ASIAN JOURNAL OF CIVIL ENGINEERING (BHRC) VOL. 14, NO. 6 (2013)
PAGES 797-808

STRENGTH AND DURABILITY STUDIES ON FLY ASH BASED GEOPOLYMER BRICKS

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Received: 10 January 2013; **Accepted:** 15 April 2013

ABSTRACT

Geopolymer, an inorganic alumina silicate polymer is synthesized predominantly from silicon and aluminum materials or from by product materials like fly ash. The application of geopolymer technology substantially reduces the CO_2 emissions by the cement industries and utilizes the solid waste materials such as fly ash. The fresh geopolymer mortar has stiff consistency and high viscosity. Further, the chemical reaction is fast. To evaluate the performance of geopolymer bricks, the tests namely Compressive Strength, Split Tensile Strength and Flexural strength are conducted. The objective of present investigation is to improve the quality of geopolymer mortar through special treatments and study the property, particularly the acid resistance. The durability tests such as water absorption test and acid resistance test (HCl and H_2SO_4) are also conducted. The main focus of the investigation is on optimum utility of the available fly ash and minimizing the water absorption and attaining high compressive strength.

Keywords: Silicon and aluminium; CO_2 emissions; fly ash; geopolymer bricks; and water absorption.

1. INTRODUCTION

Though Ordinary Portland Concrete (OPC) is widely used in concrete industry since many decades it releases green house gas, i.e. carbon dioxide (CO_2), into the atmosphere while manufacturing it [1]. Geopolymer technology is one of the recent technologies applied to

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reduce the use of Portland cement in concrete. Fly ash reacts with alkaline solutions to form a cementitious material; fly ash based geopolymer does not emit carbon dioxide. In this project, bottom ash is considered as partial - or full-replacement for sand as fine aggregate in the geopolymer mortar. Fly ash and bottom ash are residues from the combustion of coal. Fly ash is captured in the chimney while bottom ash is collected from the bottom of the furnace in the coal fired power plant. The particles of fly ash are very fine whereas the bottom ash is much larger in particle size, which is about the size of sand but more porous. One of them could be fully utilized.

Fly ash based geopolymer with bottom ash could reduce carbon dioxide emission effectively and fly ash and bottom ash could be recycled. Since fly ash and bottom ash are the solid waste materials from coal fired power plant, this research will lead to sustainable financial development in the society. At present, only limited information is available on the influence of parameters on geopolymer, especially geopolymer with bottom ash as the fine aggregate. Hence, a study on the effect of different parameters on the fly ash based geopolymer is essential. The details on the worldwide production of fly ash up to July 2012 is given in Table 1.

2. LITERATURE REVIEW

Geopolymers are amorphous to semi-crystalline three-dimensional alumino-silicate polymers similar to zeolites. Geopolymers consist of polymeric silicon-oxygen-aluminium framework with silicon and aluminium tetrahedral alternately linked together in three directions by sharing all the oxygen atoms. The negative charge created by aluminium is balanced by the presence of positive ions such as Na+, K+, and Ca+. The empirical formula of these mineral polymers is $Mn[-(SiO_2)z\text{-}AlO_2]n\cdot wHO$, where M is an alkali cation such as potassium or sodium, the symbol - indicates the presence of a bond, *z* is 1, 2 or 3, and *n* is the degree of polymerisation [2].

Table 1: World wide production of fly ash

Name of the Country	Production (Million tons)	Utilization (Million tons)
Australia	59	<25
China	>150	52
Germany	78	40
India	>132	48
Japan	55	29
Russia	102	32
South Africa	78	57.9
Spain	58	26
U.K.	60	34
U.S.A	100	26

Geopolymers are environmental friendly materials which do not emit green house gases during polymerisation process. Besides, only moderate energy is required to produce them. Geopolymers are made from source materials with silicon (Si) and Aluminium (Al) content, thus they can be prepared using fly ash, waste-product obtained from coal-fired power station, as the source materials [3]. Moreover, geopolymer possesses excellent mechanical properties which does not dissolve in acidic solution and does not generate any hazardous alkali-aggregate reaction even with alkali content as high as 9.2 percent [4].

Optimum curing temperature of 60 °C was suggested for the study of the geopolymer mortar with small 50 mm cube size. This suggestion is based on the fact that smaller cube has higher surface area-to-volume ratio compared to larger cube. As a result, the smaller cube is more vulnerable to the high curing temperature and would experience loss of moisture during curing compared with the larger samples [5]. Álvarez-Ayuso et al. [6] suggested that the optimum curing time would be 48 hours. Curing time shows commonly a positive effect to the compressive strength of geopolymer mortar, and this effect is much more noticeable at the optimum curing temperature, 80 °C, suggested by them [6]. Swanepoel and Strydom [7] also agreed that the optimum curing time for a geopolymer mortar would be 48 hours or 2 days.

On the other hand, Hardjito et al.[8] mentioned that increase in the curing time would also assist the increase in compressive strength. But, a curing time more than 48 hours does not increase compressive strength significantly [8,9]. Increase in concentration of NaOH increases the compressive strength of geopolymer. This is mainly because the concentration of NaOH solution directly affects the dissolution of the metakaolinite particulates, which affects the formation of the geopolymer framework. To have strong inter-molecular bonding strength of the geopolymer, more reactive bond for the monomer is needed. To obtain a better dissolving property to metakaolinite particulates, a higher concentration of NaOH solution is required [10]. However, in research, [5] the effect of concentration of NaOH on compressive strength was not clear. The concentration of NaOH of 10, 15, 20 M were used, and the average compressive strengths were 48.4, 49.1 and 50.2 MPa respectively. Researchers have also obtained compressive strength greater than 50 MPa for 8M NaOH solution [11].

Geopolymer with fluidized bed combustion bottom ash (FBC-BA) recorded a decrease in compressive strength with the increase of the content of FBC-BA in the prepared specimens. Increasing the content of FBC-BA to about 50 percent caused the decrease in the compressive strength [12]. In the case of normal fly ash concrete incorporating bottom ash as replacement for fly ash, the increase in bottom ash content decreased the compressive strength. Further, most of the compressive strengths were gained after 28 days. The pozzolanic reactivity of bottom ash could be improved with adequate grinding and it could be used as sand replacement in concrete, where sand is more expensive than bottom ash [13].

Water retainability is defined as the amount of water absorbed into the pores and adsorbed on the rough surface of bottom ash. The usual collapsed-cone test method adopted to determine the saturated surface dry condition is not applicable in the case of bottom ash. Therefore an alternative method based on the gravitational removal of excess water from the bottom ash was introduced to determine the water retainability of bottom ash [14].

The compressive strength of fly ash-based geopolymer mortar exposed to 400 °C increased the strength by about 100% compared to samples without any exposure to high thermal environment. Geopolymer possesses high thermal resistance up to 800°C and there is no decrease in compressive strength [15]. However, after exposure to thermal exposure above 800°C, compressive strength of geopolymer prepared using sodium based alkaline activator rapidly declined [16]. In fact, geopolymer mortar does not release water in an explosive manner or dehydrate to a powder like OPC. In brief, geopolymer mortar resist thermal exposure up to 1000°C [17] . Efforts are also on for using brick waste as a pozzalanic material in concrete [18].

3. EXPERIMENTAL INVESTIGATION

3.1 Material Properties

For the development of geopolymer concrete class F fly ash collected from Mettur Thermal Power Station has been used. The chemical composition of fly ash as determined by XRF (mass percentage) is presented in Table 2. The fly ash and its constituents are shown in Fig. 1.

Table 2: Chemical composition of fly ash

Compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	TiO_2	MgO	P_2O_5	SO_3	[*]*LoI*
Percentage (mass)	52.54	26.74	11.12	1.2 8	0.47	0.82	1.57	0.87	1.53	1.70	1.36

[*]*LoI- Loss on Ignition*

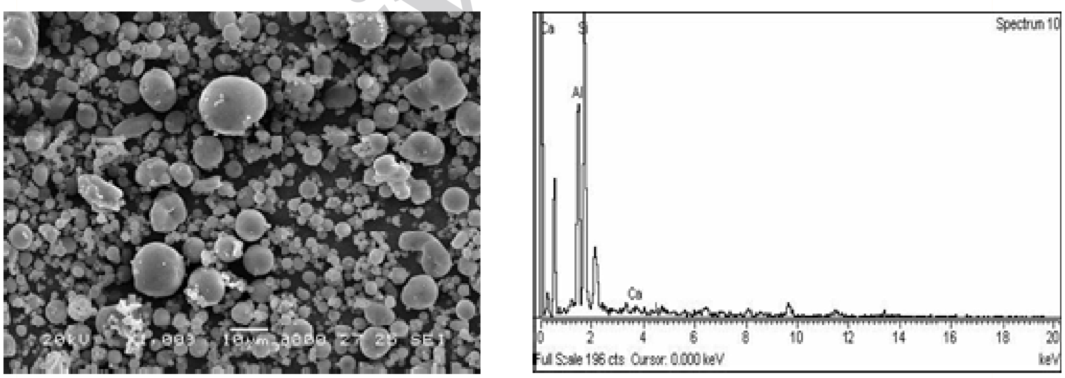

Figure 1. Fly ash and its constituents

Locally available river sand with fineness modulus of 2.72 and specific gravity of 2.64 has been used. Crushed granite coarse aggregates of size ranging from 7 mm to 20 mm have been used at the saturated surface dry condition. A combination of sodium silicate (Na_2SiO_3) solution and sodium hydroxide (NaOH) solution can be used as the alkaline liquid. It is recommended that the alkaline liquid can be prepared by mixing both the solutions together, at least 24 hours before using. The sodium silicate solution is commercially available in different grades. Sodium hydroxide with 97-98 percent purity, in flake or pellet form, is commercially available. The solids must be dissolved in water to make a solution with the required concentration. The specimens are prepared with the concentration of sodium hydroxide solution which can vary in the range between 5 Mole to 12 Mole; however, 5 Mole solutions is adequate for most of the applications.

3.2 Details of specimen

In this experimental study the geopolymer mortar specimens are prepared. The strength and durability studies are conducted using lab equipment and also the bricks are cured using steam curing chamber shown in Figs. 2 and 3. The size of geopolymer bricks is 230 mmx110 mmx70 mm.

Figure 2. Steam boiler and controls

Figure 3. Steam curing chamber

3.3 Preparation of specimen

The solid constituents of the fly ash-based geopolymer mortar, i.e. the fine aggregates and the fly ash, were dry mixed in the pan mixer for about three minutes. The alkali-activator solution (i.e. liquid sodium silicate and sodium hydroxide which are premixed), is premixed and added to the solids. The wet mixing usually continued for another five minutes. The fresh fly ash-based geopolymer mortar was dark in colour and shiny in appearance. The mixtures were usually cohesive. The workability of the fresh mix was measured by means of the conventional slump test. The geopolymer mix is prepared in 1:1.3 ratio and Alkali – Activator Solution (AAS) to Fly ash (FA) ratio was utilized 0.40, 0.45, 0.50 and 0.55. The control brick mix is also same as geopolymer brick ratio.

4. TESTS ON BRICKS

Geopolymer bricks were prepared, tested and compared with ordinary bricks. The compressive strength of geopolymer concrete cubes is influenced by the wet-mixing time. The size of the bricks cast was 230 x 110 x70 mm and were steam-cured at 60^0C for 24 hours (Fig. 4). Totally 80 bricks were cast for 1: 1.3 ratios, with 10 and 12 molarities. Later, bricks with 5M were added as the strength of 10M and 12M bricks are very high.

Figure 4. Steam curing of geopolymer bricks

4.1 Strength Tests

Strength tests such as compressive strength, tensile strength and flexural strength were conducted on geopoloymer bricks. For comparison purpose, the commercially available country bricks and fly ash bricks of same size were also tested. The test specimens were kept in chamber and steam-cured at 60^0C for 24 hours and allowed the rest period for 3 days.

4.1.1 Test Procedure

The cured specimens were placed on a steel plate which perfectly covers the whole area of the specimen and it was kept in the compressive testing machine. The specimen was placed evenly on the steel plate and one or more steel plates were placed over the specimen in the longitudinal position. The load is applied gradually over the specimen. The ultimate compressive load is recorded accurately. The same procedure is adopted for all specimens. The results were tabulated. From the table, charts were drawn to analyze the results. The compressive strength of each specimen is calculated by Compressive strength = compressive load / effective area, Average compressive strength of geopolymer brick is 53.5 MPa. It is almost three times stronger than that of commonly used bricks. The strength and durability test results on different types of bricks are tabulated in Table 3.

Table 3: Strength and durability test results on different types of bricks - a comparison

Sl.No.	**Type of Test conducted**	**Country Brick**	**Fly ash Brick**	**Geopolymer Brick (5M)**
1.	Compressive strength (MPa)	12.46	14.38	16.11
2.	Tensile strength (MPa)	1.14	1.47	2.59
3.	Flexural strength (MPa)	18.60	22.06	32.26
4.	Water absorption (Percent)	10.75	6.83	1.44
5.	Acid Resistance (HCl) (Percent)	2.65	1.36	0.33
6.	Acid Resistance (H_2SO_4) (Percent)	3.67	2.10	0.36

The Fig.5 shows a comparison of the compressive strength of geopolymer bricks between air curing and steam curing. The compressive strength of geopolymer bricks cured by steam curing is much better than the one with air curing.

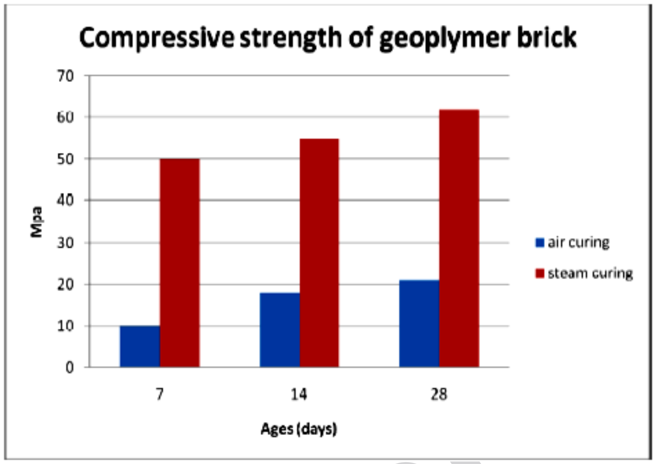

Figure 5. Compressive strength of geopolymer bricks

The Fig.6 shows a comparison of the flexural strength of geopolymer bricks, fly ash bricks and country bricks. Flexural strength results are of the geopolymer bricks much better than other types of bricks.

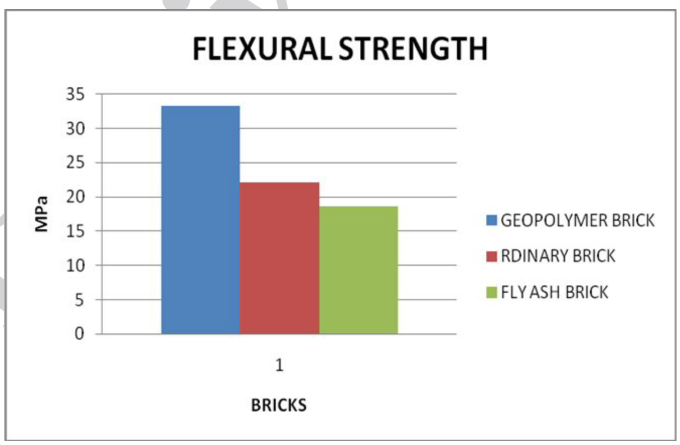

Figure 6. Flexural strength of bricks

5. WATER ABSORPTION TEST

To study the character of geopolymer bricks, the cast specimens are subjected to water absorption test. After the curing period is completed, the specimen are immersed in the water tank and kept 24 hours in water. The weight of the specimen was noted. The specimen was placed in a oven at 105°C temperature, then the weight of the specimen was recorded. From these two values, the water absorbed by the entire specimen was calculated and tabulated.

Percentage of Water absorption = $[(W_1-W_2) / W_1] \times 100$

W1 = Weight of the wet specimen

W2= Weight of the dry specimen

Geopolymer brick absorbed only very small quantity of water when compared with ordinary and fly ash bricks, almost less than one percent and it should be appreciable for non porous structures. The geopolymer brick gives ringing sound while clashing with each other and has resistivity against nail scratching and there is no powder formation. When it is dropped from one meter height it did not break. Thus the geopolymer brick satisfies all the requirements. The Table 4 and Fig.7 shows a statistical comparison of water absorption of geopolymer bricks, fly ash bricks and country bricks.

Table 4: Water absorption of different types of bricks

Sl. No.	**Type of Brick**		**Percentage increase in weight**
1	Country Bricks		10.754
2	Fly ash Bricks		6.43
3	Geopolymer Bricks	10 M	1.442
		12 M	1.612
		5 M	1.750

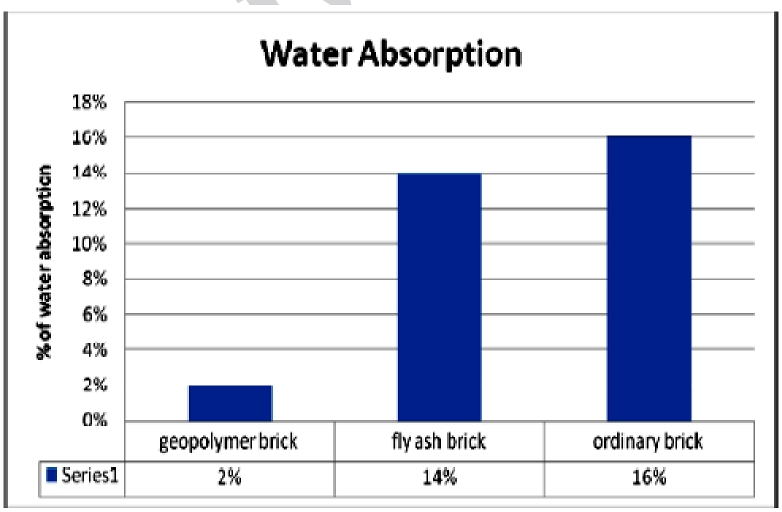

Figure 7. Water absorption test

6. ACID RESISTANCE TEST

As geopolymer brick (5M) is considered to be alkali resistive in nature, acid resistance tests were conducted for various concentrations of HCl and H_2SO_4, the percentage of solution prepared using 1 percent , 2 percent and 3 percent of diluted acids was used. The test results have been tabulated in Table 5. The results reveal that it was found to be good alkali resistive in nature. Acid resistance tests were conducted for various concentrations of HCl and H_2SO_4, the percentage of solution prepared and the test results are given in Fig. 8 and Fig. 9.

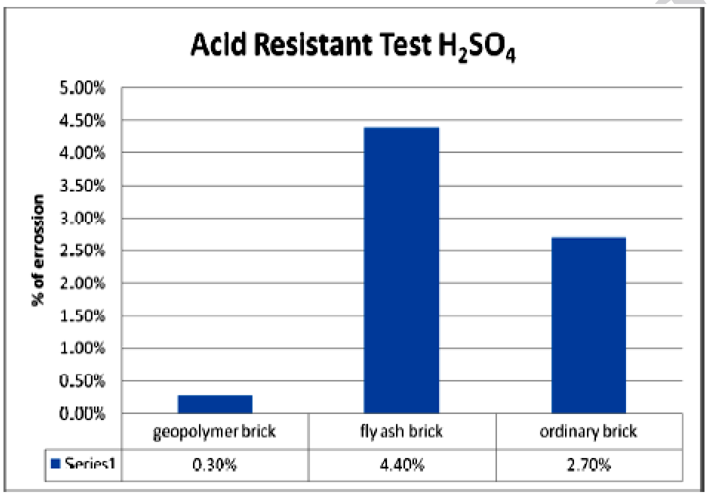

Figure 8. Acid resistance test (H_2SO_4)

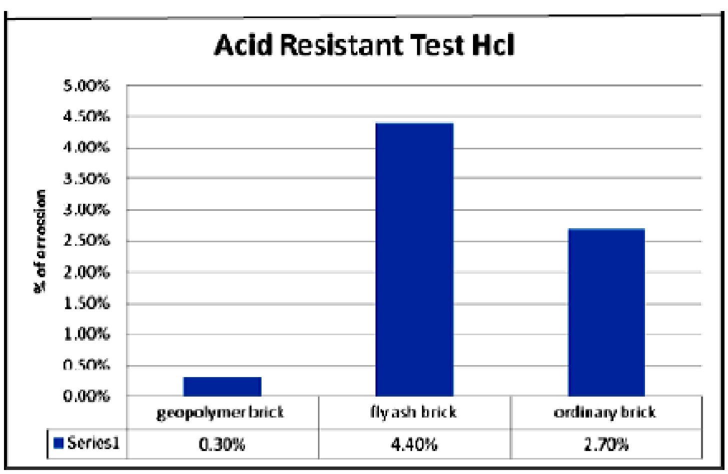

Figure 9. Acid resistance test (HCl)

Table 6 reveals a comparison of the strength of the country bricks, fly ash bricks and 5 mole geopolymer bricks. Based on the obtained average results, 5M geopolymer bricks have more compressive strength and it satisfies the durability requirements when compared with all other commercial bricks.

Table 5: Acid resistance test results of different types of bricks

Sl.No	Types of Bricks	Percentage of decrease in weight after 24 hours (gms)					
		H_2SO_4			HCl		
		1 percent	2 percent	3 percent	1 percent	2 percent	3 percent
1.	Country bricks	2.67	2.92	3.35	2.96	3.43	3.89
2.	Fly ash bricks	1.11	2.16	2.59	2.13	2.58	2.91
3.	Geopolymer bricks (5M)	0.17	0.27	0.41	0.95	0.98	1.09

Table 6: Compressive Strength of different types of bricks

Sl. No.	**Type of Brick**		**Density kg/m^3**	**Average compressive strength (MPa)**
1.	Country Bricks		1552.54	18.60
2.	Fly ash Bricks		1484.57	22.07
3.	Geopolymer Bricks	12 M	1909.46	50.38
		10 M	1867.00	53.50
		5 M	1850.26	16.11

Table 7 shows a comparison of the flexural strength of the country bricks, fly ash bricks and 12M, 10M & 5M geopolymer bricks.

Table 7: Flexural strength of different types of bricks

Sl. No.	**Type of Brick**		**Average flexural strength (MPa)**
1.	Country Bricks		10.40
2.	Fly ash Bricks		12.73
3.	Geopolymer Bricks	12 M	28.64
		10 M	32.20
		5 M	16.26

Table 8 shows a comparison of the tensile strength of country bricks, fly ash bricks and 12M, 10M & 5M geopolymer bricks.

Table 8: Tensile strength of different types of bricks

Sl. No.	Type of Brick		Average tensile strength (MPa)
1.	Country Bricks		1.14
2.	Fly ash Bricks		1.47
3.	Geopolymer Bricks	12 M	2.36
		10 M	2.59
		5 M	1.82

7. RESULTS AND DISCUSSION

i. The compressive strength of geopolymer bricks made using 10M and 12M NaOH solution is very high comparable to that of concrete. In fact concrete is not required for normal construction. But, geopolymer bricks with 5M NaOH solution give compressive strength comparable to that of country bricks and fly ash bricks used for normal construction.

ii. Increase in curing temperature increases the compressive strength of the geopolymer mortar.

iii. Steam curing increases strength and the strength of stream cured bricks is more when compared to air curing.

iv. The unit weight of geopolymer bricks is slightly higher than that of the other types of bricks.

v.The percentage weight loss of geopolymer bricks when immersed in different concentration of H_2SO_4 and HCl is very much lower when compared to other types of bricks. Further, the percentage weight loss increases with the increase in acid concentration.

vi. The increase in percentage of weight due to water absorption of geopolymer bricks is very small fraction when compared to that of other types of bricks.

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