# LIGHTWEIGHT BRICKS FROM FLY-ASH

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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 the manufacture of cement and in the concrete production industry, with the remaining majority requiring costly disposal. It is essential therefore that other cost effective methods of fly-ash utilisation are found. One area that is gaining considerable interest in many parts of the world is the utilisation of fly-ash in brick manufacture.

This paper presents the results of an extensive testing program that used Class F fly-ash as a major constituent in the production of lightweight building bricks. Scaled down, pressed bricks were made from varying proportions of fly-ash, sand, hydrated lime, sodium silicate and water. Bricks of three distinct fly-ash to sand ratios were used, namely 50/50, 70/30 and 90/10, with varying amounts of sodium silicate (5, 10, 15, 20% by mass) and a 5% hydrated lime content. Also two types of sand were used, silica sand and common sand. Thus resulting in twenty four different types of fly-ash brick.

The results suggest it is possible to produce lightweight fired bricks from fly-ash to satisfy engineering requirements. In particular, with proper proportioning, these bricks can produce compressive strengths and absorption characteristics comparable to those of clay bricks. The combination of 70/30 for fly-ash/common sand with 15% sodium silicate and 5% lime produced the best performing brick in terms of strength, mouldability and water absorption. Apart from exhibiting characteristics comparable to those of normal fired clay bricks, the fly-ash bricks produced a significant weight reduction of approximately 50% making them a viable alternative.

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## INTRODUCTION

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. The remaining coarser fraction falls to the bottom of the furnace where it sinters together to become bottom ash. The structure, composition and properties of the ash particles depend upon the structure and composition of the coal and the combustion processes by which the ashes are formed.

In the last 15 years or so the effective utilisation of fly-ash has been a major area of concentration for scientists and engineers. Large quantities of fly-ash produced as a by-product of coal-based power stations have been viewed as a serious environmental problem. This is due to its constituents being the oxides of silica, alumina, iron, calcium and magnesium along with traces of some toxic elements such as arsenic, selenium and boron. Therefore no simple disposal method has been considered safe from an environment-protection point of view.

Australia alone produces in excess of 8 million tonnes of fly-ash each year. At present 10-15% of the fly-ash produced is utilised in the manufacture of cement and concrete. In Queensland there is annually, some ten million tonnes of bituminous (black) coal burnt, producing about two and a half million tonnes of ash residue. Therefore, an effective utilisation of fly-ash can be regarded as economically fruitful and environmentally beneficial. 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.

The use of fly-ash in brick manufacturing is not new. Lishmund (1973) suggested that fly-ash can be moisturised, mixed with coarser aggregate and binding agents, pressed and fired in kilns to produce bricks, similar to clay bricks but having certain distinct advantages. The bricks are said to be approximately 30% lighter than normal bricks, can be produced with much greater compressive and tensile strengths, and can be glazed to improve their water absorption characteristics. Sloanaker (1976) studied class F fly-ashes from West Virginia and Pennsylvania to produce fired bricks for construction. He indicated that fired bricks made from feeds of 72% fly-ash, 25% bottom ash, and 3% sodium silicate met commercial specifications. It is also worth noting that recently India has been leading the way in fly-ash brick manufacturing. Rai (1992) indicated that calcium silicate type bricks using fly-ash, sand and lime mixtures can be moulded at high pressures (>19MPa).

The advantages of fly-ash over brick clays are (Hughes, 1996): (1) the saving in energy required to dehydroxylate fire clay materials, (2) the presence of spherical particles and mullite crystallites that are ideal for "opening" the brick and promoting thorough firing, (3) its mixture of mineral components gives similar ranges of refractoriness to those of clays, (4) obtaining special colours or other properties that are not possible from clays, and (5) the presence of lime (CaO) or portlandite ($Ca[OH]_2$) that will capture pyritic sulfur from clays and reduce air pollution. The disadvantages of using fly-ash in bricks include: (1) reduced plasticity to the point that extrusion becomes impossible, (2) excessive amounts of soluble salts such as calcium oxides and sulfates, which causes chalky deposits on fired bricks that are called "scumming", (3) reduced melting points below optimum levels, and (4) too much freight to be cost-competitive at the brick plant. This paper describes an experimental investigation into the use of at least 50% by weight of fly-ash in making pressed fired fly-ash bricks. Additives such as sand, lime and sodium silicate of various proportions were used in the mixes. Tests were carried out to determine the strength characteristics and water absorption properties of the bricks.

## MATERIALS

### Fly-ash

Fly-ashes are heterogeneous fine powders consisting of mostly rounded or spherical particles ranging in diameter from < 1 μm to 150 μm. The Australian Standards require a "fine-grained" fly-ash to have ≥ 75% passing a 45 μm sieve and a maximum Loss on Ignition (LOI)[4] of 4.0%. A "coarse-grained" fly-ash on the other hand, allows ≥ 40-70% passing a 45 μm sieve and a maximum LOI of 12.0%.

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. As stated earlier, the lower lime content of class F fly-ash may be an advantage for producing fired-bricks (less "scumming").

A dry processed "fine-grained" ash from Queensland, namely the Tarong fly-ash, was chosen as the main constituent in this investigation. The ash can be classed 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 LOI = 1.5 | | | | | | | | | |

### Sand

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.

[4] Loss on Ignition (LOI) represents the mass loss of the fly-ash when burned at 750°C ± 50°C and is related to the presence of "free carbon", combined water and carbonates. Of these, "free carbon" is the major component and LOI values are generally taken as the amount of "residual carbon".

**Water-glass**

Water-glass is a solution of Sodium Silicate (SS) in water. It is useful as a cheap binder for foundry castings, glazes for ceramics and as a low cost sealer for brickwork. Liquid Sodium Silicate (LSS) Grade 42 ($SiO_2$ : $Na_2O$ = 3.22, total solids = 39.3%, pH = 11.2) was used in this investigation. This material is generally considered to be non-hazardous although skin contact should be minimised to avoid irritation.

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 (Freidin and Erell, 1995). The alkali of the sodium silicate then reacts with silica present in fly-ash in the glass phase, strengthening this process of polymerization 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.

**Lime**

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.

## 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 finally firing.

**Composition**

Three different fly-ash to sand ratios (by mass) were used, namely, 50/50, 70/30 and 90/10. 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.

**Mixing**

The mixing of raw materials was performed in two stages. First, the dry materials (ash, sand, lime) were mixed thoroughly using a 15 lt mechanical mixer. This created dust and was thus performed in a sample preparation room equipped with a dust filtration system. 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.

**Moulding**

A special 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. 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±2mm; the ratio of these dimensions are similar to those of a common house building brick (225mm x 105mm x 75mm).

**Curing**

Initial curing of the bricks was achieved prior to firing by placing them within air-tight snap-lock plastic bags (for approximately one hour). This was done to prevent carbonation and reduce the rate of oxidation ensuring all materials remain moist for sufficient time to ensure the onset of pozzolanic activity and hydration. The samples were then removed from their bags and placed in a high temperature electric oven equipped with a programmable temperature controller.

**Firing**

The starting temperature of the oven was set at 25°C. This was increased to 50°C over 30 minutes and held at that temperature for one hour, before raising the temperature again, to 105°C over 30 minutes and holding it at that temperature for one hour. Note that the gradual increase to 105°C was to minimise shrinkage/cracking. Subsequently, temperature was increased to 555°C over 40 minutes and remained at 555°C for 100 minutes. During this phase organic matter would burn off along with the removal of carbon. The moisture within the sodium silicate would be completely evaporated off; leaving pure sodium silicate initially crystalline but then becoming non-crystalline upon decomposition of the microstructure into residue form. Following this step, the temperature of the oven was risen to 1150°C for the actual firing over 60 minutes and remained at that temperature for 180 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 sample bricks were subsequently removed, weighed, measured and visually inspected.

## TESTING AND RESULTS

**Moisture Content**

The moisture content of each test-brick was determined in accordance with AS/NZS4456.8-1997. Test results generally indicated that to achieve optimum performance, the moisture contents of the optimum mixtures of both fly-ash/silica sand and fly-ash/common sand mixes had to be within the range of 25±2%.

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 should be limited to 30%. To ensure the onset of pozzolanic activity moisture contents should range between 20% and 25%, which would provide adequate mouldability.

**Dry Density**

The dry density (AS/NZS4456.8-1997) of the brick products 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**

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 samples were tested for each batch of bricks in accordance with AS/NZS4456.4-1997.

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

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

where
$\sigma_c$ = unconfined 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 bricks under investigation increased rapidly with the amount of sodium silicate 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 sodium silicate in excess of 15% by mass lead to additions of liquid sodium silicate associated with 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 sodium silicate 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% sodium silicate, and strengths >25 MPa could be achieved with the 90/10 fly-ash/silica sand mixture incorporating 20% sodium silicate. It can be concluded that the 70/30 fly-ash/silica sand mixture containing 15% sodium silicate may be the most promising mixture of raw materials with respect to maximisation of fly-ash content and compressive strength

Table 2. Unconfined Compressive Strength

| | $\sigma_c$ (MPa) | |
|---|---|---|
| % SS | WITH SILICA SAND | WITH COMMON SAND |
| 50/50 ASH/SAND | | |
| 5% | 8.80 | 11.05 |
| | 8.33 | 9.44 |
| | 8.58 | 7.63 |
| 10% | 7.96 | 18.03 |
| | 7.67 | 17.61 |
| | 7.03 | 10.58 |
| 15% | 21.77 | 26.46 |
| | 25.21 | 29.84 |
| | 23.49 | 36.17 |
| 20% | 12.52 | N/A |
| | 12.05 | N/A |
| | 12.29 | N/A |
| 70/30 ASH/SAND | | |
| 5% | 7.63 | 8.35 |
| | 8.02 | 7.66 |
| | 9.10 | 8.31 |
| 10% | 11.35 | 11.54 |
| | 11.40 | 11.77 |
| | 11.45 | 11.85 |
| 15% | 26.44 | 27.50 |
| | 28.36 | 24.32 |
| | 26.14 | 25.91 |
| 20% | 26.21 | N/A |
| | 22.41 | N/A |
| | 24.31 | N/A |
| 90/10 ASH/SAND | | |
| 5% | 9.47 | 7.55 |
| | 9.29 | 8.02 |

| | | |
|---|---|---|
| | 11.27 | 7.12 |
| 10% | 16.61 | 12.55 |
| | 16.71 | 12.84 |
| | 16.66 | 12.76 |
| 15% | 27.76 | 31.07 |
| | 24.51 | 20.51 |
| | 20.61 | 20.73 |
| 20% | 29.12 | N/A |
| | 27.77 | N/A |
| | 26.53 | N/A |

For bricks containing common sand, it was also found that the compressive strength of the bricks increased rapidly with the amount of sodium silicate 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 sodium silicate in solution 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 sodium silicate were discarded as being unviable.

It is interesting to note that the bricks containing common sand with equal fly ash proportion (50/50) performed differently than bricks made with silica sand, the former clearly exhibited the greatest strength (>30MPa) out of the three mixes tried. 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% sodium silicate addition, it could again be selected as the most viable mixture alternative with respect to strength consistency and fly-ash utilisation.

**Tensile Strength**

The tensile strength of bricks may be considered as a less significant parameter. This is because the failure of brickwork due to tension is almost always the result of mortar-bond failure and not actual brick segment failures. However, tensile strength becomes important when considering the construction of brickwork containing openings (garages, windows, door-ways, etc), spans, arches, and header and soldier courses. In this investigation, three samples were tested as being representative of each batch of bricks.

The testing method was in accordance with AS/NZS4456.14-1997. 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.

$$f_s = 2F_s/(3.142bh) \quad (2)$$

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 results, as shown Tables 3, indicate that the indirect tensile strength of the bricks tends to increase with increased additions of sodium silicate. Increasing the amount of sodium silicate from 5% to 15% by mass brought about an increase in tensile strength from approximately 0.5 MPa to approximately 2.0 MPa.

The mixture of 70/30 fly-ash/sand with 15% sodium silicate displayed 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 smaller (2 to 3 MPa less).

## Water Absorption Properties

The water absorption of a brick is the percentage increase in mass of a dry brick when it has been saturated. It is the second most important criteria considered when using bricks as it is related to the degree to which rain/water could penetrate bricks/brickwork; this is related to the brick's porosity and permeability.

Due to time constraints, one sample was tested for each batch of bricks, The test for water absorption properties was performed in accordance with AS/NZS4456.14-1997. 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 sodium silicate content.

The water absorption of all brick mixes decreased with increasing sodium silicate content. This was expected as increasing the sodium silicate content, produces a more consolidated the final product becomes and hence the porosity and 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.

Table 3. Indirect Tensile Strength Values

| FLYASH/ SAND RATIO | % SS | TENSILE STRENGTH $f_S$ (MPa) WITH SILICA SAND | WITH COMMON SAND |
|---|---|---|---|
| 50/50 | 5 | 0.72 | 0.89 |
| | | 0.60 | 1.13 |
| | 10 | 0.75 | 1.45 |
| | | 0.75 | 2.39 |
| | | - | 1.75 |
| | 15 | 1.66 | 1.96 |
| | | - | 3.42 |
| | 20 | 1.51 | - |
| | | 1.85 | - |
| | | 1.36 | - |
| 70/30 | 5 | 0.77 | 1.63 |
| | | 0.68 | 1.28 |
| | | - | 2.00 |
| | 10 | 2.04 | 1.11 |
| | | 1.21 | 0.86 |
| | | - | 1.47 |
| | 15 | 2.85 | 1.82 |
| | | 2.39 | 2.07 |
| | | 1.65 | - |
| | 20 | 1.90 | - |
| | | 2.95 | - |
| | | 3.42 | - |
| 90/10 | 5 | 0.64 | 0.99 |
| | | 1.23 | 1.35 |
| | 10 | 2.71 | 0.96 |
| | | - | 1.10 |
| | | - | 0.92 |
| | 15 | 1.55 | 2.02 |
| | | 1.73 | 1.84 |
| | | 1.76 | - |
| | 20 | 2.69 | - |
| | | 2.23 | - |

Table 4. Water Absorption

| ASH/SAND RATIO | SODIUM SILICATE (%) | COLD WATER ABSORPTION (%) With Silica Sand | COLD WATER ABSORPTION (%) With Common Sand | BOILING WATER ABSORPTION (%) With Silica Sand | BOILING WATER ABSORPTION (%) 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 | - |

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% sodium silicate was used, which can still be considered comparable to that of typical clay bricks.

## CONCLUSIONS

The results of this investigation suggest that it is possible to produce lightweight fired bricks from fly-ash which could satisfy engineering requirements. 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% 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.

Although the results of this study seem to be promising, there are still a few unanswered questions. In particular, the effect of varying lime content needs further investigation and similarly, the use of lower firing temperatures (to save energy/cost) and higher moulding pressures will be studied in the near future. The possibility of developing non-fired (air-cured) fly-ash bricks also deserves immediate attention and the use of hydrophobic material to reduce water uptake should be considered (see Freidin and Erell, 1995). In addition, durability issues may also need to be resolved, particularly if fly-ash bricks are to be used in areas where large stress and temperature fluctuations occur.

## REFERENCES


Freidin, K. and Erell, E. (1995). Bricks Made of Coal Fly-Ash and Slag, Cured in the Open Air. Cement and Concrete Composites, 17, pp. 289-300.

Hughes, R.E. (1996). Brick Manufacture with Fly Ash from Illinois Coals. Final Technical Report. ICCI Project Number 95-1/3.1.A-14.

Lishmund, S.R. (1972). Flyash. The Mineral Industry of New South Wales, Australia. Report No. 47.

Rai, M. (1992). Flyash Sand Lime Bricks in India. Technical Report, 4th CANMET/ACI International Conference on Pozzolans, Central Building Research Inst., Roorkee, India.

Sloanaker (1976). Production of Forty Percent Core Area Flyash Brick Using Selected Flyashes. Proc. 4th International Ash Utilization, American Coal Ash Association, Paper 76-231, pp.231-237.

Standards Australia (1998). Supplementary Cementitious Materials for Use with Portland and Blended Cement – Fly Ash, AS 3582.1