using water. It passes through a crusher and is then delivered to ash pits to drain. This material is then loaded directly into tippers where it is predominantly used for the manufacture of concrete building blocks.

World-wide there is a wide variance in utilization, ranging from virtually all the ash being dumped to total usage. In Netherlands, for example, it is illegal to dispose fly ash in the disposal site although it is estimated that some 250,000,000 tons of fly ash exists in stockpiles throughout the country that could be used as alternatives to naturally occurring aggregates. In UK the utilization rate has remained stable at ~50% of production for a number of years (BS 3921, 1985).

The manufacture of Portland cement, by the very nature of the constituents and its chemistry, involves the production of a number of so-called greenhouse gases. The main one is carbon dioxide CO_2, not only from the burning of fossil fuels but from the calcining of calcium carbonate to calcium oxide. Approximately 1 ton of CO_2 is produced for every ton of Portland cement made.

The replacement of some of the Portland cement offers greater potential as a method of reducing environmental impact. In the UK only two additions fit this category, ground granulated blast furnace slag (GGBS) and pulverized fuel ash (PFA).

In Malaysia, coal is an energy resource of which the requirement was predicted to be more than 22.5 million tons in 2010. As a result of large utilization of coal, large volumes of coal ash are produced as waste material. Direct use of this material in construction not only provides a promising solution to the disposal problem, but also provides an alternative to be used as fill material (Muhardi, 2011).

The main objective of this study is to evaluate the utilization of PFA as a cement replacement in soil-cement bricks. This study is based on laboratory works including determination of the optimum mix design which will lead to optimum compressive strength, water absorption and initial rate of suction of soil-cement bricks enhanced with Pulverized Fly Ash (PFA).

2- USING PULVERIZED FLY ASH (PFA) IN CONCRETE

2.1- British and European Standards for Fly Ash in Concrete

In 1999 NUSTONE carried out a program of testing of UK Pulverized Fly Ash (PFA) from five power stations using the test methods described in BS 3892 Part 1 and BS EN 450. This program was designed to assess the performance and variability of UK ashes when tested to the two standards. All samples were tested using both standards testing regimes. It was found that BS 3892 Part 1 requirements were more onerous as a fixed workability of the mortars tested is required. It has shown that the strength factor results and the high degree of scatter associated with taking a ratio of two strengths, e.g. the strength of the fly ash prism divided by the Portland cement prism (NUSTONE, March 2000).

An addition is defined in BS EN 206 as a finely divided inorganic material used in concrete to improve certain properties or to achieve special properties. There are two types of addition:

- Type I: these are nearly inert additions
- Type II: these are pozzolanic or latent hydraulic additions

Many additions of both types are available:

- PFA/fly ash (BS 3892 and BS EN 450): type II
- Ground granulated blast-furnace slag (GGRS): type II
- Filler aggregates (prEN I.2620): type I
- Pigments for building materials (BS EN 12878): type I
- Meta-kaolin and silica fume (prEN 13263): type II.

These may be used singly or in combination. Combinations of PFA to BS 3892: Part 1 &2 with Portland cement to BS 12 (or BS EN 197-1 Cement 1), count fully towards the cement content and W/C ratio in concrete provided that they have satisfied the equivalence testing procedures set out in the annex to BS 3892 (also as an annex within BS 8500) and (BS EN 196-1, 1995).

2.2- Properties of PFA

It is clear that characterizing the reactivity of Pulverized Fly Ash (PFA) is somewhat complex. The pozzolanicity depends on the surface area of fly ash exposed to the pore solution, the alkalinity of that pore solution, the curing temperature and the chemical composition of the fly ash, e.g. the source and type. Utilization of PFA in concrete may enhance characteristics of concrete products as follows:

a- Fineness and workability/strength characteristics

The particle shape and finer fractions of Pulverized Fly Ash are capable of reducing the water content needed for a given workability. These effects are felt to be due to void filling on a microscopic scale replacing water within the concrete mix. As with the pozzolanic activity, there is a trend towards a reduction in water requirement with increasing fly ash fineness. However, the strength performance may not be directly related to the fineness. Fly ash chemistry and surface area are the controlling factors. Fly ash affects the rate of gain of strength in concrete. At early ages, the rate of gain of strength is lower than an equivalent Portland cement concrete of similar grade. In the long term, however, it may be higher (Brown JH, 1980).

b- Heat of hydration

The development of concrete mix design has seen an increase in the proportion of cement being replaced by fly ash. Early uses of fly ash in concrete are concerned reducing the heat evolution in hardening concrete. In particular, for mass concrete in large dams it was found that by replacing a proportion of the cement with fly ash a large reduction in heat was achieved (Bogdanovic M., 1978).

The hydration of cement compounds is exothermic, with up to 500J/g being liberated. Concrete is a poor conductor of heat, with the result that the temperature at the interior of a concrete mass will raise significantly during the hydration cycle. At the same time, external surfaces will be cooled by ambient temperatures and damaging temperature gradients may occur, resulting in cracking in the section.

The introduction of fly ash to replace a proportion of cement in concrete influences the temperature rise during the hydration period. The rate of the pozzolanic reaction increases with increasing temperature; however, the peak temperatures in fly ash concrete are significantly lower than in equivalent Portland cement concretes.

c- Setting time and formwork striking

The inclusion of fly ash in concrete will increase the setting time compared with an equivalent grade of Portland cement concrete. There is undoubtedly a delay in the onset of the hydration of fly ash concrete, but it has been shown that the actual gain in strength once hydration has started is greater for fly ash concrete at normal temperature regimes. When 30% fly ash is used to replace Portland cement in a mix, the setting time may be increased by up to 2h. This increased setting time reduces the rate of workability loss. However, it may result in practical difficulties for finishing, particularly during periods of' low temperature.

Form work striking times at lower ambient temperatures normally will need to be extended in comparison to Portland cement concrete, especially with thin sections. In practice, vertical form work striking times can be extended without these affecting site routines, e.g. the formwork is struck on the following day. For soffit formwork, greater care has to be taken. Reference should be made to BS 8110 for recommended striking times.

d- Elastic modulus

The elastic modulus of fly ash concrete is generally equal to or slightly better than that for an equivalent grade of concrete. It has shown that the slower rate of gain in strength experienced with fly ash concrete followed by the ongoing development in strength. In a similar manner at early ages, the elastic modulus of fly ash concrete is marginally less than for equivalent Portland cement concretes at later ages (Dewar JD., 1980).

e- Creep

The greater strength gains of fly ash concretes have shown lower creep values, particularly under conditions of no moisture loss. These conditions may be found in concrete remote from the cover zone of a structure. Where significant drying is permitted the strength gain may be negligible and creep of ordinary Portland cement and fly ash concretes would be similar (Bouzoubaa N et al, 1997).

f- Tensile strain capacity

The tensile strain capacity of fly ash concretes has been found to be marginally lower than for Portland cement, and fly ash concretes exhibit slightly more brittle characteristics. There is possibly a greater risk of early thermal cracking for given temperature drop, partially offsetting the benefits of lower heat of hydration in the fly ash concrete.

g- Curing

The hydration reaction between cement and water provides the mechanism for the hardening of concrete. The degree of hydration dictates strength development and all aspects of durability. If concrete is allowed to dry out hydration will cease prematurely- fly ash concrete has slower hydration rates and the lack of adequate curing will, as with other concretes, affect the final product. Thin concrete sections are more vulnerable than constructions of thicker section, where heat of hydration will promote earlier hydration (Bouzoubaa N et al, 1997).

h- Durability of the concrete made with fly ash

Listed benefits of using fly ash e.g. low permeability, resistance to sulfate attack, alkali silica reaction and heat of hydration has gave references to the conclusions that concrete, which does not contain fly ash, belongs in a museum.

Penetration of concrete by fluids or gases may adversely affect the durability. The degree of penetration depends on the permeability of the concrete, and since permeability is a flow property it relates to the ease with which a fluid or gas passes through it under the action of a pressure differential.

i- Alkali Silica Reaction

The Alkali Silica Reaction (ASR) is potentially a very disruptive reaction within concrete. However, the amount of damage that has occurred is small in comparison with the amounts of concrete produced. The first reported occurrence in the UK was in 1976 and by 1983 some 50 cases were known. ASR involves the higher pH alkalis such as sodium and potassium hydroxides reacting with certain forms of silica, usually within the aggregates, producing gel. This gel has a high capacity for absorbing water from the pore solution, causing expansion and disruption of the concrete. The main source of the alkalis is usually the Portland cement or external sources such as cleaning fluids containing sodium hydroxide. Fly ash contains some sodium and potassium alkalis but these are mainly held in the glassy structure and therefore are not available for reaction. Typically, only some 16-20% of the total sodium and potassium alkalis in fly ash arc water soluble.

Many researchers have found that fly ash is capable of preventing ASR. The glass in fly ash is in a highly reactive fine form of silica. It has been found that the ratio of reactive alkalis to surface area of reactive silica is important in ASR. However, by adding more reactive silica the dilution of the reaction with the alkalis, coupled with the low permeability of fly ash concrete, effectively means that no disruptive reaction happens. The recommendations within the UK require a minimum of 25% BS 3892 Part 1 fly ash to prevent ASR.

It has found that the mechanism by which fly ash reduces the risk of ASR can be summarized as:

- The fly ash pozzolanic reaction is similar to the alkali silica reaction,
- Pessimum proportions of SiO_2 /Na_2O must exist for disruptive ASR to occur,
- As the *Ca/Si* ratio decreases the alkali cations are more readily taken up by the SiO_2,
- More C-S-H hydration products are formed rather than expansive gel.

j- Carbonation

The ingress of CO2 into concrete and the subsequent conversion of lime to carbonate reduce the pH of the matrix to about 9.To occur this mechanism requires two factors, some moisture in the concrete, but not saturated, and a path by which the CO_2 can diffuse through concrete. This reaction is not detrimental to the concrete as such; in fact, it may help to reduce permeability and improve sulfate resistance, but is deleterious to the reinforcing steel in reinforced concrete. The high pH found in normal concrete maintains a passivity layer on the reinforcements which prevents corrosion. As fly ash pozzoianically reacts with lime, this potentially reduces the lime available to maintain the pH within the pore solution. However, fly ash reduces the permeability of the concrete dramatically when the concrete is properly designed and cured.

It is clear that carbonation is a complex function of permeability and available lime. With properly designed, cured and compacted fly ash concrete, carbonation is not significantly different front other types of concrete. With extended curing and the low heat of hydration properties of fly ash concrete, the resulting low permeability may more than compensate for the reduced lime content.

3- RESULTS AND ANALYSIS

216 PFA soil-cement brick samples was tested in which the quantity of PFA in the mixture was gradually increased by ten percentage points, starting at 0% and going to 30%, were examined in order to determine the maximum amount of cement that can be replaced by PFA while maintaining the desirable physical and mechanical properties of the brick. Twenty-eight days after the bricks were cast; their properties were tested in the BD lab in Universiti Tenaga Nasional. The Water Absorption test, Initial Rate of Suction, Compressive strength and Prism for 3 and 5 layers were determined.

3.1- Water Absorption

Water absorption test was performed in accordance with the BS 3921(British Standards Institute, 1985). 40 samples were examined, 10 samples for each percentage. The samples were first dried in oven at a temperature of 110 ^{o}C for 48 hours, and then the weight was taken after cooling the samples in a ventilated room for 4 hours. Immediately after weighting, the samples was place in a water tank boiled for 5 hours continuously, as shown in figure (1), and then allow to cooling to room temperature by natural loss of heat for 19, then the samples was removed from the water tank and wiped off the surface water with a damp cloth and weighted.

Results of water absorption were presented by Fig (1). The experimental results showed that the water absorption of the bricks increases as the amount of the PFA increases till a certain limit and then start decreasing, figure (1), that limit is when brick became durable because all the pores inside the brick are filled with PFA hence it will decrease the penetration of the water. The average water absorption of the 30% PFA brick is 20.65% and based on the BS 3921 there is no limitation for the load bearing brick. Therefore, interlocking bricks that contain up to 30% PFA may be used for construction.

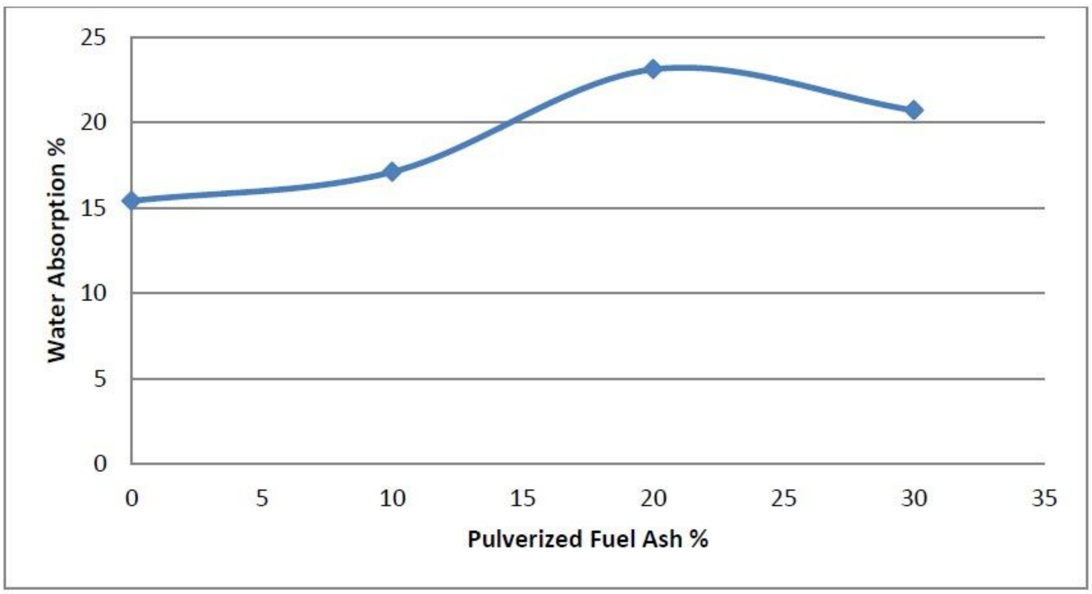

Fig (1) Relationship between water absorption and percentage of PFA

3.2- Initial Rate of Suction

Initial rate of suction test was performed in accordance with the BS 3921 (British Standards Institute, 1985). 40 Samples were examined, 10 samples for each percentage. The samples were first dried in oven at a temperature of 100 ^{o}C for 48 hours, and then the weight was taken after cooling the samples in a ventilated room for 4 hours. Cooling was assisted by passing an air oven over the bricks using an electric fan for period of 2 hours upon the cooling, the bricks weighed and then the dry mass was recorded. The pre-weighed dry bricks were placed on the large shallow rectangular pan whilst the water level is closely observed with measuring gauge to ensure that the depth of the immersion for the bricks was maintained at 3±1 mm as shown in figure (2), throughout the duration of immersion for the bricks which was for 60 seconds. After 60 seconds the bricks were removed from the water and excess water was wiped out with damp cloth. The bricks were reweighed and the wet mass was recorded. The Initial Rate of Suction was evaluated from the equation: $IRS = \frac{1000(m_2-m_1)}{A}$ Where IRS is the Initial rate of Suction (kg/m2.min), m_1 is the mass of the dry brick in grams, m_2 is the mass of the wet brick in grams and A is the area of the immersed face of the brick in mm^2.

The experimental results showed that the Initial Rate of Suction of the bricks increases as the amount of the PFA increases till a certain limit and then start decreasing (Fig 2), that limit is when brick became durable because all the pores inside the brick are filled with PFA hence it will decrease the penetration of the water. The Initial Rate of Suction of the 30% PFA brick is 6.46 Kg/min, and based on the BS 3921 there is no limitation for the load bearing brick. Therefore, interlocking bricks that contain up to 30% PFA may be used for construction.

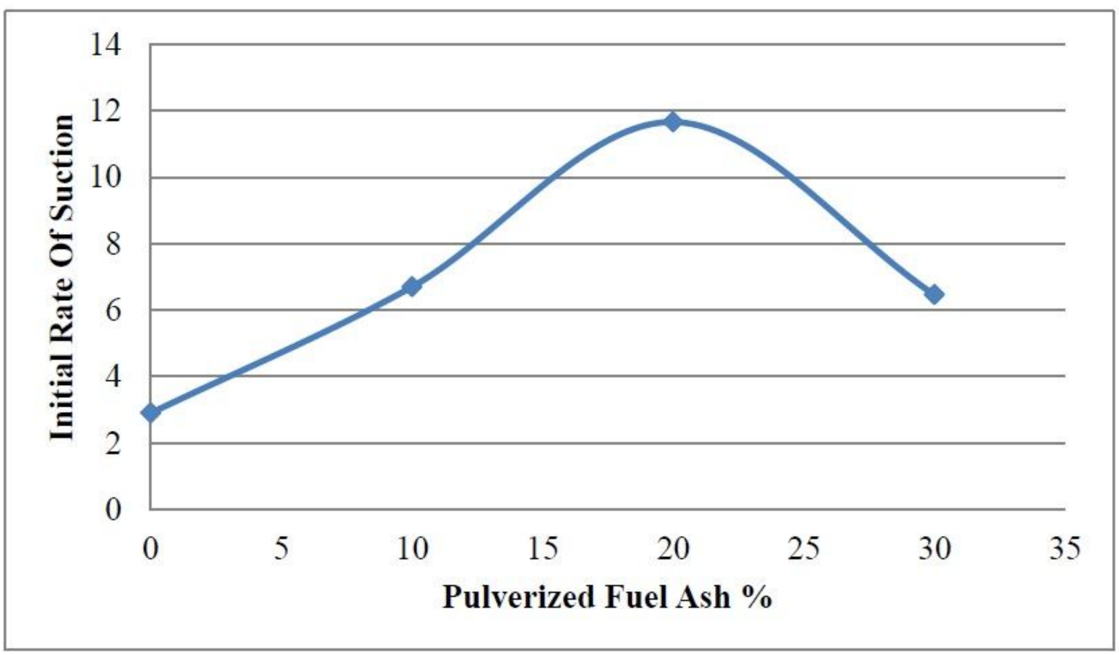

Fig (2) Relationship between water absorption and percentage of PFA

3 .3- Compressive Strength

Compressive Strength test was performed in accordance with the ASTM: C67 for bricks with and without mortar filling (Fig 3). 30 Samples were examined, 5 samples for each percentage. The samples were first flatten, then examined. The compressive strength of the samples was calculated from the equation: $C = W/A$, Where C: is the compressive strength of the specimen (MP_a), W: is the maximum load (N) and A: is the average of gross area (mm^2).

Fig (3) Flatted surface of Soil –cement interlocking brick without mortar fill

According to the results of the 0%, 10%, 20% and 30% of PFA, the average compressive strength of soil-cement interlocking bricks ***without mortar*** is around 10.5, 7.72, 8.48 and 6.59 N/mm^2 respectively which illustrates that based on BS 3921 the interlocking brick unit, all can be classified as load bearing brick class 1. Table (1) shows a sample of tabulated test results.

Table (1) Results of the Compressive Strength for 0% PFA bricks without Mortar Filling, Results was taken from (Ahmed Z. et al., 2011)

Sample No	**Length (mm)**	**Width (mm)**	**True Area A (mm^2)**	**Maximum load W (kN)**	**Strength C (MPa)**
1	250	125	20455.5	158.2	7.73
2	250	125	20455.5	214.62	10.49
3	250	125	20455.5	194.65	9.52
4	250	125	20455.5	253.34	12.39
5	250	125	20455.5	252.36	12.34
Average				**214.634**	**10.494**

The compressive strength of the soil-cement interlocking bricks without mortar fill decreased as the amount of PFA increased. The statistical analyses determined the average values and then the relationship between PFA (on the X-axis) and the compressive strength (on the Y-axis) could be identified, as shown in figure (4). The compressive strength of the bricks was highest for 0% PFA, and decreased gradually as the amount of PFA increased from 0% to 30% as shown in figure (4).

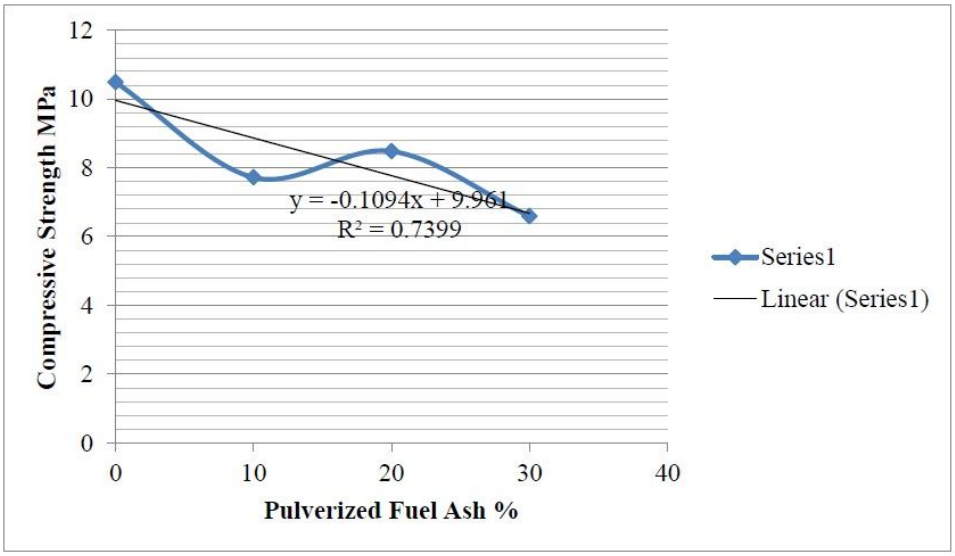

Fig (4) Relationship between Compressive Strength and Percentage of PFA (Without Mortar Fill)

According to the results of the 0%, 10%, 20% and 30% PFA the average compressive strength of soil-cement interlocking bricks ***with mortar*** fill was around 13.52, 9.42, 9.86 and 7.81 N/mm^2 respectively, which illustrates that based on BS 3921 the interlocking brick unit, all can be classified as load bearing bricks class 1.

The compressive strength of the soil cement interlocking bricks with mortar fill decreased as the amount of PFA increased. The statistical analyses determined the average values and then the relationship between PFA (on the X-axis) and the compressive strength (on the Y-axis) could be identified, as shown in figure (5). The compressive strength of the bricks was highest for 0%

PFA, and decreased gradually as the amount of PFA increased from 0% to 30% as shown in figure (5).

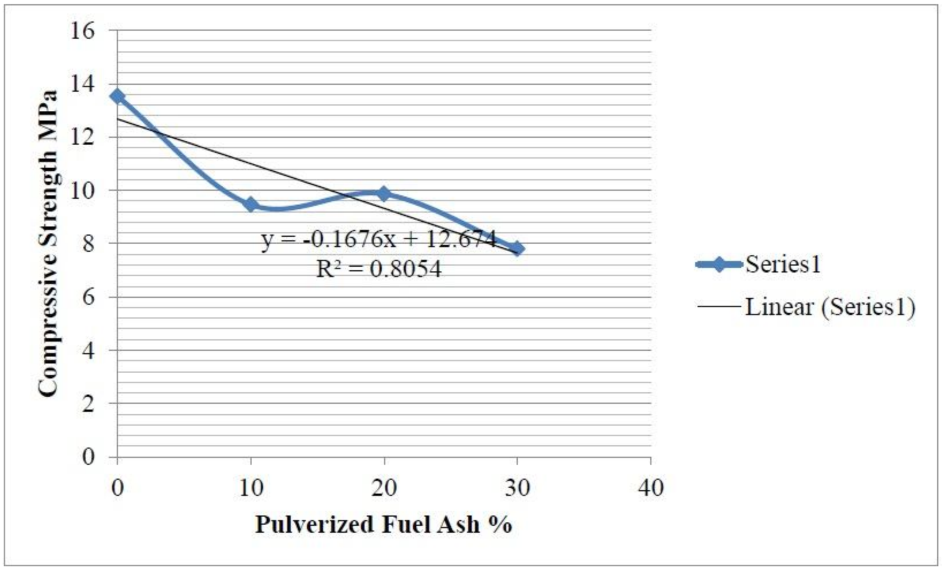

Fig (5) Relationship between Compressive Strength and Percentage of PFA, (With Mortar Fill)

3.4- Prism

Compressive Strength of Prism was performed in accordance with (ASTM C 1314, 2003), 3-layer and 5-layer Soil-cement interlocking bricks with mortar fill were examined. After 14 days from the prisms was built, they were tested for compression. Loading on prisms was performed in accordance with the ASTM C1314. The compressive strength of the prisms is calculated using the gross area of the brick which is equal to 31416.76 mm^2. According the (ASTM C 67, 1989), the compressive strength is multiplied by a correction factor corresponding to the aspect ratio for that prism.

Three layers prism, height equal to 312.5 mm and width of 125.583 mm and that gives an h/t of 2.49 hence, according to results, correction factor was 1.04. The results of compressive strength of 3-layer prisms and stress strain relationship graphs are presented below.

According to figure (6), (7) and (8), Stress-Strain relationship of 3 samples of 3-layer prism will be as follows:

i. For 10% PFA the average modulus of elasticity is equals to 678.9 Mpa, maximum Stress is 2.979 Mpa, and Strain is 0.00395.

ii. For 20% PFA the average modulus of elasticity is equals to 2522.73 Mpa, maximum Stress is 2.758 Mpa, and Strain is 0.00397.

iii. For 30% PFA the average modulus of elasticity is equals to 2286.95 Mpa, maximum Stress is 3.190 Mpa, and Strain is 0.00154.

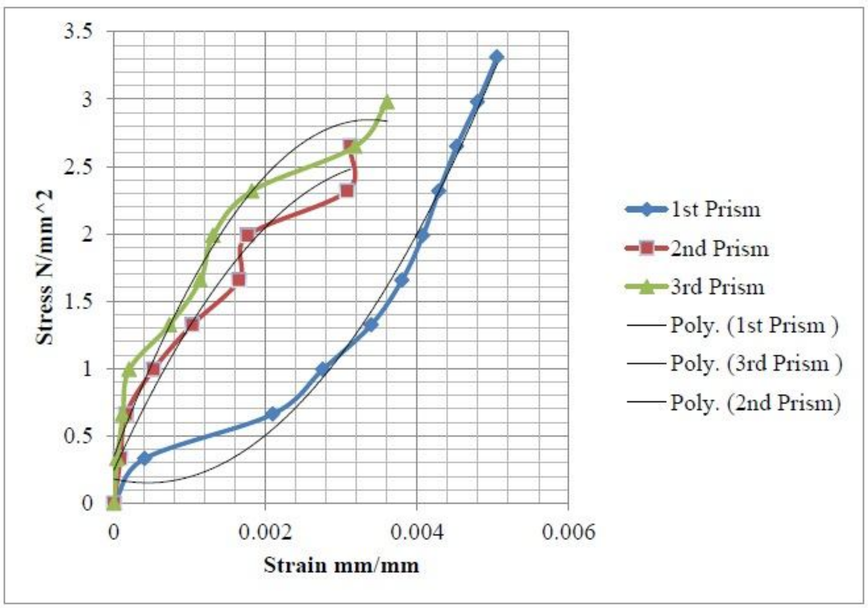

Fig (6) Stress-Strain curves of 3-layer prisms for 10% PFA

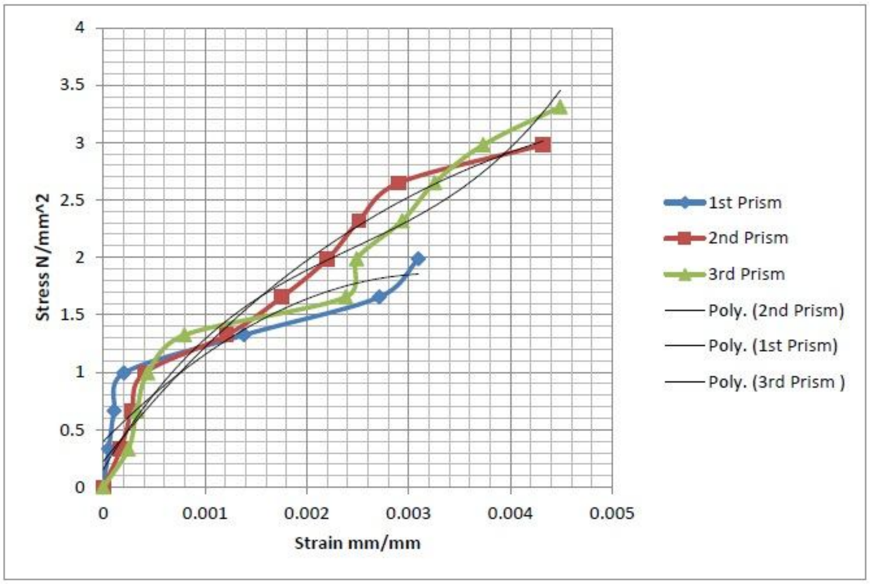

Fig (7) Stress-Strain curves of 3-layer prisms for 20% PFA

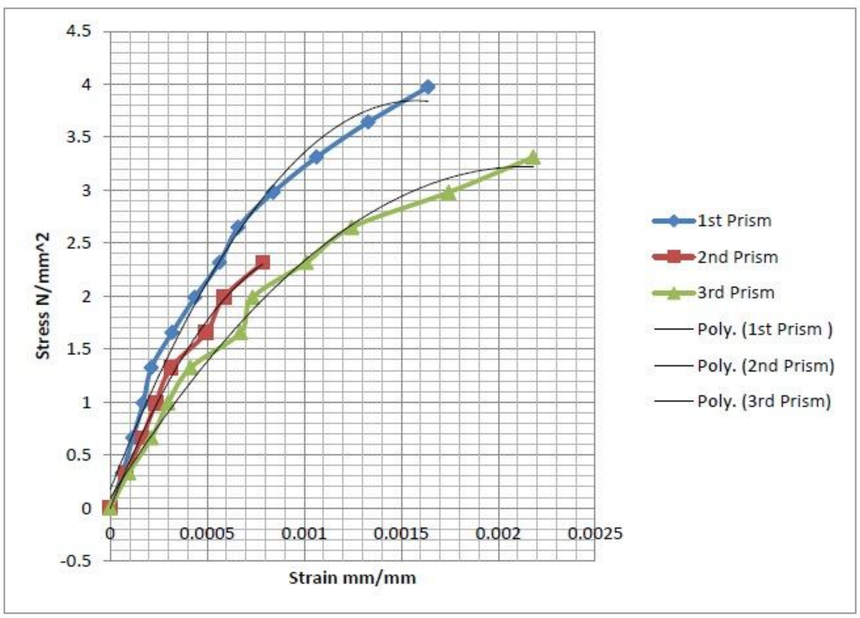

Fig (8) Stress-Strain curves of 3-layer prisms for 30% PFA

For the 5-layer prisms the height was equal to 518.6 mm and the width of 125.583 mm and that give h/t of 4.13 and the correction factor is 1.16. The results of compressive strength of 5-layer prisms and stress strain relationship graphs are presented below.

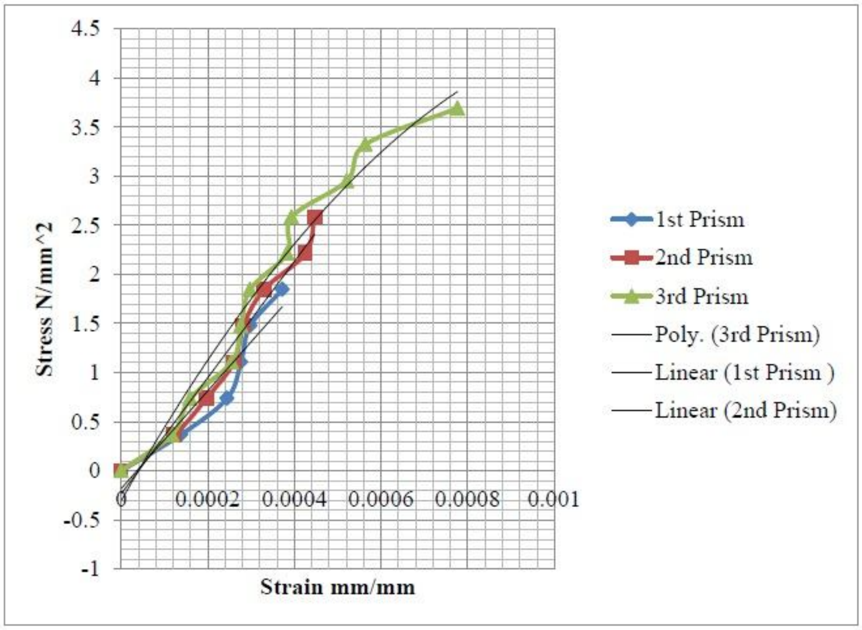

Fig (9) Stress-Strain curves of 5-layer prisms for 10% PFA

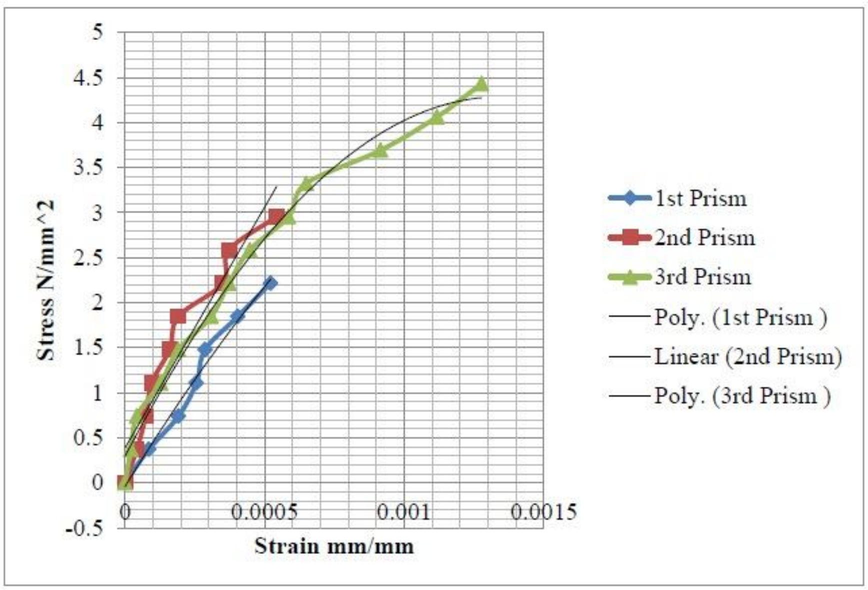

Fig (10) Stress-Strain curves of 5-layer prisms for 20% PFA

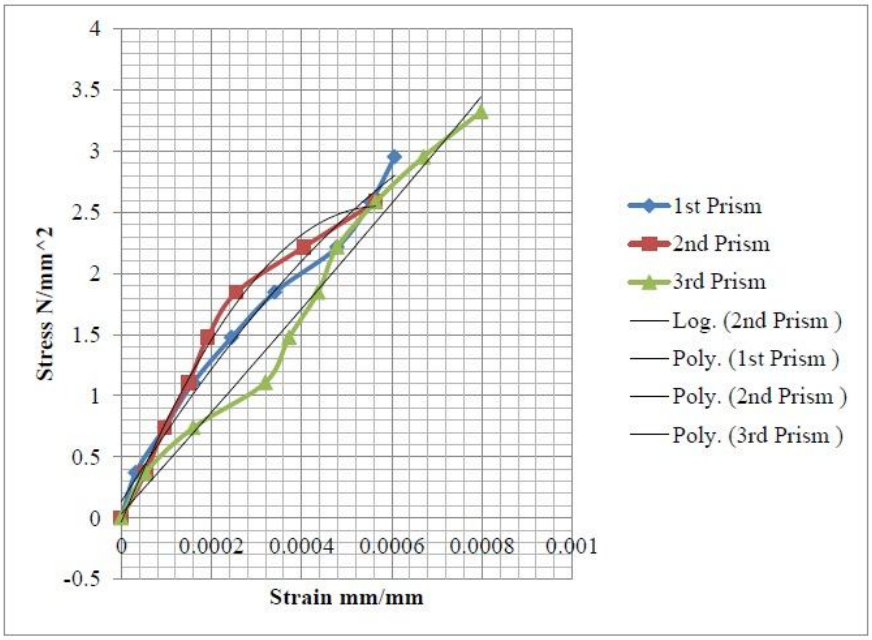

Fig (11) Stress-Strain curves of 5-layer prisms for 30% PFA

According to figures (9) ,(10) and (11) Stress-Strain relationship of 3 samples of 5-layer prism for 10%, 20% and 30% PFA soil-cement brick, are as follows:

i. 10% PFA - the average modulus of elasticity equals to 5579.76 Mpa, maximum Stress is 2.831 Mpa, and strain is 0.000557.
ii. 20% PFA - the average modulus of elasticity equals to 7233.44 Mpa, maximum Stress of 3.20 Mpa, and strain of 0.00078.
iii. 30% PFA - the average modulus of elasticity equals to 5300.2 Mpa, maximum Stress is 2.954 Mpa, and strain is 0.00235.

4- CONCLUSION

Based on the experimental investigation and analysis done, the objective of the research stated above has been successfully achieved. It, also, can be concluded that:

1- The research results supported the use of 20% Pulverized Fuel Ash extracted from Kapar Energy Vantures Sdn. Bhd. Malaysia, for making soil-cement bricks that have the appropriate mechanical and chemical properties to be used as a load bearing PFA soil-cement interlocking bricks.

2- The average water absorption of the 30% PFA brick is 20.65% and based on the BS 3921 there is no limitation for the load bearing brick. Therefore, interlocking bricks that contain up to 30% PFA may be used for construction.

3- The Initial Rate of Suction of the 30% PFA brick is 6.46 Kg/min, and based on the BS 3921 there is no limitation for the load bearing brick. Therefore, interlocking bricks that contain up to 30% PFA may be used for construction.

4- Soil-Cement Interlocking brick containing up to 20% PFA shows a unit optimum compressive strength of 9.86 Mpa.

5- The 3-layer and 5-layer brick prism tests for 20% PFA soil-cement interlocking have the average maximum stress of 2.76 Mpa and 3.20 Mpa respectively.

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