DEVELOPMENT OF FLY ASH BASED GEOPOLYMER CONCRETE PRECAST ELEMENTS

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PREFACE

I am very happy to write the preface about the research project entitled **Development of fly ash based geopolymer concrete precast elements** funded by Ministry of Environment and Forests, New Delhi.

Approximately half of the electricity consumed in the world is generated by burning coal. The majority of the waste left behind during the coal burning process is called fly ash, consisting of fine spherical particles composed mainly by silica and alumina. Fly ash disposal costs are expected to increase due to government regulations aimed at regulating fly ash disposal. Storage lagoons, commonly used as long-term storage facilities, also are potential environmental hazards. Inorganic polymer concrete (geopolymer) is an emerging cementitious material, synthesized from materials of byproducts such as fly ash (FA). Geopolymer concrete, unlike the normal cement concrete does not contain Ordinary Portland Cement (OPC). This inorganic alumino-silicate polymer is created via a chemical reaction under highly alkaline conditions between fly ash and an activator solution of sodium hydroxide and sodium silicate.

The development of engineered geopolymer concrete could contribute to a widespread recycling of fly ash into geopolymer concrete, greatly reducing the amount of fly ash placed in long-term storage facilities, while at the same time producing valuable carbon off-set credits to the coal-fired power generation industry. This investigation is aimed at gaining a better understanding of manufacture of geopolymer concrete and study of the structural behavior of geopolymer concrete elements.

This extensive investigation has led the investigators of this research project to fabricate India's first biggest steam curing chamber among the technical institutions of our country. Also they have studied the durability of geopolymer concrete using corrosion analyser equipment. The outcome of the project focuses the geopolymer concrete (GPC) as acid and sulfate resistant, corrosion resistant and confirms that it possesses the high compressive and tensile strengths, rapid strength gain rate.

I appreciate the extensive facilities created by the investigators for carrying out this research project. Further, I would to like to add that the Annamalai University has the unique credit of being first in starting a post graduate course in Structural Engineering in 1953 (which I came to know from **Prof. C. Antony Jeyasehar** while writing the Preface) besides being first in fabricating the first biggest steam curing chamber.

Dr. B. K. Raghuprasad
Former Professor of Civil Engg.
IISC, Bangalore and
Chairman, Project Review Committee

This new technology is Dedicated to

Mr. SHASHI SHEKHAR, IAS

Addl. Secretary, Ministry of Environment and forests
Government of India

He is among the pioneers who initiated work on
Fly Ash utilization in India.
His outstanding contribution in the
field of environment will be
remembered for ever.

ACKNOWLEDGEMENT

Annamalai University, Tamil Nadu is thankful to the Ministry of Environment and Forests, Government of India, for entrusting to us the study on “Development of Fly Ash Based Geo-polymer Concrete Pre-cast Elements”.

We are highly grateful to Mr. Vijai Sharma, IAS, Dr. T. Chatterjee, IAS, Mr. R.H. Khwaja, IAS, Mrs. Gauri kumar, IAS, Mrs. Meera Mehrishi, IAS, Mr. Shashi Shekhar, IAS, Mr. R.K. Vaish, IAS, Dr. Raajneesh Dube, IAS, Dr. Rashid Hasan, Goverment of India, Ministry of Environment and Forests whose ideas, initiatives and decision became a guiding force.

We also extend our special thanks to Dr. B.K. Raghuprasad, Professor of civil Engineering, Indian Institute of science, Bangalore whose guidance and support helped to make this project successful. He as Chairman, Project Review Commitee took extra pain and motivated the entire team to achieve the target.

We are thankful to Prof. L. Kannan, former vice Chancellor, Thiruvalluvar University, Dr. K.Muthumani,

Chief Scientist, CSIR-SERC, Chennai. Dr. K. Anantha narayanan, Professor, IIT Madras, chennai, Dr. C. Natarajan, Professor, National Institute of Technology, Trichirapalli for their valuable suggestions and inputs to make this Project successful.

We express our thanks to Mr. G. Saravanan, Assistant Professor in civil Engineering, Goverment College of Engineering, Bargur, and Dr. A. Ganapathi, Assistant Professor, Chemistry Section (Engineering), Annamalai University (Project team members) for their constant support and hard work for the successful completion of the project.

Annamalai University, Tamil Nadu

CONTENTS

1. BACKGROUND OF THE PROJECT

Concrete made with Portland cement is the most widely used material on earth. The concrete industry is the largest user of natural resources in the world [1]. Globally, over 14 billion tonnes of concrete is placed per year and accounts for the annual 2.8 billion tonnes of Portland cement produced [2]. Significant increases in cement production have been observed and are anticipated to increase due to the massive increase in infrastructure and industrialization in India, China and South America [3].

It is generally agreed that the production of Portland cement clinker is expensive and ecologically harmful [4]. The emissions generated by Portland cement productions are principal contributors to the greenhouse gas (GHG) effect. For instance, the production of Portland cement for concrete accounts for an estimated 5 percent of global anthropogenic carbon dioxide [5]. Recent estimates of the emissions from cement production reveals that 377 million metric tons of carbon was generated in 2007; this indicates that emissions have more than doubled since the mid 1970s from fossil-fuel burning and cement production [6]. Whilst measures may be undertaken to reduce the generation of carbon dioxide from cement kilns, carbon dioxide emission is still in the order of 600 kg of carbon dioxide per ton of cement of which 400 kg per tonne is the result of the calcination of limestone [7]. The United Nations Intergovernmental Panel on Climate Change (IPCC) has identified the unmindful pumping of CO_2 into the atmosphere is the main culprit for the climate change and highlighted that the “largest mitigation potentials are in the steel, cement and pulp and paper industries…” [8]. Carbon emission data is alarming; the 2007 carbon emission estimate was an all time high and a 1.7 percent increase from the previous year alone [6]. The highest average growth rates in industrial-sector CO_2 emissions are projected for developing countries [9]. As one such rising economy, India has an international obligation of reducing CO_2 emissions.

In view of the serious impact of carbon dioxide on the environment and the continued anticipated growth of industrialization and urbanization, there is a need to redirect the building industry away from its overwhelming reliance on Portland cement by developing alternative binder systems. The two options which have attracted attention as alternative binders are (i) the partial replacement of cement by industrial byproducts like fly ash and slag and (ii) the use of geopolymer binders. The first alternative has been widely researched and abundant information on the fresh and hardened properties of concrete with partial replacement of cement has led to the use of such blended cements [10, 11, 12, 13, 14]. In one such application, a post-tensioned structure with 50-70 percent replacement of cement by slag resulted in an estimated reduction on carbon dioxide emissions for the project of 4500 tonnes [12]. Partial replacement of cement in binders has been found to comply with Indian standards for masonry cement and could be used up to 25 percent partial replacement without deleterious effect on strength [15]. The second alternative, geopolymer binders, is an emerging area of technology. Davidovits [16] first proposed that an alkaline liquid could be used to react with the silicon (Si) and aluminum (Al) in a source material of geological origin or in by-product materials such as fly ash and rice husk ash to produce cementitious binders. Because the chemical reactions that takes place in this case is a polymerization process and the source materials are of geological origin, he coined the term ‘geopolymer’ to represent these binders.

Geopolymers are members of the family of inorganic polymers. The polymerization process involves a substantially fast chemical reaction under alkaline condition on Si-Al minerals, that results in a three-dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds [16]. According to Davidovits [16], geopolymers have a wide range of applications determined by the chemical structure in terms of the atomic ratio Si: Al as shown in Table 1.

Research is currently moving from the chemistry domain that includes binder (mortar) composition and properties to engineering, in which mechanical and structural behaviour of geopolymer concretes are studied researched. It has been found that geopolymer concrete has good engineering properties including compressive strength, enhanced tensile strength, bond strength, sulphate and acid resistance and the potential for enhanced durability [17, 18, 19].

Table 1: Applications of Geopolymers Based on Silica-to-Alumina Atomic Ratio

Si:Al ratio	Applications
1	- Bricks - Ceramics - Fire protection
2	- Low CO_2 cements and concretes - Radioactive and toxic waste encapsulation
3	- Fire protection fibre glass composite - Foundry equipments - Heat resistant composites, 200°C to 1000°C - Tooling for aeronautics, titanium process
>3	- Sealants for industry, 200°C to 600°C - Tooling for aeronautics, SPF aluminum
20 - 35	- Fire resistant and heat resistant fibre composites

2. INTERNATIONAL SCENARIO OF GEOPOLYMER CONCRETE

Lloyd and Rangan [20] conducted a study on geopolymer concrete with fly ash. For their study, they used low calcium (ASTM Class F) fly ash as their base material. The observations are made with the effect of water – geopolymer solids. They concluded that geopolymer possess excellent properties and is well suited to manufacture precast concrete products that are needed in rehabilitation and retrofitting of structures after disaster.

Hardjito and Rangan [21] studied fly ash based Geopolymer Concrete. The material used was low calcium ASTM class F dry fly ash obtained from power station. The calcium content of the fly ash was about 2 percent by mass. They observed the compressive strength data and concluded that fly ash based geopolymer concrete has good compressive strength and is suitable for structural application. The fly ash based geopolymer concrete also showed excellent resistance to sulphate attack and the elastic properties of hardened concrete and the behaviour and the strength of reinforced structural members are similar to the Portland cement concrete.

The fresh geopolymer concrete was easily handled upto 120 minutes without any sign of setting. The addition of high range water reducing admixture improved the workability of concrete. They concluded that higher concentration of sodium hydroxide solution and curing temperature in the range of 30ºc to 90ºc results in a higher compressive strength of geopolymer concrete. Higher concentration (in terms of molar) of sodium hydroxide solution results in a higher compressive strength of geopolymer concrete. The rest period between casting of specimens and the commencement of curing up to 60 minutes has no effect on the compressive strength of geopolymer concrete [22].

Rangan et al [23] carried out experiments on Reinforced low – calcium fly ash based Geopolymer concrete beams and columns. Heat-cured low-calcium fly ash-based geopolymer concrete has advantages such as excellent structural properties, low creep, very little drying shrinkage, excellent resistance to sulfate attack, and acid resistant. Heat-cured low-calcium fly ash-based geopolymer concrete has an excellent compressive strength and is suitable for structural applications. The elastic properties of hardened concrete and the behaviour and strength of reinforced structural members are similar to those of Portland cement concrete. Therefore, the design provisions contained in the current standards and codes can be used to design reinforced fly ash-based geopolymer concrete structural members.

Kunal kupwade – patil and Erez Allouche [24] conducted test on the effect of alkali silica reaction in geopolymer concrete. In their study, alkali silica reaction occurs due to chemical reactions between hydroxyl ions in the pore water within the concrete matrix and certain forms of silica. This reaction could lead to strength loss, cracking, volume expansion and potentially failure of the structure. The results suggest that the extent of alkali silica reactions owing to the presence of reactive aggregates in flyash based geopolymer concrete is substantially lower than OPC based concrete, and well below the ASTM specified threshold.

3. OBJECTIVES OF THE PROJECT

The aims of the project are:

i) to develop structural grade Geopolymer concrete using indigenous source materials and alkaline liquids cured under heated regimes,

ii) to determine the short term mechanical properties viz. strength characteristics and elastic modulus,

iii) to establish the durability characteristics for different exposure conditions and assessment of geopolymer concrete against current durability performance criteria, and

iv) to develop and evaluate the geopolymer concrete products suitable for precast manufacture viz. products such as beams, sleepers and bricks. Originally precast beam has been envisaged in the project. Later, the scope has been enlarged to accommodate railway sleepers and bricks.

4. METHODOLOGY

The work elements for the project are listed as below:

i) Identification of source material, alkaline solutions, and other ingredients. The source material is flyash and the suitability of flyash from nearby power stations has been investigated.

ii) Material characterization of ingredients, such as particle size, LoI, and chemical composition.

iii) Development of Geopolymer concrete formulation with heat curing. In this geopolymer concrete of different strengths have been formulated. As heat curing quickens the polymerisation process, this has been resorted to.

iv) Studies on short-term and long-term mechanical properties. Strength tests such as cube compression test, cylinder compression test and split tension test at various time intervals upto 9 months have been conducted.

v) Studies on durability characteristics. In addition to the routine water absorption test and acid resistance tests, the following tests using corrosion analyser have been conducted:

    i. Open circuit potential test
    ii. Impedence test
    iii. LPR sweep test
    iv. Custom sweep test

vi) Development of geopolymer precast products like beams, sleepers and bricks. The development of high strength geopolymer concrete leads to the enlargement of scope incorporating the precast products like geopolymer railway sleepers. Further, millions of units of bricks are required for the building industry, and hence geopolymer bricks have been developed.

vii) Strength and behaviour tests on precast products. As the precast products like beams and sleepers are primarily flexural members, flexural behaviour has been studied.

5. EXPERIMENTAL INVESTIGATION

5.1 Facilities Developed

Following equipment / facilities have been procured / developed under this project:

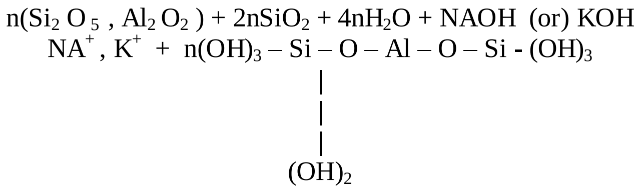
i) Corrosion Analyser
ii) Steam curing chamber
iii) Pan mixer

5.2 Geopolymers

Davidovits proposed that an alkaline liquid could be used to react with the silicon (SI) and the aluminium (Al) in a source material of geological origin or in by –product materials such as fly ash and rice husk ash to produce binders. Because the chemical reaction that takes place in this case is polymerization process coined the term '**Geopolymers**' to represent these binders.

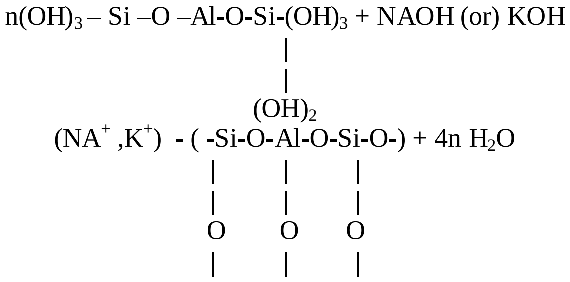
Geopolymers are member of the family of inorganic polymers. The chemical composition of the geopolymer material is similar to natural zeolitic materials, but the microstructure is amorphous. The polymerization process involves a substantially fast chemical reaction under alkaline condition on Si-Al minerals, that results in a three-dimensional polymeric chain a ring structure consisting of Si-O-Al bonds. [25].

The schematic formation of geopolymer material can be shown as described by equations (1) and (2) [25].



$$n(Si_2O_5, Al_2O_2) + 2nSiO_2 + 4nH_2O + NAOH \text{ (or) } KOH$$
$$NA^+, K^+ + n(OH)_3 - Si - O - \underset{\substack{|\\|\\|\\(OH)_2}}{Al} - O - Si - (OH)_3$$

(geopolymer procursor) ---------- (1)



$$n(OH)_3 - Si - O - \underset{\substack{|\\|\\(OH)_2}}{Al} - O - Si - (OH)_3 + NAOH \text{ (or) } KOH$$
$$(NA^+, K^+) - (-\underset{\substack{|\\|\\O\\|}}{Si} - O - \underset{\substack{|\\|\\O\\|}}{Al} - O - \underset{\substack{|\\|\\O\\|}}{Si} - O -) + 4n\,H_2O$$

(geopolymer backbone) ---------- (2)

The last term in equation (2) reveals that water is released during the chemical reaction that occurs in the formation of geopolymers. This water expelled from the geopolymer matrix during the curing and further drying periods, leaves behind discontinuous nano-pores in the matrix, which provide benefits to the performance of geopolymers.

5.2.1 Geopolymer Cements [26]

There are nine different classes of geopolymers, but the classes of greatest potential application for transportation infrastructure are comprised of aluminosilicate materials that may be used to completely replace Portland cement in concrete construction. These geopolymers rely on thermally activated natural materials (e.g., kaolinite clay or weathered rocks) or industrial byproducts (e.g., fly ash or slag) to provide a source of silicon (Si) and aluminum (Al), which polymerizes into molecular chains and networks to create the hardened binder.

The polymerization process involves a substantially fast chemical reaction under alkaline conditions on silicon-aluminum minerals that results in a three-dimensional polymeric chain and ring structure. The ultimate structure of the geopolymer depends largely on the ratio of Si to Al (Si:Al), with the materials most often considered for use in concrete application typically having an Si:Al between 2 and *3.5*. This type of geopolymer will take one of the following three basic forms (where "sialate" is an abbreviation for silicon-oxo-aluminate) [27]:

- Poly (sialate) Si:Al = 1, which has [-Si-O-Al-O-] as the repeating unit.
- Poly (sialate-siloxo) Si:Al = 2, which has [-Si-O-Al-O-Si-O-] as the repeating unit.
- Poly (sialate-disiloxo) Si:Al = 3, which has [-Si-O-Al-O-Si-O Si-O-] as the repeating unit.

A critical feature is that water is present only to facilitate workability and does not become a part of the resulting geopolymer structure. In other words, water is not involved in the chemical reaction and instead is expelled during curing and subsequent drying.

This is in contrast to the hydration reaction that occurs when Portland cement is mixed with water (Figure 1), which produce the primary hydration products calcium silicate hydrate and calcium hydroxide. This difference has a significant impact on the mechanical and chemical properties of the resulting geopolymer concrete, and also renders it more resistant to heat, water ingress, alkali-aggregate reactivity, and other types of chemical attack.

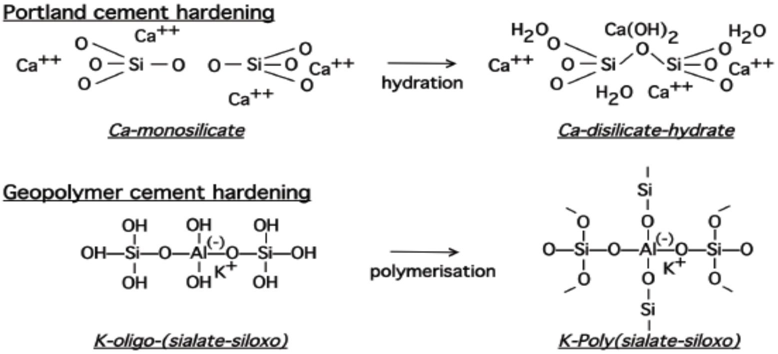


Fig. 1: Polymerisation Process

(Top) hardening of Portland cement through hydration of calcium silicate into calcium-di-silicate hydrate (CSH) and lime $Ca(OH)_2$; (Bottom) setting of geopolymeric structure through polymerisation of potassium-oligo-(sialate-sioxo) into potassium poly(sialate-siloxo) crosslinked network.

Conceptually, the formation of geopolymers is quite simple. In the case of geopolymers based on aluminosilicate, suitable source materials must be rich in amorphous forms of Si and Al. One distinguishes three types of geopolymer cement, so far:

- Metakaolin *(MK-750)* / Slag / Alkali-silicate - based;
- Rock (volcanic tuffs, granitic) / Slag / Alkali-silicate - based;
- Fly ash / Slag / Alkali-silicate - based.

5.2.2 Geopolymer Concrete

There are two main constituents of geopolymers, namely the source materials and the alkaline liquids. The source materials for geopolymers based on alumina-silicate should be rich in silicon (Si) and aluminium (Al). These could be natural minerals such as kaolinite, clays, etc. Alternatively, by-product materials such as fly ash, silica fume, slag, rice-husk ash, red mud, etc could be used as source materials. The choice of the source materials for making geopolymers depends on factors such as availability, cost, type of application, and specific demand of the end users.

The alkaline liquids are from soluble alkali metals that are usually Sodium or Potassium based. The most common alkaline liquid used in geopolymerisation is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate.

5.2.3 Constituents of Geopolymer Concrete

Geopolymer concrete can be manufactured by using the low-calcium (ASTM Class F) fly ash obtained from coal-burning power stations. Most of the fly ash available globally is low-calcium fly ash formed as a by-product of burning anthracite or bituminous coal. Although coal burning power plants are considered to be environmentally unfriendly, the extent of power generated by these plants is on the increase due to the huge reserves of good quality coal available worldwide and the low cost of power produced from these sources.

Low-calcium fly ash has been successfully used to manufacture geopolymer concrete when the silicon and aluminum oxides constituted about 80% by mass, with the Si-to-Al ratio of about 2. The content of the iron oxide usually ranged from 10 to 20% by mass, whereas the calcium oxide content was less than 5% by mass. The carbon content of the fly ash, as indicated by the loss on ignition by mass, was as low as less than 2%. Coarse and fine aggregates used by the concrete industry are suitable to manufacture geopolymer concrete. A combination of sodium silicate solution and sodium hydroxide (NaOH) solution can be used as the alkaline liquid. It is recommended that the alkaline liquid is prepared by mixing both the solutions together at least 24 hours prior to use.

5.2.4 Mixture Proportions of Geopolymer Concrete

The primary difference between geopolymer concrete and Portland cement concrete is the binder. The silicon and aluminum oxides in the low-calcium fly ash reacts with the alkaline liquid to form the geopolymer paste that binds the loose coarse aggregates, fine aggregates, and other un-reacted materials together to form the geopolymer concrete.

As in the case of Portland cement concrete, the coarse and fine aggregates occupy about 75 to 80% of the mass of geopolymer concrete. This component of geopolymer concrete mixtures can be designed using the tools currently available for Portland cement concrete.

5.2.5 Curing of Geopolymer Concrete

The ordinary cement concrete hardens due to hydration process in presence of water. The Geopolymer concrete revealed that can not attain any strength by water curing since it hardens due to polymerization process in presence of heat. The Geopolymer concrete will harden at steam curing or hot air curing and the minimum curing period shall be 24 hours. After casting the specimens, they are kept in rest period in room temperature for 2 days. The term ‘Rest Period’ was coined to indicate the time taken from the completion of casting of test specimen to the start of curing at an elevated temperature. The geopolymer concrete specimens are demoulded and then placed in steam curing chamber for 24 hours at a temperature of 60^{o} C. The geopolymer concrete specimens are then allowed to cool in room temperature for 24 hours.

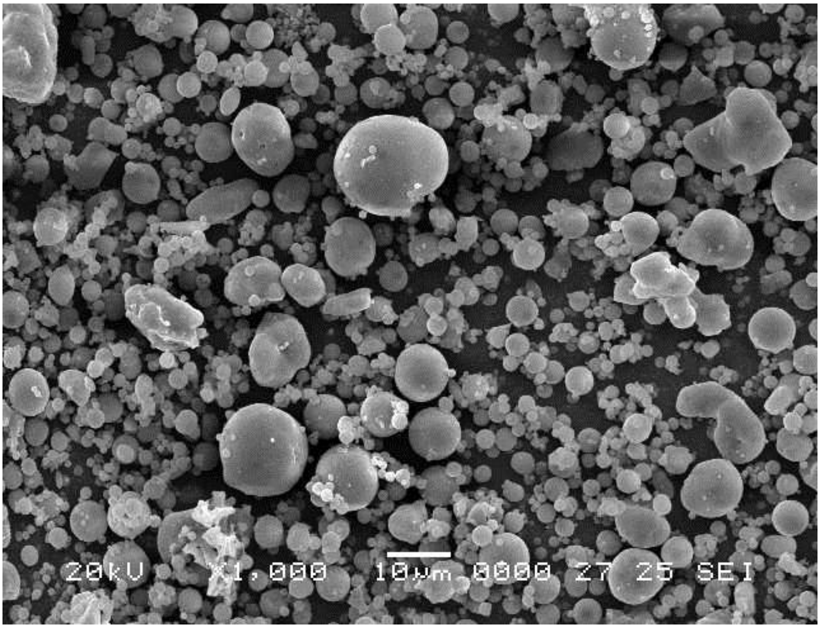
If the geopolymer concrete is allowed to cure in ambient conditions, the strength development upto the full capacity will not take place. To improve the strength development under ambient conditions, materials like silica fume and slag should be added upto 30 to 40 percent. In that case, the geopolymer concrete is not fully based on flyash and the cost will be more than that of concrete with ordinary Portland cement.

5.3 Materials Used

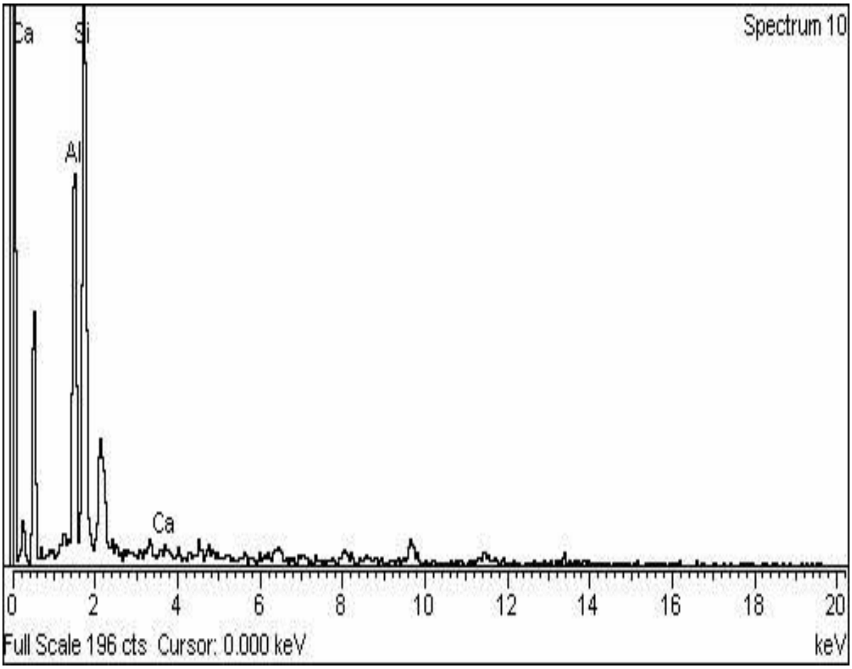
Low-calcium fly ash has been successfully used to manufacture geopolymer concrete when the silicon and aluminum oxides constituted about 80 percent by mass, with the Si-to-Al ratio of about 2. The content of the iron oxide usually ranged from 10 to 20 percent by mass, whereas the calcium oxide content was less than 5 percent by mass. The carbon content of the fly ash, as indicated by the loss on ignition by mass, was as low as less than 2 percent. Coarse and fine aggregates used by the concrete industry are suitable to manufacture geopolymer concrete. The aggregate grading curves currently used in concrete practice are applicable in the case of geopolymer concrete. The properties of aggregates used are listed below:

- Specific gravity of fine aggregate (G) = 2.68
- Specific gravity of coarse aggregate (G) = 2.67
- Fineness modulus = 2.77 (medium sand)
- fine aggregate is confirmed to zone-II (IS: 383 – 1970)
- Fineness modulus = 2.21 (coarse aggregate of size ranging from 12.5 to 5mm)

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



a) SEM Photograph



b) Chemical Composition

Fig. 2 Fly ash and its Constituents

Table 2 Chemical Composition of Fly ash

Compound	Percentage (mass)
SiO_2	52.54
Al_2O_3	26.74
Fe_2O_3	11.12
CaO	1.28
Na_2O	0.47
K_2O	0.82
TiO_2	1.57
MgO	0.87
P_2O_5	1.53
SO_3	1.70
*LoI	1.36

*LoI- Loss on Ignition

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 solution and sodium hydroxide (NaOH) solution can be used as the alkaline liquid. It is recommended that the alkaline liquid is prepared by mixing both the solutions together at least 24 hours prior to use. The sodium silicate solution is commercially available in different grades. The sodium silicate solution A53 with SiO_2-to-Na_2O ratio by mass of approximately 2, i.e., SiO_2 = 29.4 percent, Na_2O = 14.7percent, and water = 55.9 percent by mass, is generally used.

The 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 concentration of sodium hydroxide solution can vary in the range between 8 Molar and 16 Molar; however, 8 Molar solution is adequate for most applications. The mass of NaOH solids in a solution varies depending on the concentration of the solution. For instance, NaOH solution with a concentration of 8 Molar consists of 8 x 40 = 320 grams of NaOH solids per litre of the solution, where 40 is the molecular weight of NaOH. The Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3) solutions are used to desiccate the Silicate and Aluminum compounds in the fly ash.

5.4 Preparation of Specimens

The concrete batch was mixed on a water tight, non-absorbent steel platform with a shovel, trowel and similar suitable implement, using the following procedure:

i. The flyash and fine aggregate were mixed dry until the mixture is thoroughly blended and is uniform in colour.

ii. The coarse aggregate was added and mixed with the flyash and fine aggregate until the coarse aggregate was uniformly distributed throughout the batch.

iii. The chemical solution was added and the entire batch was mixed until the concrete appeared to be homogenous and had the desired consistency. If repeated mixing was necessary, because of the addition water in increments while adjusting the consistency, the batch is to be discarded and fresh batch is made.

5.5 Mixing, Casting and Curing

The fresh fly ash classified as low calcium (ASTM Class F) dry ash collected from Mettur Thermal Power Station was used. The aggregates were prepared in saturated surface dry condition. The liquid part of the mixture, ie. the sodium silicate solution, the sodium hydroxide solution (Figure 3) mixed twenty four hours earlier for thorough mixing and reaction. The solids constituents of the fly ash based geopolymer concrete, (Figure 4) ie. the aggregates and the fly ash were dry mixed by a Pan mixer (Figure 5) for about three minutes. The wet mixing of liquid and dry mixture of aggregates usually continued for another four minutes (Figure 6). The wet mixing usually is in cohesive condition. The workability of the fresh concrete was measured by means of the conventional slump test. The slump measured was 178 mm.

Fig. 3 Preparation of Alkaline Activator Solution

Fig. 4 Constituents of Geopolymer Concrete

Fig. 5 Pan Mixer

Fig. 6 Mixing of Geopolyer Concrete

After casting, the specimens were covered using vacuum bagging film. Curing at sixty degree centigrade was done in steam curing chamber. A boiler was used to generate the steam at a specified temperature (Figure 7). Curing process in the steam - curing chamber is shown in Figure 8. In the event of casting geopolymer concrete specimens in the open field, steam curing can also be carried out with simple low cost method using polyethylene sheet covering. The compressive test on hardened fly ash-based geopolymer concrete was performed on a 2000 kN capacity hydraulic testing machine in accordance to the relevant Indian Standards. Five 100 x 100 x100 mm concrete cubes were tested to find out mean compressive strength.

Fig.7 Steam Boiler and Controls

Fig. 8 (a) Open view

Fig. 8 (b) Closed view

Fig.8 Specimens in Steam Curing Chamber

5.6 Case Study 1:Development of Minimum Strength Geopolymer Concrete

The Indian Standard Specification for Plain and Reinforced Concrete (IS: 456 – 2000) recommends the minimum strength of concrete to be used in Civil Construction is M 20 and the nominal mix ratio suggested by the code is 1:1.5:3. In this study, same mix ratio has been investigated for Geopolymer concrete with different ratios of alkaline solutions which is one of the main ingredients. The ratio of Sodium Silicate and Sodium hydroxide is kept as 2.5. The ratio of Alkali Activator solution (Na$_2$SiO3 + NaOH) and flyash is kept as 0.45. The strength properties of geopolymer concrete at different ages are given in the Table 3.

Table 3 Strength Properties of Geopolymer Concrete (Per 1m^3)

Sl. No.	**Mix Ratio**	**NaOH Solution**		**Sodium Silicate kg.**	**Slump mm**	**Compressive Strength N/mm^2**			
		Mass kg.	**Mole**			**1 day**	**3 month**	**6 month**	**9 month**
1	1:1.5:3	17.94	8 M	140.14	175	20.9	26.2	30.1	31.1
2	1:1.5:3	26.9	12 M	140.14	178	24.8	30.2	35.7	40.2

The compressive strength of Geopolymer Concrete at later ages is showing 49 percent and 62 percent increase with 9 months age at room temperature.

5.7 Case Study 2: Development of High Strength Geopolymer Concrete

In the second study, a mix ratio of M 40 grade concrete obtained using IS:10262-2009 was used with a partial modification of replacement of cement and water by fly ash and alkaline solutions. The strength properties of geopolymer concrete are shown in Table 4.

Table 4 Strength Properties of Geopolymer Concrete (Per 1m^3)

Sl. No.	Mix Ratio	NaOH Solution		Sodium Silicate kg.	Slump mm	Comp. Strength N/mm^2
		Mass kg.	Molarity			
1	1:1.3:2.7	57.88	8 M	144.68	30	42.35

5.8 Case Study 3: Development of Normal Strength Geopolymer Concrete

In the third study, a mix ratio of M 20 grade concrete obtained using IS:10262-2009 was used (1:1.7:3.1) with a partial modification of replacement of cement and water by fly ash and alkaline solutions. The constituents of geopolymer concrete are calculated as same as above and the strength properties are shown in Table 5.

Table 5 Workability and Strength Properties

Sl. No.	Mix Ratio	Molarity of NaOH Solution	Slump mm	Comp. Strength N/mm^2	Split tensile strength (N/mm^2)
1	1:1.7:3.1	8 M	120	30.70	3.38
2	1:1.7:3.1	10 M	105	32.5	3.64
3	1:1.7:3.1	12 M	85	37.5	5.98
4	1:1.7:3.1	14 M	60	20.5	3.38

5.9 Case Study 4:Parametric Study on High Strength Geopolymer Concrete

A mix ratio 1:1.3:2.7 (1 flyash: 1.3 fine aggregate: 2.7 coarse aggregate) had been obtained for a cube compressive strength of 40 N/mm^2 (approximately) by trial and error method. In this study, various concentrations of NaOH solutions 8M, 10M and 12M were used along with different Alkali Activator Solution (AAS) / fly ash ratios 0.40, 0.45, 0.50 and 0.55. The strength parameters obtained are shown in Table 6.

Table 6 Compressive and Tensile Strength for Cubes and Cylinders

Sl. No.	Molarities of NaOH	AAS/ Fly ash Ratio	Cube compressive strength (N/mm^2)	Cube Tensile strength (N/mm^2)	Cylinder compressive strength (N/mm^2)	Cylinder split tensile strength (N/mm^2)
1	8M	0.40	49.50	9.18	36.18	4.66
2	10M		48.33	10.22	35.83	4.13
3	12M		46.72	8.63	34.92	3.96
4	8M	0.45	50.02	9.37	37.36	5.13
5	10M		49.13	10.56	36.23	4.78
6	12M		47.24	8.69	35.67	4.02
7	8M	0.50	52.08	9.86	38.72	5.48
8	10M		50.73	10.88	37.00	4.97
9	12M		49.26	8.93	36.45	4.24
10	8M	0.55	49.75	9.02	36.27	4.58
11	10M		48.63	10.13	35.54	4.17
12	12M		47.84	8.09	36.13	3.85

5.10 Elastic Modulus of Geopolymer Concrete

Compression test was conducted on geopolymer concrete cylinders made out of concrete mix 1:1.3:2.7 with NaOH molarity of 8 and different AAS / fly ash ratios (0.4, 0.45, 0.5 and 0.55) to evaluate the modulus of elasticity. The result shows that the modulus of elasticity does not vary much with the variations in AAS / fly ash ratio and the values range from 39951 to 41092 N/mm^2.

5.11 Discussion on Strength of Geopolymer Concrete

Geopolymer concrete is a cementless concrete where the cement is replaced by flyash and water is replaced by a combination of alkali activator solution. The alkali activator solutions are Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3). Different molarities of Sodium Hydroxide solution have been tried in this study.

Four case studies have been tried in this project, depending upon the different uses of structural concrete in the field.

From the case study 1, it is found that the average compressive strength of Geopolymer concrete with 12 Mole concentration of Sodium Hydroxide is 24.83 N/mm^2 which is very much suitable for minimum strength of concrete for Civil Construction suggested by IS: 456 – 2000. The average compressive strength of Geopolymer concrete of 8 Mole Sodium Hydroxide is 20.92 N/ mm^2. The reduction in concentration of Sodium Hydroxide reduces the strength of concrete. This strength is very well suited for M20 grade concrete. The compressive strength of 8M and 12M concentration of NaOH Geopolymer concrete at later ages are showing 49percent and 62percent respectively increase at 9 months age in room temperature. From the case study 2, it is found that the average compressive strength of Geopolymer concrete of M 40 grade with 8 Mole Sodium Hydroxide is 42.35 N/ mm^2. This concrete is very much suitable for applications with high strength concrete.

From case study 3, a mix ratio of M 20 grade concrete obtained using IS: 10262-2009 was used (1:1.7:3.1) with a partial modification of replacement of cement & water by fly ash and different concentration of NaOH. The compressive strength of Geopolymer with 8, 10, 12 and 14 Mole concentration of NaOH shows 30.75, 32.50, 37.50 and 20.50 N/ mm^2. It is found that Geopolymer concrete with 12 M concentration of NaOH gives maximum compressive strength.

In the case study 4, a concrete mix with different concentrations of NaOH such as 8, 10 and 12 were tried with different ratio of AAS (sodium silicate plus sodium hydroxide) per flyash as 0.40, 0.45, 0.50 and 0.55. Geopolymer Concrete with 8M NaOH solution with

AAS/flyash ratio of 0.50 gives higher strength of 52.08 N/ mm^2. Concrete of this strength is very much suitable for pre-stressing operations.

6. DURABILITY TESTS ON GEOPOLYMER CONCRETE

6.1 Acid Resistance Test on Geopolymer Concrete

To perform the acid attack studies in the present investigation immersion technique was adopted. After 28 days of casting, 100 x 200 (mm) cylinder specimens were immersed in H_2SO_4 solution. The solution was kept at room temperature and the solution was stirred regularly, at least twice a day to maintain uniformity. The solution was replaced at regular intervals to maintain concentration of solution throughout the test period. The evaluations were conducted after 60 days from the date of immersion. After removing the specimens from the solution, the surfaces were cleaned with a soft nylon wire brush under the running tap water to remove weak products and loose material from the surface. Then the specimens were allowed to surface dry and all the measurements were taken. From the initial measurement and measurements at particular intervals, the loss or gain of the weight were studied. All the geopolymer concrete were showing percentage of mass increase when compared with initial mass. Hence, geopolymer concrete showed an excellent resistance to acid attack.

The compressive strength of GPC specimens immersed in H_2SO_4 about 60 days got reduced while increasing the concentration of acid as shown in Table 7. The 8M NaOH specimen shows reduction in strength of 9.3 percent, 18.1 percent and 31.8 percent in 0.5 percent, 1 percent, and 2 percent H_2SO_4 concentration respectively with respect to control specimen. The 10M NaOH specimen shows reduction in strength of 13.7 percent, 24.1 percent and 41.5 percent in 0.5 percent, 1 percent, and 2 percent H_2SO_4 concentration with respect to control specimen. The 12M NaOH specimen shows reduction in strength of 18.41 percent, 27.5 percent and 33.4 percent in 0.5 percent, 1 percent, and 2 percent H_2SO_4 concentration respectively with respect to control specimen. The 14M NaOH specimen shows reduction in strength of 15.7 percent, 21.0 percent and 26.4 percent in 0.5 percent, 1 percent, and 2 percent H_2SO_4 concentration respectively with respect to control specimen.

Table7 Compressive Strength (N/mm^2) of Specimen with Different H_2SO_4 Concentration

NaOH concentration	**H_2SO_4 Concentration**			**Reference specimen @ age**	
	0.5 %	**1 %**	**2 %**	**1 day**	**60 days**
8M	25.40	22.93	19.10	22.92	28.00
10M	31.85	28.00	21.60	30.57	36.9
12M	34.30	30.50	28.00	40.76	42.04
14M	20.40	19.10	17.80	26.75	24.20

6.2 Sulphate Resistance Test on Geopolymer Concrete

To perform the acid attack studies in the present investigation immersion technique was adopted. After 28 of casting days, 100 x 200 (mm) Cylinder specimens were immersed in five percent Na_2SO_4 solution. The solution was kept at room temperature and the solution was stirred regularly, at least twice a day to maintain uniformity.

The compressive strength of Geopolymer Concrete (GPC) specimens immersed in Na_2SO_4 about 60 days are reduced while increasing the concentration of acid as shown in Table 8. The strength of GPC specimen kept in Na_2SO_4 solution for 60 days shows reduction in strength in all the NaOH concenteted GPC specimens. The compressive strength of 8M, 10M, 12M and 14M of NaOH, GPC specimens show 22.2 percent, 12.5 percent, 24.5 percent and 19.2 percent reduction in strength when it is immersed in Na_2SO_4 for 60 days.

Table 8 Compressive Strength (N/mm^2) of Geopolymer Concrete [Cylindrical Specimen]

NaOH concentration	Specimen immersed in Na_2SO_4 for 60 days	Reference specimen @ age	
		1 day	60 days
8M	17.82	22.92	28.00
10M	26.74	30.57	36.9
12M	30.57	40.76	42.04
14M	21.60	26.75	24.20

6.3 Durability Tests using Corrosion Analyser

The corrosion mostly affects steel and concrete structures. Using Electrical analyser (Figure 9), all types of corrosion test can be carried out. In this research work, four important corrosion tests only are conducted. The geopolymer concrete specimens were cast using different mole solutions of NaOH such as 8M, 10M and 12M and various Alkali Activator Solution (AAS) to Fly Ash (FA) ratios say

0.40, 0.45, 0.50 and 0.55. The normal concrete specimens (CC) were also cast with Water to Cement (W/C) ratio 0.38 and the design mix ratio adopted was 1:1.3:2.7 for both the concrete specimens. The following tests were conducted on concrete specimens:

(i) Open circuit potential test
(ii) Impedance test
(iii) LPR Sweep
(iv) Custom Sweep

Fig. 9 Electrical Analyser

6.3.1 Open Circuit Potential Test

For conducting open circuit potential test concrete cube specimens of size 100 mm x100 mm x100 mm had been cast with 10 mm dia tor steel rod inserted at the centre up to a depth of 70 mm. Geopolymer concrete with different AAS/FA ratios had been considered along with normal concrete for this test. The cube specimens were placed in the Electrical analyser, the rebar was connected to working electrode 1 and the reference electrode and also auxiliary electrode directly connected to Guard ring was placed over the specimen. The schematic diagram and the electrode connections of Electrical analyser are shown in Figure 10.

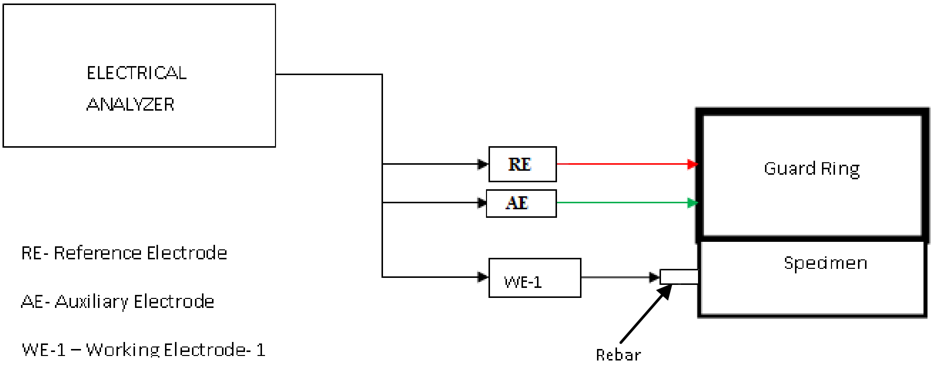
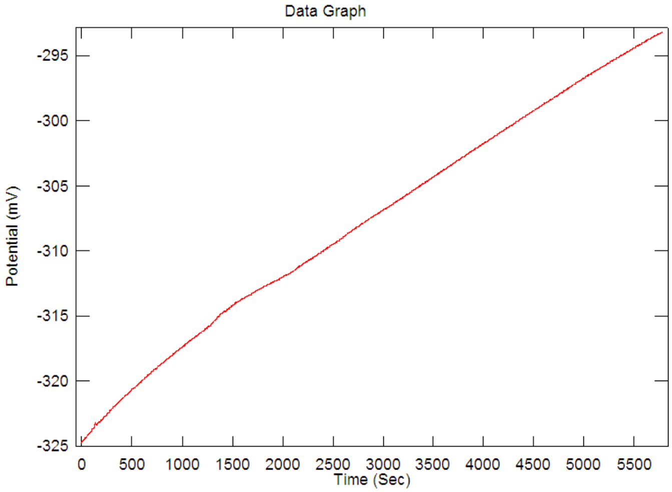


Fig. 10 Schematic Diagram of Electrical Analyser

The function of Working Electrode (WE-1) is to pass the voltage in to the rebar embedded in concrete. The Auxiliary Electrode (AE), converts the passed voltage in to the required current and the current spreads the entire specimen. The Reference Electrode using the converted current and locate the corrosion/weak points available in the specimen.The output is given as a graph showing time Vs potential (Figure 11). From the graph voltage ratio has been calculated by the machine. The experiments were conducted for Geopolymer concrete specimens and cement concrete specimens using Electrical analyser. The open circuit potential measurement results are tabulated in Table 9.



Delta V (mV) = - 8.781, Average V (mV)= – 307.65, Voltage ratio = - 0.025

Fig. 11 Open Circuit Potential - Good Concrete

Table 9 Open Circuit Potential Test Results

Sl. No.	Details	AAS/F.A	Voltage ratio (Geopolymer)			Voltage ratio (CC)	Corrosion level as per ASTM standards
			8M	10M	12M		
1.	CC	W/C -0.38	---			- 0.1890	Moderate
2.	GPC	0.40	-0.0285	-0.0712	-0.0928		Low
3.	GPC	0.45	-0.0470	-0.0843	-0.0919		Low
4.	GPC	0.50	-0.0510	-0.0895	-0.1041		Moderate
5.	GPC	0.55	-0.0612	-0.0950	-0.1234		Moderate

CC- Normal Concrete, GPC- Geopolymer Concrete,
AAS/F.A – Alkali Activator Solution / Fly ash

Inference

The result indicates voltage ratio is less in Geopolymer concrete (8M) specimens gives very low corrosion risk when compared to ASTM guide lines given.

For the Geopolymer concrete 10M specimen voltage ratio expressed indicates Low corrosion risk and for 12M specimens voltage ratio indicates moderate corrosion risk and also control concrete specimens have moderate corrosion risk. This clearly indicates that geopolymer concrete has better corrosion resistance when compared to normal concrete. Further, it can be concluded that the ratio of AAS/FA has a bearing on corrosion resistance. Hence open circuit potential measurement (ASTM B611-2005) [28] is a useful technique in finding out the anodic and cathodic sites in reinforced concrete structures provided the reinforcing bars are exposed to the environments.

6.3.2 Impedance Test

The Impedance test method measures the corrosion rate using I_{corr} values and also determines the corrosion points available inside the specimens. The schematic diagram and the electrode connections of Electrical analyser are available in section 8.3.1.

Calculation of Corrosion rate

$I_{corr}=B/R_p$

Corrosion rate = $0.129 \mathrm{x} I_{corr}$ x EW/ dA

B = B is the Stern–Geary constant, Stern–Geary range of 10–30 mV

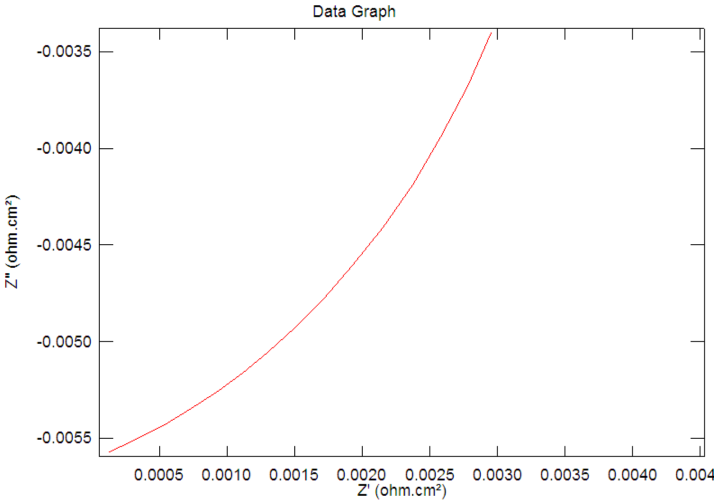
R_p = Polarization Resistance

E.W=equivalent weight of the corroding species, (g).

A=exposed surface area of the reinforcing steel,

d = the density of the reinforcing steel, in g/cm^3

The experiments are conducted in Geopolymer specimens and cement concrete specimens using Electrical analyser. The Impedance test graphical representation is shown in Figure 12. The impedance test results are tabulated in Table 10.



Icorr (mA/cm²) -0.002327, Corrosion Rate (mm/year)-0.04628, Corrosion rate (mils/yr) – 1.8215808

Fig. 12 Impedance Test - Good Concrete

Table 10 Impedance Test Results

Sl. No.	Details	AAS/F.A	Corrosion rate (mm/year)			Corrosion rate (mm/year) (CC)	Corrosion condition as per ASTM standards
			8M	10M	12M		
1.	CC	W/C -0.38	---			9.9897	Moderate risk
2.	GPC	0.40	0.046	2.581	3.846		Medium risk
3.	GPC	0.45	0.739	2.924	4.182		Medium risk
4.	GPC	0.50	1.954	3.116	4.750		Medium risk
5.	GPC	0.55	1.973	3.473	5.125		Medium risk

CC- Control Concrete, GPC- Geopolymer Concrete,
AAS/F.A – Alkali Activator Solution/Fly ash

Inference

The geopolymer concrete specimens (8M) corrosion rate becomes less than 1mm/year so it is termed as very low risk corrosion as detailed in ASTM CSA/S413-94 [29] and for 10M and 12M specimens corrosion rates ranges between 1mm/year to 3mm/year so it is low risk corrosion. For the control concrete specimens, corrosion rate becomes 7mm/year to 10mm/year so it is termed as moderate risk corrosion.

6.3.3 LPR Sweep Test

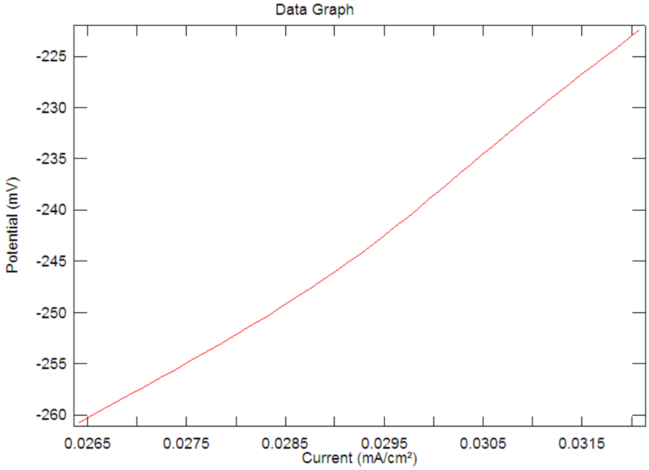
The Linear polarization resistance sweep method measures the instantaneous corrosion rates as compared to other methods on which metal loss is measure over a finite period of time. Instantaneous means that each reading on the instrument can be translated directly into corrosion rate. The experiment can be completed in a matter of minutes and the small polarization from the corrosion potential does not disturb the system. This permits rapid rate measurements (ASTM D2776 & G59) [30] and can be used to monitor corrosion rate in various process streams.The LPR data enables a more detailed assessment of the structural condition and is a major tool in deciding upon the optimum remedial strategy to be adopted. It is thus imperative that the LPR measurements obtained are accurate. In LPR measurements the reinforcing steel is perturbed by a small amount from its equilibrium potential. This can be accomplished potentiostatically by changing the potential of the reinforcing steel by a fixed amount, ΔE- reinforcing steel and monitoring the current decay, ΔI, after a fixed time. Alternatively it can be done galvanostatically by applying a small fixed current, ΔI-to the reinforcing steel and monitoring the potential change, ΔE- after a fixed time period. In each case the conditions are selected such that the change in potential, ΔEfalls within the linear Stern–Geary range of 10–30 mV [31]. The polarization resistance, Rp, of the steel is then calculated from the equation

$$R_p=\Delta E/\Delta I$$

where, B is the Stern–Geary constant. A value of 25 mV has been adopted for active steel and 50 mV for passive steel [32].
From which the corrosion rate, Icorr, can then be calculated

$$I_{corr}=B/R_p$$

The experiments are conducted for Geopolymer concrete specimens and cement concrete specimens using Electrical analyser. The LPR sweep graphical representation is shown in Figure 13.



I_{corr}= (mA/cm²)- 0.029321, Corrosion Rate (mm/year)- 0.378475, Corrosion rate (mils/yr) - 14.89677

Fig. 13 LPR-Sweep - Good Geopolymer Concrete

The LPR Sweep technique may be used for accurately measuring corrosion rates in geopolymer concrete specimen and the test results are tabulated in Table 11.

Table 11 LPR Sweep Test Results

Sl. No.	Details	AAS/F.A	Corrosion rate (mm/year)			Corrosion rate (mm/year) (CC)	Corrosion condition as per ASTM Standards
			8M	10M	12M		
1.	CC	W/C -0.38	---			5.1330	Moderate risk
2.	GPC	0.40	0.379	0.791	1.277		Medium risk
3.	GPC	0.45	0.407	0.935	1.384		Medium risk
4.	GPC	0.50	0.594	1.105	1.424		Medium risk
5.	GPC	0.55	0.749	1.263	1.673		Medium risk

CC- Normal Concrete, GPC- Geopolymer Concrete,
AAS / F.A – Alkali Activator Solution/Fly ash

Inference

For the geopolymer concrete specimens (8M) corrosion rate is lies between 0.1 mm/year to 1 mm/year so it is low risk corrosion and 10M and 12M corrosion rate is lies between 1 mm/year to 3 mm/year so it is medium risk corrosion. The control concrete specimens corrosion rate is lies between 3 mm/year to 7 mm/year so it is moderate risk corrosion. The corrosion rates for geopolymer concrete gave better results compared to control concrete and hence the geopolymer concrete can be utilized in Hydraulic structures.

6.3.4 Custom Sweep Test

The Custom sweep method or Tafel Extrapolation Method measures the instantaneous corrosion rates. This technique uses data obtained from cathodic and anodic polarization measurements. Cathodic data are preferred, since these are easier to measure it experimentally. In this method, the total anodic and cathodic polarization curves corresponding to hydrogen evolution and metal dissolution are superimposed as dotted lines. It can be seen that at relatively high-applied current densities the applied current density and that corresponding to hydrogen evolution have become virtually identical. To determine the intercept corrosion rate from such polarization measurements, the Tafel region is extrapolated to the corrosion potential.

$$i_{corr} = \frac{\alpha\beta}{2.3(\alpha+\beta)}\frac{\Delta i}{\Delta E}$$

$$i_{corr} = \frac{\alpha\beta}{2.3(\alpha+\beta)}\frac{1}{R_p}$$

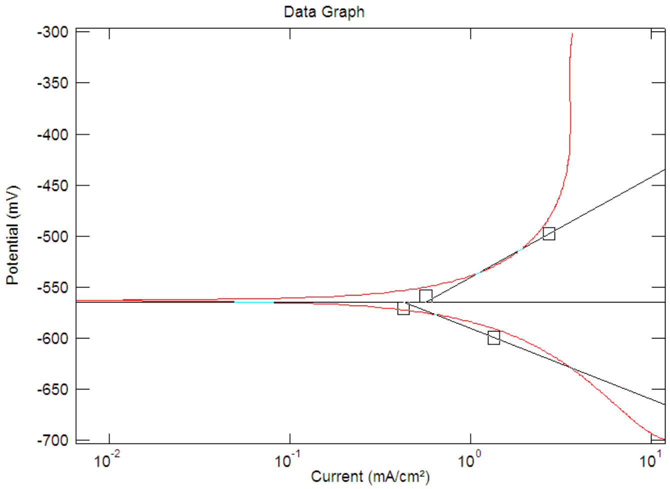
where ΔE/Δi=slope of the polarization curve = Polarization Resistance= Rp.

α and β = Cathodic and Anodic Tafel constants.

The experiments were conducted for Geopolymer concrete and cement concrete specimens using Electrical analyser. The Custom sweep graphical representation is shown in Figure 14. This technique can be used for accurately measuring intercept corrosion rate in geopolymer concrete specimens and the results are shown (Table 12).

Inference

The geopolymer concrete specimens (8M) intercept corrosion rate is lies between 0.1 mm/year to 1 mm/year so it is termed as low risk corrosion as detailed in ASTMC1543-10a [33] and 10M and 12M intercept corrosion rate lies between 1 mm/year to 3 mm/year so it is termed as medium risk corrosion. The control concrete specimens corrosion rate is lies between 3mm/year to 7mm/year so it is moderate risk corrosion. The intercept corrosion rates for geopolymer concrete gave better results compared to control concrete.



InterceptI$_{corr =}$ (mA/cm²) - 0.0373, Intercept corrosion rate (mm/year)- 0.3118, Intercept corrosion rate (miles/year) – 12.2724

Fig. 14 Custom Sweep - Good Geopolymer Concrete

Table 12 Custom Sweep Test Results

Sl. No.	Details	AAS/F.A	Intercept Corrosion rate (mm/year) (GPC)			Intercept Corrosion rate (mm/year) (CC)	Corrosion condition as per ASTM
			8M	10M	12M		
1.	CC	W/C - 0.38	---			4.6917	Moderate risk
2.	GPC	0.40	0.312	0.927	1.394	--	Medium risk
3.	GPC	0.45	0.491	1.102	1.687	--	Medium risk
4.	GPC	0.50	0.510	1.124	1.950	--	Medium risk
5.	GPC	0.55	0.590	1.286	2.330	--	Medium risk

CC- Normal Concrete, GPC- Geopolymer Concrete,
AAS/F.A – Alkali Activator Solution / Fly ash

7. 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 (Figure 15). Totally 80 bricks were cast for 1: 1.4 ratios, with 10 molarities (10M) and 12 molarities (12M). Later, bricks with 5M were added as the strength of 10M and 12M bricks are very high.

Fig. 15 Steam Curing of Geopolymer Bricks

7.1 Strength Tests

Strength tests like compressive strength, flexural strength and tensile strength were conducted on geopoloymer bricks. For comparison purpose, the commercially available country bricks and fly ash bricks of same size were also tested. A comparison of strength of various bricks are presented in Figures 16 and 17.

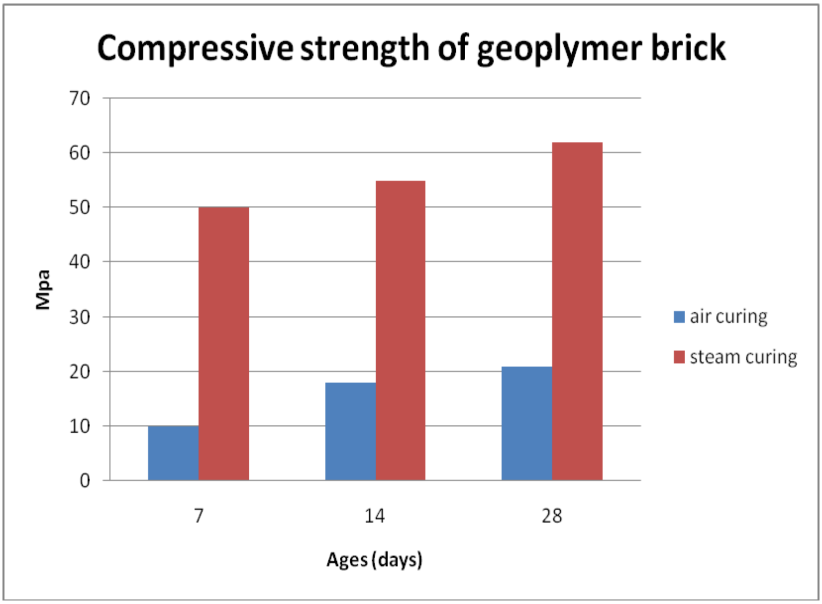


Figure 16 Compressive Strength of Geopolymer Bricks

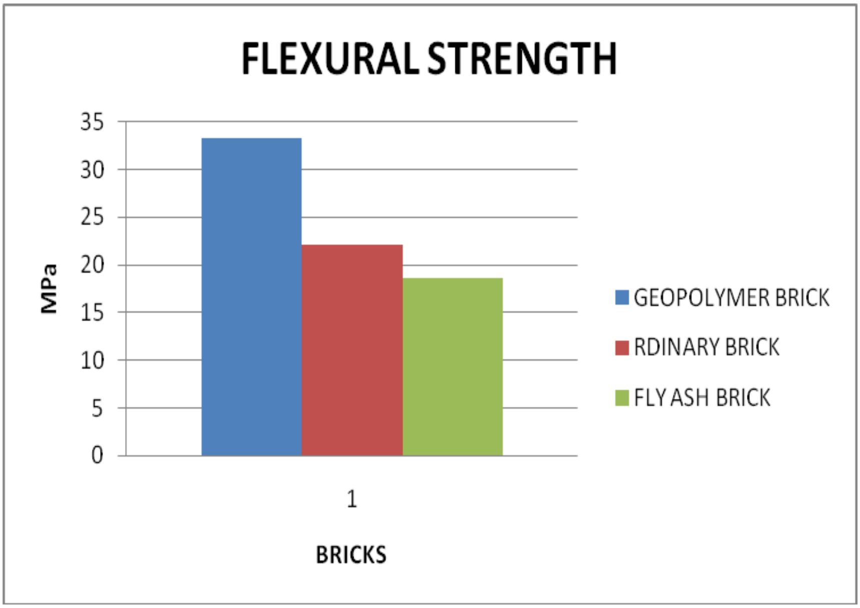


Fig.17 Flexural Strength of Bricks

7.2 Durability Tests

Acid resistance tests were conducted on the three types of bricks namely geopolymer bricks (with 10M NaOH solution) country bricks and fly ash bricks by immersing in different concentrations of sulphuric acid (H_2SO_4) and hydrochloric acid (HCl). A comparison of weight loss is presented in Figures 18 and 19.

Water absorption test were also conducted on the three types of bricks and the test results are presented in and Figure 20.

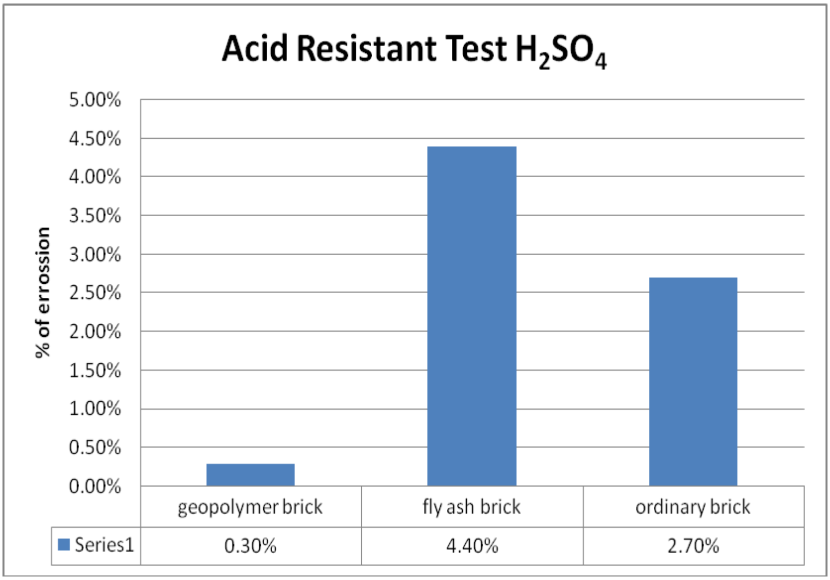


Figure 18 Acid Resistance Test (H_2SO_4)

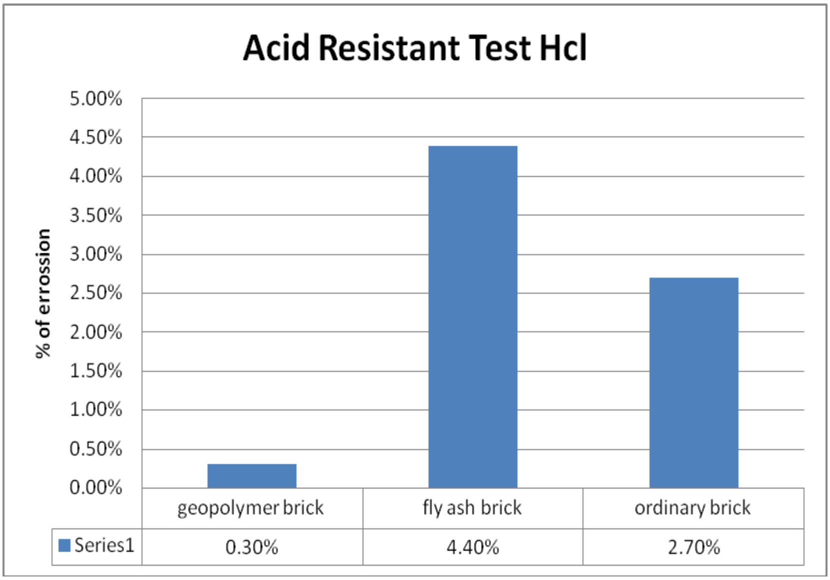


Figure 19 Acid Resistance Test (HCl)

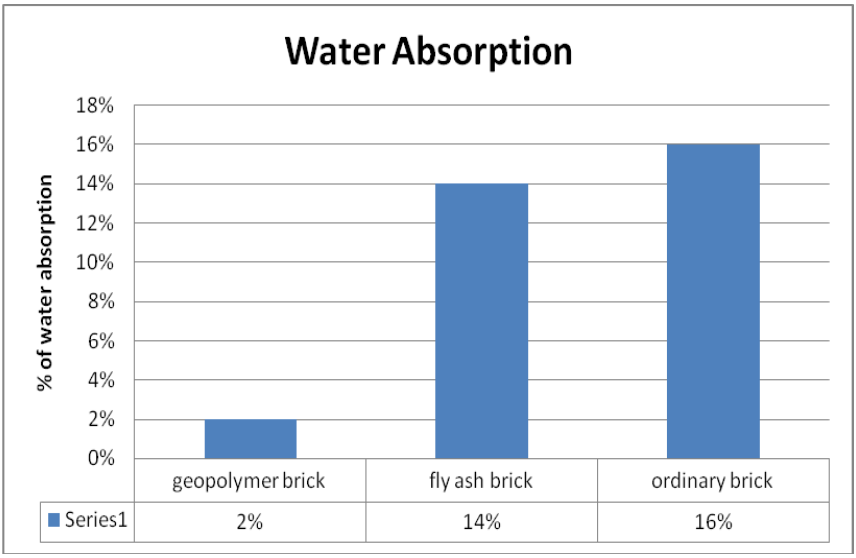


Figure 20 Water Absorption Test

7.3 Discussion on Bricks Test Results

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

(ii) Steam curing aids in gaining strength and the increase in strength of steam cured bricks is more when compared to air curing (Fig. 16).

(iii) The unit weight of geopolymer bricks is slightly higher than that of the other type of bricks.

(iv) 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 increase in acid concentration.

(v) The increase in percentage of weight due to water absorption of geopolymer bricks is a small fraction as to that of other types of bricks.

8. TESTS ON GEOPOLYMER CONCRETE BEAMS

Totally five beams were cast and tested in the laboratory over an effective span of 3000 mm. Four geopolymer concrete beams were tested until failure; the remaining one beam was used as a Reinforced Cement Concrete (RCC) control specimen. The beams were designed as under reinforced section, reinforced with 2-Y12 at bottom, 2-Y10 at top using 6 mm diameter stirrups at 150 mm c/c and Fe 415 grade steel was used.

The geopolymer concrete beams with mix proportion of 1:1.3:2.70 with different AAS/fly ash ratios 0.4 (GCB1), 0.45 (GCB2), 0.5 (GCB3) and 0.55 (GCB4) were cast. For RCC beam (CB), Ordinary Portland Cement (OPC) 53 grade, natural river sand conforming Zone III (IS 383-1970) and coarse angular aggregate of 20 mm were used as the concrete ingredients. The shuttering was removed after 24 hours from the time of casting and the specimens were cured using steam curing.

Beams were tested in four point bending (ASTM C78) the maximum stress is present over the center, 1/3 portion of the beam under static monotonic loading which is shown in Figure 21. The crack pattern of tested beams is shown in Figure 22. The crack pattern of geopolymer resembles very much to that of reinforced cement concrete beams.

Fig. 21 Loading Setup

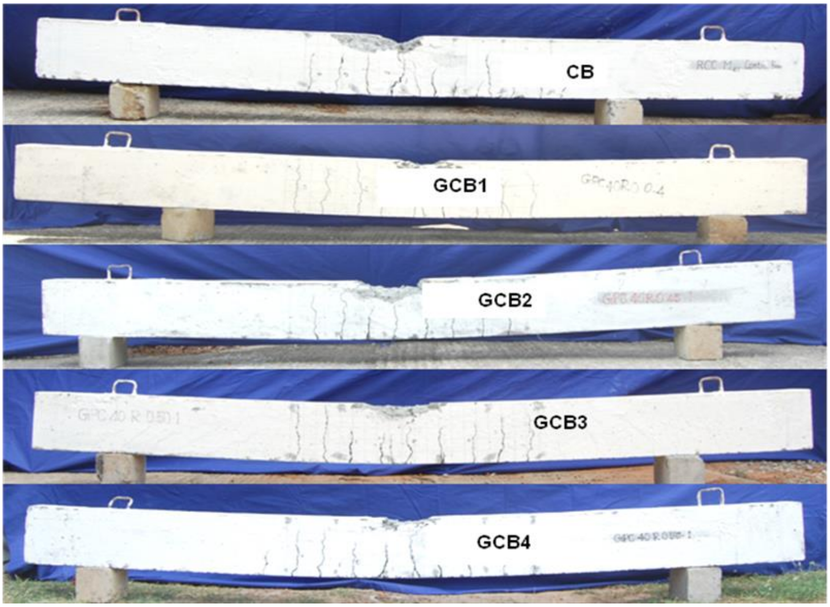


Fig.22 Crack Pattern of Beams

The moment - curvature and load-deflection relationships were obtained using deflection measurements from LVDTs and strain data collected from demec gauges for the control beam and geopolymer concrete beams (CB and GCB1 – GCB4), under static monotonic loading, and are presented in Figures 23 and 24. From the load - deflection, it is seen that the geopolymer concrete beams GCB1 to GCB4 exhibit decreased deflection and appreciable flexural strength when compared to control beam. The first crack loads were obtained by visual examination only. The crack width with respect to load under monotonic condition is shown in Figure 25.

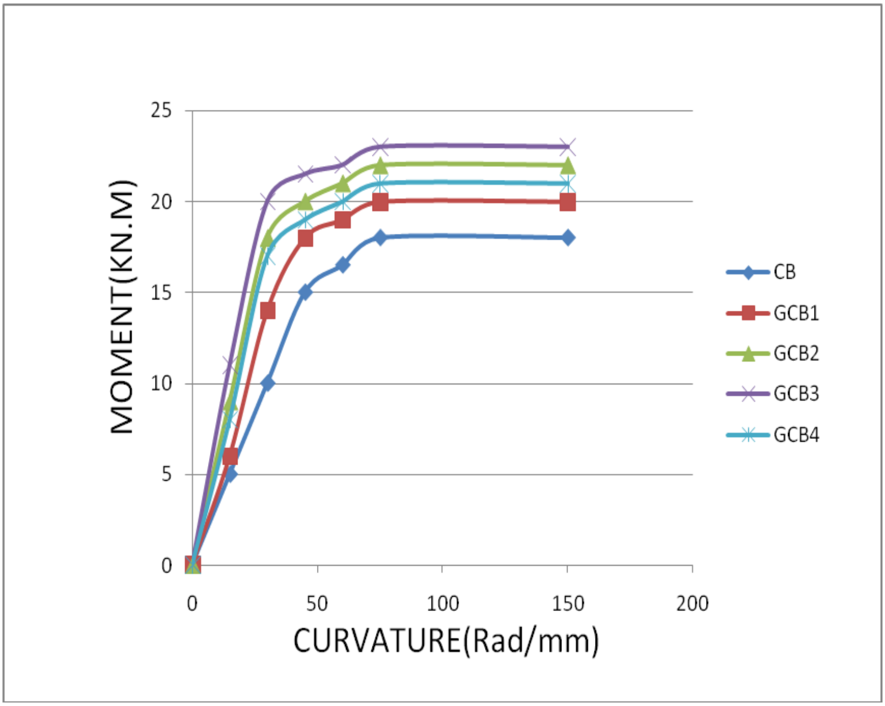


Fig. 23 Moment - Curvature Relationship

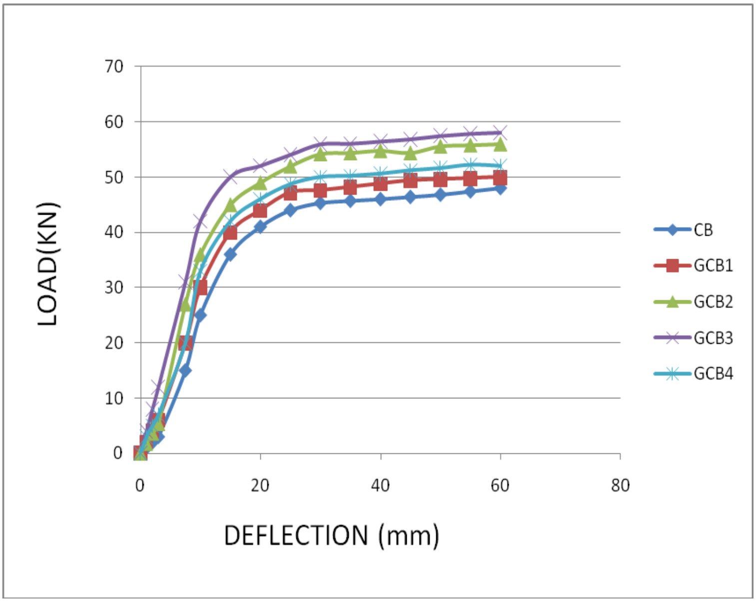


Fig. 24 Load – Deflection Curve

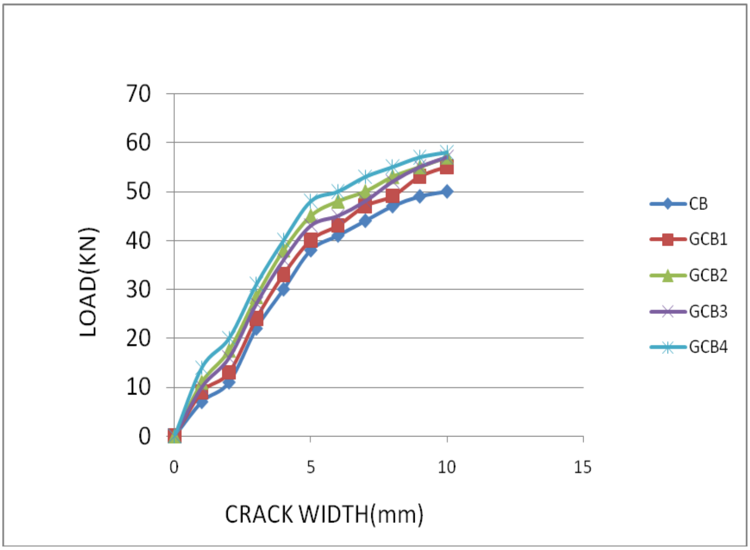


Fig. 25 Load – Crack Width

8.1 Theoretical Load – Deflection behavior of Beams (Section Analysis)

The theoretical multilinear moment - curvature (M-∅) relationships were derived using the section analysis procedure. The three important stages or points identified in the M-∅ curve are the cracking stage, yielding stage, and ultimate stage. In this study, one more stage which corresponds to the start of non-linearity in stress strain curve of steel is proposed and thus making it a multilinear curve. From the multilinear M-∅ relationship multilinear load-deflection curve was derived by adopting a curvature distribution similar to that of a bending moment variations and conjugate beam method of analysis. The same procedure was adopted for geopolymer concrete beams. The experimental and theoretical moment - curvature and load-deflection curves are compared for both control beam (CB) and geopolymer concrete beam GCB1 and are shown in Figures 26 and 27. It can be seen that the predicted deflections are in fairly close agreement with the experimental results.

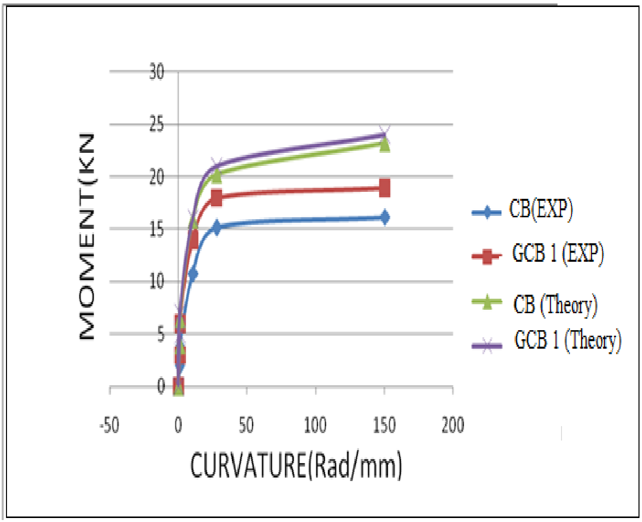


Fig. 26 Theoretical Moment - Curvature Curve

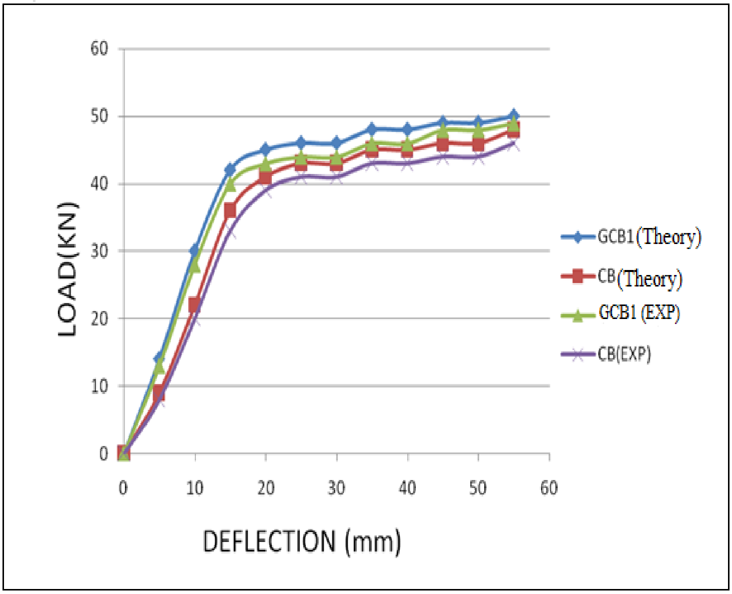


Fig. 27 Theoretical Load - Deflection Curve

From the tests on beams, the following findings are made from the experimental study:

i) Geopolymer Concrete can be developed for structural applications from low calcium flyash.

ii) The strength of Geopolymer Concrete increases with increase in AAS/ flyash ratio upto 0.5

iii) Geopolymer Concrete with 8 molority NaOH solution gives higher strength

iv) The behavior of Geopolymer concrete beams are comparable with that of ordinary concrete beams made out of concrete using OPC.

9. TESTS ON RAILWAY SLEEPERS

On development of high strength geopolymer concrete with strength above 50.0 MPa, it was decided to use Geopolymer Concrete for pretensioned Railway sleepers. A special sleeper mould with pretensioning bed has been fabricated (Figure 28). The mould is similar to that of ordinary sleeper mould used in the railways. But in railways, many sleepers are cast using long line method of Pretensioning. In this study, Pretensioning has been done for individual sleepers. The railway sleepers are cast with Ordinary Portland Cement (OPC) and Geopolymer concrete (GPC).

Fig. 28 Sleeper Mould

9.1 Pretensioning of OPC and GPC Sleepers

The various stages of the pre-tensioning operation are summarised as follows:

i) Anchoring of tendons at the ends of the sleeper mould by using barel and wedges.
ii) The stressing of the strands are done manually. The prestessing jack piston are inserted into the strands.
iii) Applying tension to the tendons. The load is applied from the jack to the piston to stress the strands.

9.2 Casting of Railway Sleepers

For geopolymer concrete, the flyash and the aggregates were first mixed together in the Pan mixer for about 3 minutes. Then the alkaline liquid mixed with super plasticizer was then added with the dry mixers in the pan mixer itself. Two numbers of sleepers were cast with conventional concrete and two sleepers were cast with geopolymer concrete. Companion cubes and cylinders of both geopolymer concrete and conventional concrete were cast.

9.3 Steam Curing of sleepers

All the specimens were kept in steam curing chamber for 24 hours. The specimens were covered with tarpaulin during steam curing. The constant temperature was maintained at 60˚ C.

9.4 Testing of Sleepers

All the sleepers were tested under two point loading (four point bending).The sleepers were placed in the 50 Ton frame for testing. The displacements were measured using the LVDT placed at the bottom of the sleeper at center, left 1155mm and right 1155mm from the support. Additional dial gauges were placed at center of the sleeper. The experimental setup of the sleeper is shown in Figure 29. From the experimental work the load and deflection curve was obtained for GPC and OPC sleepers as shown in Figures 30 and 31. The GPC sleeper behaves in the same way as that of OPC sleeper. The load and deflection details of both sleepers at salient load stages are given in Table 13. The ultimate load carrying capacity of GPC sleeper is slightly higher than the OPC sleeper. The crack pattern of railway sleepers made out of GPC is shown in Figure 32.

Fig. 29 Experimental Setup of the Sleeper (GPC)

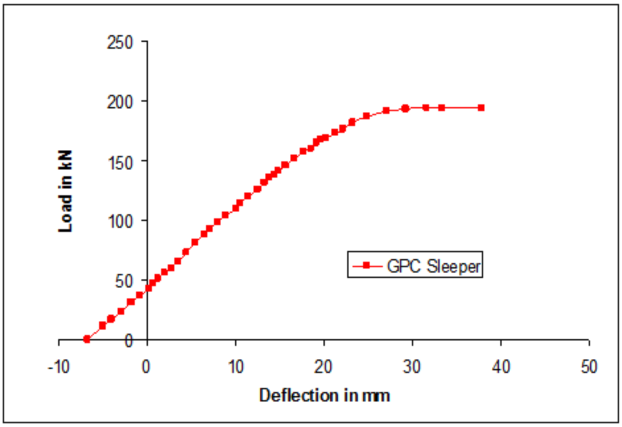


Fig. 30 Load - Deflection of GPC Sleeper

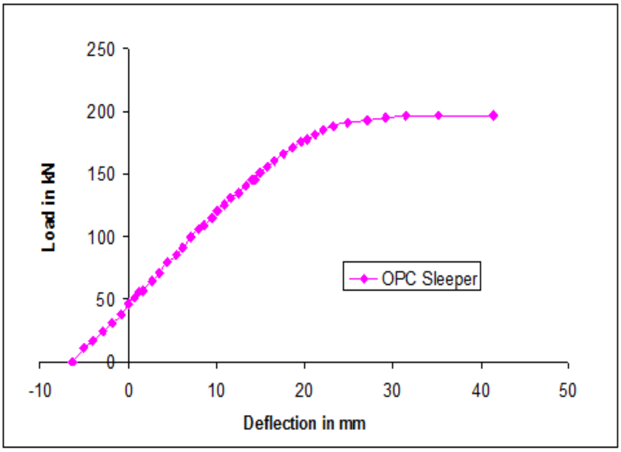


Fig. 31 Load - Deflection of OPC Sleeper

Table 13 Experimental Results of OPC and GPC Sleepers

OPC sleeper				**GPC sleeper**			
First crack		**Yield stage in kN**	**Ultimate stage in kN**	**First crack**		**Yield stage in kN**	**Ultimate stage in kN**
Load in kN	**Deflection in mm**			**Load in kN**	**Deflection in mm**		
30	730	73	230	35	1100	120	250

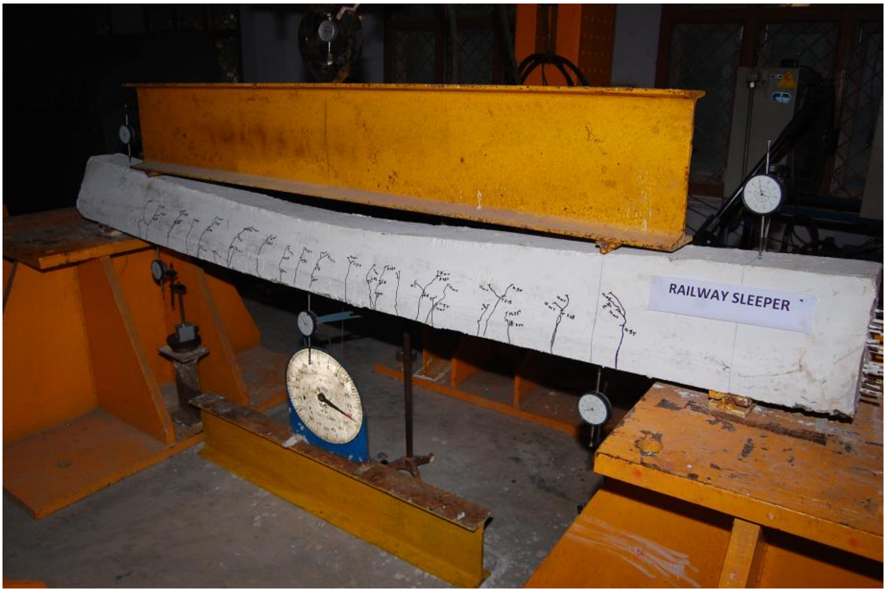


Fig. 32 Crack Pattern of GPC Sleeper

10. TESTS ON PRESTRESSED CONCRETE BEAMS

As we have attained concrete of strength more than 50 MPa, it was decided to use Geopolymer Concrete for prestressed concrete beams cast using post tensioning technique.

10.1 Specimen Details

In this study four beams of size 3200 x 250 x 125 mm were cast (Two conventional concrete and two geopolymer concrete beams). At the time of casting hollow ducts of 60 mm size with grouting provisions were installed for post tensioning operations. The ducts were placed at a constant eccentricity of 40 mm at both ends of the beam, spiral rings of 6 mm diameter at a length of 600 mm was placed. It gave the shear capacity to take care of end anchorage. The above arrangements are shown in Figure 33.

Fig. 33 Arrangement of Duct Before Casting

10.2 Casting of Prestressed Geopolymer Concrete beam

The fly ash and the aggregates were first mixed together in the pan mixer for about 3 minutes. Then the alkaline liquid mixed with super plasticizer (Conplast SP 430) was added with the dry mixes in the pan mixer itself. The workability of the fresh concrete was measured by conducting slump test and was about 50 mm. All the specimens were cast using geopolymer concrete and conventional concrete of grade M50. Each specimen was cast in three layers by using a needle vibrator. The casting process is shown in Figure 34.

Fig. 34 Casting of Post Tensioned Beam

10.3 Curing of Geopolymer Concrete

Steam curing substantially assists the chemical reaction that occurs in the geopolymer concrete. Both curing time and curing temperature influence the compressive strength of the concrete. The geopolymer concrete specimens undergoes a steam curing (60ºC) of 24 hours. Before steam curing the concrete specimens were wrapped with polythene papers for the affection hot water into the specimens. The specimen placed inside the steam chamber is shown in Figure 35.

Fig.35 Specimens kept in Steam Curing Chamber

10.4 Post Tensioning of Beams

Compressive forces were induced in a concrete structure by tensioning steel tendons of strands placed in ducts embedded in the concrete. The tendons were installed after the concrete was placed. The strands were properly anchored by end blocks. The end blocks are rigid steel plates of size 125 × 250 mm and thickness of 20 mm.

10.5 Grouting

All the beams were grouted manually with cement paste through the holes placed inside the beams.

10.6 Experimental Setup

The beams were tested under two point loading which was monotonically increased. The schematic view of test setup is shown in Figure 36. The load deflection behaviors of post tensioned beam are shown in Figures 37 and 38. The view of crack pattern of geopolymer concrete post tensioned beam is shown in Figure 39. From the experimental results, it is found that the flexural behavior of OPC and GPC post tensioned beams are same.

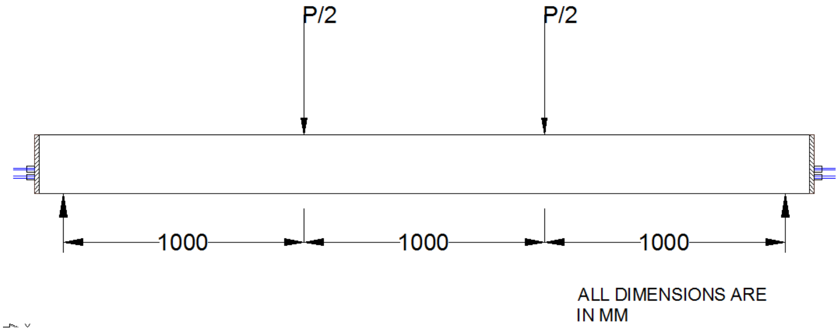


Fig. 36 Schematic View of Test Setup

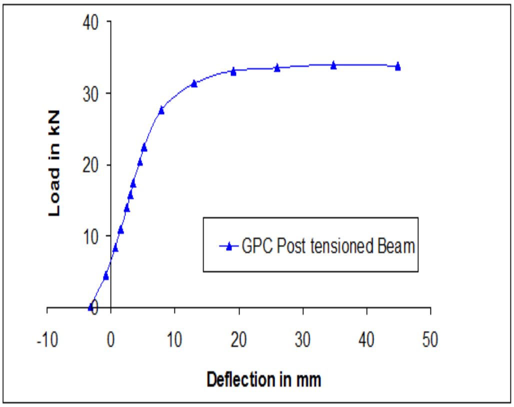


Fig. 37 Load - Deflection of GPC Post Tensioned Beam

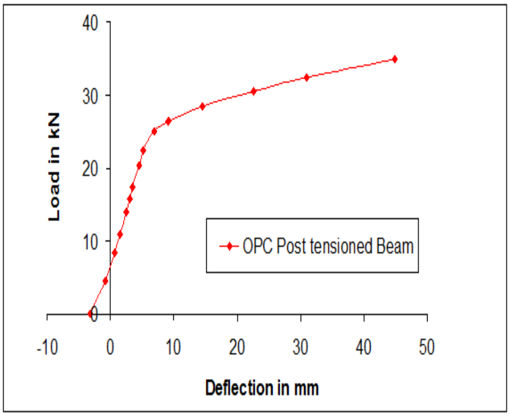


Fig. 38 Load - Deflection of OPC Post Tensioned Beam

Fig. 39 Crack Pattern of GPC Post Tensioned Beam

11. ENVIRONMENTAL BENEFITS OF THE TECHNOLOGY

The use of fly ash as a source material has environmental advantages in addition to those presented by the replacement of Portland cement. The use of the industrial byproducts such as fly ash in a high value product like concrete imparts better value-addition to these materials rather than low end usage as landfills and pavement sub-bases. It significantly decreases the use of natural resources and energy, for example, every million tons of fly ash that replaces Portland cement helps to conserve one million tons of lime stone, 0.25 million tons of coal and over 80 million units of power. The cement industry is the main culprit for the atmospheric pollution and mainly responsible for the emission of Green House Gases like CO_2. Production of one ton of cement approximately releases one ton of CO_2 into the atmosphere. Hence every million ton of fly ash used for geopolymer concrete helps the abatement of 1.0 million tons of CO_2 to atmosphere [34]. It also obviates the problem of their safe storage and/or disposal. Presently, most fly ash is being handled in wet form and disposed off in ash ponds which are harmful for the environment and occupy a vast area. The World Bank has cautioned India that by 2015, disposal of coal ash would require 1000 square kilometres or one square metre of land per person [34]. Hence, use of geopolymer concrete helps us to increase the land available for agricultural and other purposes. Further, non toxic chemicals are used for the production of geopolymer concrete. These chemicals can be handled by land without any additional protection. Hence, geopolymer concrete developed using fly ash is an environment friendly green material.

12. ECONOMIC BENEFITS OF THE TECHNOLOGY

In preparing the geopolymer concrete, the Ordinary Portland Cement is replaced 100 percent by fly ash and hence geopolymer concrete is termed as cementless concrete. The price of fly ash based geopolymer concrete is estimated about 10 to 30 percent cheaper than Portland cement concrete. Heat-cured low-calcium fly ash-based geopolymer concrete offers several economic benefits over Portland cement concrete. One ton low-calcium fly ash can be utilized to manufacture approximately three cubic meters of high quality fly ash-based geopolymer concrete, and hence earn monetary benefits through carbon-credit trade. The heat-cured low-calcium fly ash-based geopolymer concrete may yield additional economic benefits when it is utilized in infrastructure applications.

In the case of infrastructure applications, space available for keeping precast elements is very much restricted. Precast elements made out of normal concrete require 28 days for gaining full strength. But at the same time, heat cured geopolymer concrete attains full strength in one day. This results in savings in cost of expensive moulds and at the same time less space is required to keep the geopolymer concrete precast elements as they can be moved out of casting yard quickly.

Further, expensive steam curing chamber is not required at site. Cost effective steam curing arrangement made out of tarpaulins would be sufficient at site.

13. CONCLUSIONS

From the experimental investigation the following conclusions are made:

(i) Geopolymer concrete can be manufactured with low calcium fly ash with different molarities of NaOH. The steam cured geopolymer concrete beams with 8 Molarity NaOH solutions attain higher strength.

(ii) Adequate curing temperature (60^0C – 75^0C) and adequate curing time (minimum 24 hrs) can give better results.

(iii) The geopolymer concrete with steam curing at 75^0C increases the strength by 35-50 percent when compared to geopolymer concrete without steam curing.

(iv) Workability which influences the properties of the fresh concrete and cube compressive strength, flexural strength which influences the properties of the hardened concrete have been identified. Low-calcium fly ash-based geopolymer concrete has an excellent compressive strength and is suitable for structural applications.

(v) The reason for the improvement in compressive strength of geopolymer concrete is the chemical reaction due to the speedy polymerization process and aging of the alkaline liquid.

(vi) While testing the geopolymer concrete specimen, the one cast with 8 Molarity NaOH solution showed higher strength compared with other molarity specimens because when H_2O-to-Na_2O molar ratio increases the strength of geopolymer concrete decreases.

(vii) Geopolymer binders have emerged as one of the possible alternative to OPC binders due to their reported high early strength and resistance against acid and sulfate attack apart from its environmental friendliness.

(viii) As geopolymer has better corrosion resistance, evidenced from corrosion tests, it can be used for making precast products like under ground pipes, box culverts etc.

(ix) Since it is possible to produce geopolymer concrete of strength higher than 50 MPa it could be used for prestressed Concrete works.

(x) Geopolymer bricks show very high compressive strength when compared to ordinary bricks. The strength of geopolymer bricks can be brought to the level of ordinary bricks by using lower molar solutions of NaOH.

14. REFERENCES

1) Mehta, P. K. 2002 “Greening of the Concrete Industry for Sustainable Development”, ACI Concrete International, 24(7):pp.23-28.
2) Cembureau 2007 “Cement in Cembureau Countries Statistics 2005-2007” available at http://www.cembureau.be/Documents/KeyFacts/STATISTICS/Cementpercent20inpercent20 CEMBpercent20countries.pdf.
3) Portland Cement Association 2006 “World Cement Consumption Growth Expected to Continue” in Portland Cement Association Executive Report, available at http://www.cement.org/exec/10-23-06.html.
4) Mehta, P. K. 2001 “Reducing the Environmental Impact of Concrete”, ACI Concrete International 23(10):pp. 61-66.
5) Karstensen, K. H. 2006 “Cement Production in Vertical Shaft Kilns in China –Status and Opportunities for Investment” UNIDO Contract RB-308-D40-8213110-2005.
6) Boden, T.A., G. Marland, and R.J. Andres. 2010. Global, Regional, and National Fossil-Fuel CO_2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi 10.3334/CDIAC/00001_V2010.
7) Lieblang, P. 2009 “Green Europe: Emission trading on a large-scale and individual Green Concrete Housing on a small-scale” in Proceedings of International Concrete Conference and Exhibition ICCX Oceania “Concrete Solutions for Oceania” editor Katutz, H., Sydney, Australia, pp. 26-26.
8) IPCC 2007 “Climate Change 2007: Working Group III: Mitigation of Climate Change, Emission Trends (global and

regional)" available at http://www.ipcc.ch /publications_and_data/ar4/wg3/en/tssts-ts-7-2-emission-trends.html.

9) Department of Environment and Water 2007 "Industrial Process Sector Greenhouse Gas Emissions Projections 2007" available at http://www.climatechange.gov.au/projections/pubs/industrial2007 .pdf
10) Mehta, P. K. 2004 "High Performance, High Volume Fly Ash Concrete for Sustainable Development" in Proceedings of International Workshop on Sustainable Development and Concrete Technology, Beijing, China, pp. 3-14
11) Stevenson, M. and Panian, L. 2009 "Sustainability through Strength" Concrete International, 31(3), pp. 34:39
12) Poon, C. S., Lam, L. and Wong, Y. L. 2000 "A Study on High Strength Concrete Prepared with Large Volumes of Low-Calcium Fly Ash", Cement and Concrete Research, 30(3), pp.447-455.
13) Papadikis, V. G. 1999 "Effect of Fly Ash on Portland Cement Systems, Part I: Low-Calcium Fly Ash" Cement and Concrete Research, 29(11), pp. 1727-1736
14) Malhotra, V. M. 2002 "High-Performance High-Volume Fly Concrete", Concrete International 24(7): pp. 30-34
15) Singh, M and Garg, M. 1999 "Cementitious binder from fly ash and other industrial wastes", Cement and Concrete Research, Volume 29, Issue 3, March 1999, Pages 309-314
16) Davidovits, J. 1991 "Geopolymers: inorganic geopolymeric new materials" Journal of Thermal Analysis, 37, pp. 1633-1656.
17) Sofi, M., van Deventer, J. S. J., Mendis, P. A. and Lukey, G. C. 2007 "Bond performance of Reinforcing Bars in Inorganic Polymer Concrete (IPC)", Journal of Materials Science, 42(9), pp. 3107-3116.

18) Sofi, M, van Deventer J, S. J. , Mendis, P, A, and Lukey G. C. 2007 "Engineering Properties of Inorganic Polymer Concretes (IPCs)" Cement and Concrete Research, 37(2), 251-257.

19) Provis, J. L., Muntingh, Y., Lloyd, R. R., Xu, H., Keyte, L. M., Krivenko, P. V. and van Deventer, J. S. J 2007 "Will Geopolymers Stand the Test of Time?" Ceramic Engineering and Science Proceedings, 28(9), 235-248

20) Lloyd, N and Rangan, B.V 2009 Geopolymer Concrete – sustainable cementless concrete, proceedings of Tenth ACI International conference on recent advances in concrete tehnology and sustainability issues, Seville, PP 33-53

21) Hardjito, D. and Rangan, B.V. (2005 Development) and properties of Low calcium fly ash-based Geoploymer Concrete Research Reprot GCI Faculty of Engineering Curtin University of Technology, Perth.

22) Djwantoro Hardjito, Steenie E. Wallah, Dody M.J.Sumajowand B.Vijaya Rangan (2009). On the development of fly ash based geopolymer concrete. ACI materials journal. Title No 101 M 52.

23) Rangan, B,V. and Wallah, S.E. (2006), Low – Calcium fly Ash-Based Geopolymer concrete: long- Term Properties, Research Report GC2, Faculty of Engineering Curtin University of Technology, Perth.

24) Kunal kupwade – patil and Erez Allouche (2011), Effect of alkali silica reaction in Geopolymer concrete.World of coalash conference,May,9-12-2011,Denver,CO, USA.

25) Davidovits, J. (1994) "High – Alkali cements for 21st century concretes in concrete technology, past, present and future". IN proceedings of V.Mohan Malhotra Symoposium. Editor: P. Kumar Metha, ACI SP -144. pp383-397.

26) Davidovits, J. (2010) “Geopolymer Cements, Proceedings of the International Workshop on Geopolymer Cement and Concrete, Annamalai University, 7th December, 2010, pp 1-67.

27) Davidovits, J., Davidovits, R., and Davidovits, M, (2008), “Geopolymer Cement based on Fly ash and harmless to use, PCT Publication WO 2008/01238, Indian Patent Application 1861 MUMNP/2009-05-15.

28) ASTM Committee on Standards B611-2005 (Revised), Standard test method for abrasive wear resistance of cemented carbides.

29) ASTM Committee on Standards CSA/S413-1994

30) ASTM Committee on Standards D2776, & G59, Volume3.02. Metal Corrosion ASTM 2010 (Revised), test method corrosivity of water in the absence of heat electrical method.

31) M. Stern and A.L. Geary. J Electrochem Soc 104 (1957) 56

32) K.R. Gowers, S.G. Millard, J.S. Gill and R.P. Gill. Brit Corr J 29 (1994) 25

33) ASTM Committee on Standards C1543-10a, Standard Test Method for Determining the penetration of chloride ion in to concrete by ponding.

34) Australian Coal Association 2010, Coal and its uses-Electricity generation, www.australian.com.au

15. PROJECT REVIEW COMMITTEE MEMBERS

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