Development of low-cost fly ash bricks

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Abstract

Fly ash is produced in vast quantities as a by-product of the burning of fossil fuels for the thermal generation of electricity. At present 10-15% of the fly ash produced in Australia is utilised in cement manufacturing and concrete industry, with the remaining majority requiring costly disposal processes. Due to growing environmental concerns and the need for cleaner production, the management of fly ash has become an important issue facing the power generation industry. For that reason, many researchers are actively working to find new and improved methods of combating the fly ash waste disposal problem, particularly by establishing its useful and economic utilisation. One such example that is gaining considerable interest in many parts of the world is the utilisation of fly ash in brick manufacturing.

This paper examines the potential for using Class F fly ashes from Queensland as major constituents in the manufacture of common residential building bricks. Scaled-down pressed bricks were made by varying proportions of fly ash, sand, hydrated lime, sodium silicate and water. Both fired, oven-dried and air-cured bricks were tested for their properties including compressive strength, tensile strength, water absorption, and durability. In the paper, the test results are analysed and effects of variables discussed. Recommendations and conclusions as to whether or not the fly ash bricks can perform adequately alongside the clay bricks are included.

Keywords: Construction material, Brick, Fly ash, Sodium silicate, Masonry

1. Background

Housing shortages in many developing countries have stimulated efforts to develop construction methods that use cheap and durable local materials. It is essential to develop technologies that use minimal resources because of the increasing shortage of energy and raw materials. In this regard, the International Development Research Centre (IDRC) in Canada [1] noted that one of the most promising building materials for many countries is the fired clay brick. Traditionally produced in a cottage industry setting, fired clay brick production plays a major role in the informal economy of such countries. However, it is hampered by a number of problems:

Brick makers have little training;

The quality of bricks produced is low, and supply is irregular;

Great quantities of firewood are needed for production while energy loss (in the form of heat) is high at 40-50%; and

The process is damaging to the environment.

On the other hand, in many countries, electricity is often supplied by coal-powered generators. In the power stations, approximately 80-90% of the ash formed from burnt coal is carried out of the furnace, then extracted from the flue gas and is known as fly ash. Large quantities of fly ash produced as a by-product of coal-based power stations have been viewed as a serious environmental problem. It is not surprising that with growing environmental awareness, there has been considerable interest in the use of fly ash in the brick manufacturing industries. At present, India has been leading the way in fly ash brick manufacturing.

The use of fly ash in brick manufacturing is not new. Sloanaker [2] studied class F fly ashes from the USA to produce fired bricks for construction. It was indicated that fired bricks made from feeds of 72% fly ash, 25% bottom ash, and 3% sodium silicate met commercial specifications. In India, Rai [3] was able to produce calcium silicate type bricks using fly ash, sand and lime mixtures, while in Australia, Kayali [4] patented a new process to produce bricks from 100% fly ash which has a compressive strength of more than 40 MPa using a kiln with a firing temperature of 1000°C - 1300°C. In addition, it is worth noting that the possibility of developing non-fired (air-cured) fly ash bricks was studied in Israel [5].

This paper describes an experimental investigation into the use of fly ash in making pressed fly ash bricks by firing, oven-drying and air-curing. Tests were carried out to determine the strength characteristics and water absorption properties of the bricks.

2. Materials

In the current investigation, pressed bricks were made using fly ash and other materials such as sand, lime and sodium silicate of various proportions, wherein the amount of fly ash was at least 50% by mass.

A dry processed "fine-grained" ash from Queensland, namely the Tarong fly ash, was chosen as the main constituent in this investigation. The ash is classified as a low iron mix with more than 75% of constituents as oxides of Silica and Alumina (see Table 1).

Table 1: Main Constituents and Properties of Tarong Fly ash

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	TiO_2	Mn_2O_3
0.1%	70%	25%	1%	0.1%	0.01%	0.1%	0.5%	1.6%	0.03%
Note: pH = 4 Particle density = 2.14 Loss on ignition = 1.5									

Fly ashes are pozzolanic materials, i.e. they react with water with the addition of lime (CaO) to form cement materials. Some fly ashes have a sufficient amount of "free lime" such that they have self-cementing characteristics. However, Queensland fly ash contains low (< 4%) CaO contents (i.e. class F fly ash) and hence, it does not show appreciable self-cementation behaviour.

To improve the mix gradation and workability, two types of sand were used in this study, namely:

- Silica sand: this sand is normally used for the manufacture of domestic glass and has a silica content of about 98%.
- River sand: common sand normally used in concrete manufacture.

Liquid Sodium Silicate (LSS) Grade 42 (SiO_2 : Na_2O = 3.22, total solids = 39.3%, pH = 11.2) was used as an additive in this investigation. This material, also known as water-glass, is generally considered to be non-hazardous although skin contact should be minimised to avoid irritation. It is expected that by adding water-glass, silicon-oxygen anions found in fly ash go into solution and form polymers which begin to coagulate in the liquid during curing [5]. The alkali of the sodium silicate then reacts with silica present in fly ash in the glass phase, strengthening this process of polymerisation and coagulation, ending with the generation of a water-stable silica gel. Dehydration of the silica gel and consolidation of the structure subsequently produces an increase in the strength of the bonds, resulting in the creation of a hard, solid material.

Commercial building lime (hydrated lime) was used to trigger the pozzolanic reaction of the class F fly ash (and hence improve the strength and durability of the bricks). Care was taken to avoid "scumming" and after trial and error testing, each fly ash brick was prepared with a constant amount of lime (5% of total mass). This additional lime did not seem to cause any "scumming" after firing.

3. Specimen preparation

There were four major steps involved in producing the test specimens. These included, proportioning of constituents, mixing, moulding/pressing of green bricks and followed by firing, oven-drying or air-curing.

Initially, three different combinations of fly ash and sand (i.e. primary raw materials) were used, namely, 50/50, 70/30 and 90/10. Liquid Sodium Silicate (5, 10, 15 and 20%) and hydrated lime (5%) contents were added to the mix with proportions calculated by multiplying the percentages in parenthesis by the total mass of primary raw materials.

The mixing of constituent materials was performed in two stages. First, the dry materials (ash, sand, lime) were mixed thoroughly using a 15 litre mechanical mixer. The second stage involved the addition of LSS and water (as required). This was done gradually until the mixture was of a uniform and mouldable consistency.

A steel mould with moveable top and bottom platens was used to produce the green bricks. With the bottom platen supported by four springs, the mould assembly was placed on a hydraulic press machine (Figure 1). It was found by trial and error that 150 grams of mix, moulded using pressure of around 10 MPa would produce a test brick of approximately 78 mm x 38 mm x 27 mm; the ratio of these dimensions are similar to those of a common house building brick (225mm x 105mm x 75mm).

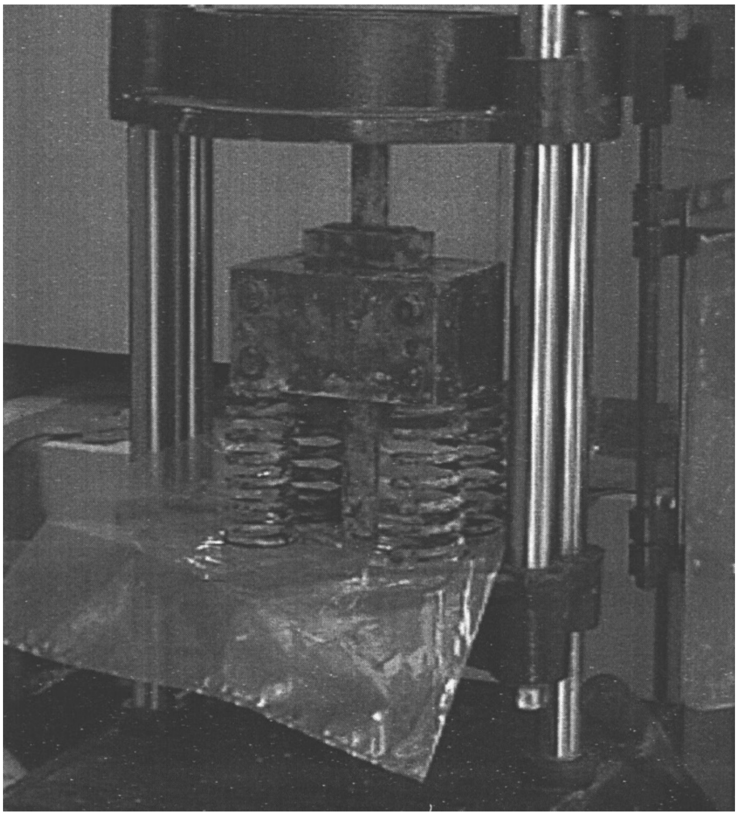

Figure 1: Brick Casting Using a Hydraulic Press Machine

To produce fired bricks, a high temperature oven was used. An initial study carried out to find the effect of firing temperature indicated that a firing temperature of 555°C was adequate. The green bricks were placed in the oven with an initial temperature of 25°C. This was increased gradually to 555°C in 120 minutes and subsequently kept at 555°C for 100 minutes. Thereafter, the oven temperature was dropped back to 35°C over 100 minutes and the bricks were then cooled to ambient temperature with the oven door ajar. The brick specimens were subsequently removed, weighed, measured and visually inspected.

In addition to the above, a number of non-fired bricks were studied in the present investigation. The first was air-cured bricks, which were placed in airtight plastic bags for 28 days before testing. The use of airtight bags was intended to reduce the effects of carbonation, which is a problem known to affect concretes high in fly ash and lime content. Other bricks were cured in a standard oven at 105°C for 24 hours, and a limited number of bricks were cured in open air prior to testing.

4. Testing and results

4.1 Fired bricks

It was observed that bricks with high moisture content values usually developed hairline surface cracks after firing. Excessive moisture contents were associated with gross shrinkage, leading to the development of severe cracks and loss of strength, and hence moisture contents were kept below 30%. Test results generally indicated that to achieve optimum performance, the moisture contents of both fly ash/silica sand and fly ash/common sand mixes had to be within the range of 25±2%.

The dry density of the green bricks is proportional to the densities of the brick constituents and primarily the moulding pressure used to form the bricks. The moulding pressure used was 10 MPa, a value commonly used in clay brick production. This produced brick specimens having dry densities ranging from approximately 1.15 t/m^3 to 1.65 t/m^3. For optimum performance, however, bricks made from fly ash/silica sand and fly ash/common sand would need dry densities of approximately 1.40 t/m^3 and 1.60 t/m^3, respectively. Compared to dry densities of 2.25 t/m^3 to 2.8 t/m^3 for clay bricks, the proposed fly ash brick was remarkably lighter.

Compressive strength is the only mechanical property used in normal brick specification; it is the failure stress measured normal to the bed face (as the majority of brickwork only experiences vertical compressive loads due to the self-weight of the brickwork and bearing loads). Three specimens were tested for each batch of bricks in accordance with AS/NZS4456.4.

For each tested specimen, the failure load was noted and recorded to estimate the uniaxial compressive strength; given by Equation 1 below.

$$\sigma_c = K_a(1000P/A) \qquad (1)$$

Where σ_c = uniaxial compressive strength (MPa),

P = failure load (kN),

A = net cross-sectional area (mm^2), and

K_a = aspect ratio factor (to allow for height-to-thickness ratio), in this case 0.61.

The results, as shown in Table 2, indicate that the compressive strength of the fired bricks under investigation increased rapidly with the amount of LSS up to approximately 15% by mass. It can also be seen that for bricks containing silica sand, higher proportions of fly ash to sand tend to exhibit greater strengths.

Additions of LSS in excess of 15% by mass lead to high moisture content values in the green bricks made with 50/50 and 70/30 fly ash/silica sand. Consequently, these bricks experienced more shrinkage/cracking, which caused a weakening of microstructural bonds and ultimately a decrease in compressive strength. Bricks made with 90/10 fly ash/silica sand, however, continued to increase in compressive strength with additions of LSS up to twenty percent. It can be seen from the results that compressive strengths greater than 20 MPa were easily achieved by all mixes containing silica sand and 15% LSS, and strengths >25 MPa could be achieved with the 90/10 fly ash/silica sand mixture incorporating 20% LSS.

Table 2: Uniaxial Compressive Strength (Average Values)

	COMPRESSIVE STRENGTH, σ_c (MPa)	
% LSS by mass	WITH SILICA SAND	WITH COMMON SAND
50/50 FLY ASH/SAND		
5%	8.57	9.37
10%	7.55	15.41
15%	23.49	30.82
20%	12.29	-
70/30 FLY ASH/SAND		
5%	8.25	8.11
10%	11.40	11.72
15%	26.98	25.91
20%	24.31	-
90/10 FLY ASH/SAND		

5%	10.01	7.56
10%	16.66	12.72
15%	24.29	24.10
20%	27.81	-

For bricks containing common sand, it was also found that the compressive strength increased rapidly with the amount of LSS up to approximately 15% by mass. As with the bricks made using silica sand, the bricks containing common sand also became saturated when amounts of LSS were increased to 20% by mass to an extent that the raw mixture was non-workable; rendering moulding, extraction and handling impossible. Hence, mixtures containing 20% by mass of LSS were discarded as being unviable.

At 15% LSS, the 50/50 fly ash/common sand mixture performed differently than bricks made with silica sand; the former clearly exhibited the highest average strength (>30MPa). However, with the objective being to maximise fly ash utilisation and the fact that the 70/30 mixture of fly ash/common sand produced the most consistent results averaging around 25MPa with 15% LSS, it could be selected as the most viable mixture alternative.

For the indirect tensile strength, the testing method was in accordance with AS/NZS4456.14. The test simply involves applying a line load to a brick, supported by a linear reaction in the plane of linear loading to cause the brick to fail/split.

The failure load is indirectly related to the tensile strength of the brick (Equation 2).

$$f_s = 2F_s/(3.142bh) \tag{2}$$

Where f_s = tensile strength (MPa),

F_s = maximum splitting load (N),

b = width of chosen cross-section (mm), and

h = height of chosen cross-section (mm).

The average results, as shown Tables 3, indicate that the indirect tensile strength of the bricks tends to increase with increased additions of LSS. Increasing the amount of LSS from 5% to

15% by mass brought about an increase in tensile strength from less than 1 MPa to something close to 2 MPa.

The mixture of 70/30 fly ash/silica sand with 15% LSS produced consistent results averaging around 2.3 MPa. In general, compared to the tensile strength of common clay bricks, the tensile strength of the fly ash bricks was lower (2 to 3 MPa less).

The water absorption of a brick is the percentage increase in mass of a dry brick when it has been saturated. The test for water absorption properties was performed in accordance with AS/NZS4456.14. Two types of water absorption tests were performed, i.e. cold water 24-hour immersion test and 5-hour boiling water test. The results are shown in Table 4.

It can be seen from Table 4 that the experimental bricks exhibited distinct water absorption characteristics with respect to their constituent proportions of fly ash, sand and LSS content.

The water absorption of all brick mixes decreased with increasing LSS content. This was expected as increasing the LSS content, produces more impermeable bricks and hence, the potential for capillary action reduces, subsequently decreasing the water absorption capacity of the product.

The percentage water absorption of all bricks increased with increased fly ash content. The 90/10 fly ash/sand brick exhibited the greatest water absorption characteristics, whereas the 50/50 fly/sand brick exhibited the lowest and most promising water absorption characteristics, and the 70/30 fly ash/sand brick exhibited water characteristics between the two mentioned extremes.

In comparing cold and boiling water absorption results, it is evident that little difference exists between these properties. This is due to the fact that the testing method period was lengthy enough for the test bricks to become saturated during both testing procedures.

The results achieved for the bricks made with silica sand are slightly irregular when compared to those of the bricks made with common sand. The tendencies described above still apply but are not as distinct to the eye as those derived for bricks with common sand.

The optimum blends of 70/30 fly ash/sand showed distinct differences in water absorption properties for the different sand types used. The bricks made with silica sand exhibited unacceptable water absorption as compared with those of the bricks made with common sand. The latter averaged approximately 13% water absorption, when 15% LSS was used, which can still be considered comparable to that of typical clay bricks.

Table 3: Indirect Tensile Strength (Average Values)

FLYASH/SAND RATIO	% LSS BY MASS	TENSILE STRENGTH, f_S (MPa) WITH SILICA SAND	WITH COMMON SAND
50/50`	5	0.66	1.01
	10	0.75	1.86
	15	1.66	2.69
	20	1.57	0
70/30	5	0.73	1.64
	10	1.63	1.15
	15	2.30	1.95
	20	2.76	-
90/10	5	0.94	1.17
	10	2.71	0.99
	15	1.68	1.93
	20	2.69	-

4.2 Non-fired bricks

As mentioned earlier, Freidin & Erell [5] reported the results of an experiment whereby air-cured bricks were made from fly ash, slag and water-glass. If air-cured bricks could perform adequately, it would certainly be the most economical option. In the present investigation, it was decided to prepare non-fired bricks with 70/30 fly ash/sand ratio. Only common sand was used with either 0 or 5% lime and with either 12% or 15% sodium silicate. Table 5 shows the results from air-cured and oven-cured bricks (tested in moist, dry and wet conditions), along with those shown in [5].

It is seen that, in general, the results from the present investigation agree with those from [5]. Curing in a sealed bag produced the worst performing bricks, especially when tested in moist conditions. Curing in open air for 28 days produced much better performance when testing was carried out after oven drying the bricks (at 105°C) to a constant mass. The best performance was achieved when green bricks were placed in an oven (105°C) for 24 hours before testing; the results were comparable to, if not better than, those of the fired bricks. In general, the addition of lime improved the brick's performance. It should be noted that whilst bricks cured in open-air have reasonably high dry compressive strength, the strength completely disappeared after 48-hours soaking.

Table 4: Water Absorption Results

		COLD WATER ABSORPTION (%)		BOILING WATER ABSORPTION (%)	
FLY ASH/SAND RATIO	% LSS BY MASS	With Silica Sand	With Common Sand	With Silica Sand	With Common Sand
50/50	5	25.00	22.73	20.37	22.73
	10	24.07	20.91	21.30	20.91
	15	18.97	-	15.52	-
	20	17.69	-	15.04	-
70/30	5	33.66	31.37	29.70	31.37
	10	25.00	28.85	21.00	27.88
	15	22.93	13.16	19.27	14.04
	20	19.64	-	17.86	-

90/10	5	34.38	36.73	30.21	35.71
	10	20.00	31.96	17.89	30.93
	15	26.73	20.56	22.77	20.56
	20	25.25	-	21.21	-

5. Conclusions

The results of this investigation suggest that it is possible to produce lightweight bricks from fly ash at a firing temperature of around 550°C. In particular, with proper proportioning, these bricks can produce compressive strengths comparable to those of common clay bricks. Although their tensile strength is somewhat below the typical values of clay bricks, the absorption characteristics may be comparable to those of clay bricks.

There appears to be an optimum composition for the fly ash bricks studied. A combination of 70/30 for fly ash/common sand with 15% liquid sodium silicate and 5% lime would produce the best performing brick in terms of strength, mouldability and water absorption.

As compared with fly ash bricks containing silica sand, it was found that fly ash bricks containing common sand performed better in terms of water absorption while their strength characteristics were not significantly different. It is obvious that common sand would be a much better choice in terms of cost.

Table 5: Results from Non-Fired Bricks (Average Values)

	LIME (%)	LSS (%)	CURING METHOD	TEST COND.	σ_c (MPa)	f_S (MPa)	COLD WATER ABSORP. (%)	BOILING WATER ABSORP. (%)
Current Study	0	15	Sealed bag	Moist	0.5	0.06	18.2	18.1
	5	15	Sealed bag	Moist	2.8	0.36	17.1	18.3
	5	15	Sealed bag	Dry^^	6.4	-	-	-

	5	15	Open air	Dry^^	21.0	-	-	-
	5	15	Oven dry#	Dry	30.0	4.21	-	-
	5	15	Open air	Wet^	Fail	-	-	-
	5	15	Oven dry#	Wet^	22.4	-	-	-
	0	12	Oven air	Dry^^	20.5	2.50	18.2	21.2
	0	12	Oven dry#	Dry	35.0	-	17.6	20.7
	0	12	Oven air	Wet^	Fail	-	-	-
	0	12	Oven dry#	Wet^	16.4	-	-	-
Freidin & Erell [5]	0**	20	Open air	Moist	1.6	-	36.5	-
	0*	15	Open air	Moist	4.0	-	22.5	-
	0**	20	Open air	Dry^^	3.2	-	-	-
	0*	15	Open air	Dry^^	8.0	-	-	-

* With slag ** Without slag # Oven dry at 105°C for 24 hrs

^^ Tested after oven-drying to a constant mass

^ Tested after soaking in water for 48 hrs

The possibility of developing oven-dried fly ash bricks has also been explored and the results show that it is possible to simply dry green bricks at 105°C to obtain performance similar to that of the fired fly ash bricks. Translated into the conditions found in many developing countries, this could mean an affordable small/home industry with low energy requirements and minimal energy losses. More than that, the process is making use of waste material (fly ash) in large quantities and hence, is more environmentally acceptable.

It is difficult to provide a cost estimate for the manufacture of fly ash bricks since it depends on the availability and cost of the raw materials (fly ash, sand, sodium silicate). However, the above results suggest that aside from material and transportation costs, it is possible to manufacture the bricks using a much cheaper and simpler technique and hence, compete directly with clay bricks.

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