An Experimental Investigation on the Mechanical Properties of Geo Polymer Concrete

Rajesh S [1],
[1] P.G Scholar,
Department of Civil Engineering,
James College of Engineering & Technology,
Nagercoil, Tamil Nadu, India.

Gnanaraj A [2],
[2] Assistant Professor,
Department of Civil Engineering,
James College of Engineering & Technology,
Nagercoil, Tamil Nadu, India.

Abstract: **To reduce the greenhouse gas emission, efforts are needed to develop environment friendly construction materials. This paper presents the development of fly ash based geopolymer concrete. In geopolymer concrete, a by product material rich in silicon and aluminium, such as low calcium (ASTM class F) fly ash is chemically activated by a high alkaline solution to form a paste that binds the loose aggregates and fine aggregates and other unreacted materials in mixture. The test results presented in this paper show the effect of various parameters on the properties of geopolymer concrete. The concrete obtained after the reaction between sodium hydroxide, sodium silicate has high strength. In this research the geopolymer mix design & experimental studies on are made on the Mechanical properties. Viz, Compressive Strength, Split Tensile strength, Flexure strength & Modulus of Elasticity of concrete. Results of investigation indicated that there was improvement in Mechanical properties with increase in Alkaline/Fly ash ratio. (0.30 to 0.45). Strength also increased with increase in curing time and temperature.**

Keywords: Alkaline, Strength,

1. INTRODUCTION

Portland cement (PC) production is under critical review since high amount of carbon dioxide gas is released to the atmosphere. Therefore, attempts to utilise the Fly ash (FA) to partially replace the Portland cement in concrete are gathering momentum. Most of the FA produced as by-product material in thermal power plants is currently dumped in landfills, thus creating a threat to the environment. However, geopolymer concrete is a "new" material that does not need the presence of Portland cement as a binder, because, the fly ash, which is rich in silicon (Si) and Aluminium (Al), can be activated by alkaline liquids to produce the geopolymeric material to act itself as binder.

There are two environment related situations in production of FA and PC:

1. The high amount of carbon dioxide released to the atmosphere during the production of Portland cement.
2. The large scale availability of fly ash, a by-product from power stations worldwide.

The rate of production of these two by-products (CO_2 and fly ash) is increasing due to the escalating demand on infrastructure development, and hence there is an urgent need for proper attention and to minimize their impact on the sustainability of our living environment. De-carbonation of limestone in the kiln during manufacturing of cement is responsible for the liberation of one ton of carbon dioxide to the atmosphere for each ton of Portland cement, as can be seen from the following reaction equation.

$5\ CaCO_3 + 2\ SiO_2 \rightarrow 3\ CaO.SiO_2 + 2\ CaO.SiO_2 + 5\ CO_2$
$CaCO_3 = 40+12+48 = 100$, $CaO=40+16=56$
$SiO_2=28+32=60$, $CO_2=12+32=44$
$5x100 + 2x60 \rightarrow (3x56+60) + (2x56+60) + 5x44$
$500 + 120 \rightarrow 228 + 172 + 220$ /Parts by weight
$500 + 120 \rightarrow 400 + 220$/Parts by weight
$1.25 + 0.3 \rightarrow 1 + 0.55$ Tonnes

To the above, we have to add the CO_2 produced during use of fuel for burning / clinkering operations of cement production. The production of Portland cement worldwide is increasing 3% annually. The current contribution of green house gas emission from the Portland cement production is about 1.35 billion tons annually or about 7% of the total greenhouse gas emission to the earth's atmosphere (Malhotra 2002). Furthermore, Portland cement is also reported to be among the most energy-intensive construction materials, after aluminium and steel.

Portland cement (PC) has been a very satisfactory binder for structural applications for more than 150 years. However, since the very nature of production of PC involves emission of CO_2 gas because limestone has to be calcined before formation of anhydrous calcium silicate based clinker (Taylor, 1998), an alternate system needs to be developed. It is estimated that for every ton of cement produced, the average energy requirement is about 1.6 MWh (Neville 1996). Though, it is possible to design PC concretes to possess any desired level of mechanical strength and durability characteristics, ecological aspects of PC are being scrutinised seriously and many alternate binder systems are proposed and studied (Gartner, 2004). Towards this, research works on geo-polymer based cements involving production of alumina-silicates are of great significance (Davidovits, 1994). Though, fly ash based geo-polymeric binders have been investigated, however, very often very low compressive strengths were reported (Swanepoel and Strydom, 2002; Katz, 1998.

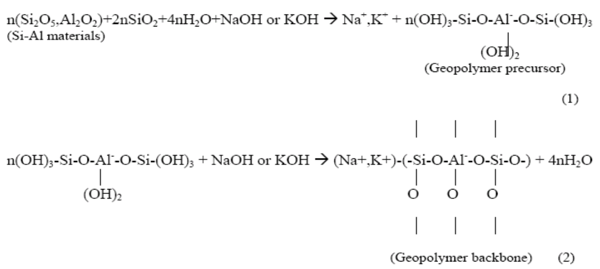
1.2 Origin of Term "Geopolymer"

The term 'Geopolymers' was first introduced to the chemical world by Davidovits in the mid 1970's (Davidovits, 1993), and in so doing a new field of research and technology was created. He explained that "geosynthesis" is the science of manufacturing artificial rock at a temperature below 100^0C (Davidovits, 1993) in order to obtain natural characteristics (hardness, longevity and heat stability). Geopolymers were thus viewed as mineral polymers resulting from geochemistry or geosynthesis.

1.3. Geopolymer as Construction Material

Geopolymer is an inorganic alumino-silicate polymer synthesized from predominantly silicon and aluminium based source materials of geological origin or by-product materials such as fly ash and blast furnace slag. The polymerization process involves a chemical reaction under highly alkaline conditions on Al-Si minerals, yielding polymeric Si-O-Al-O bonds, as described below:

$Mn[-(Si–O_2)z–Al–O]n.wH_2O$



Where M is the alkaline element, the symbol-indicates the presence of a bond, z is 1, 2. or 3, and n is the degree of polymerization.

The schematic formation of geopolymer material can be shown as described by Equations (1) and (2)

Setting or polycondensation / polymerisation of monomers into polymeric structures.

The chemical composition of geopolymer materials is almost similar to zeolite, but they possess an amorphous microstructure. The polymerization process can be assisted by applied heat, followed by drying. The chemical reaction period is fast and the required curing period may vary from 24 to 48 hours. Geopolymer based materials are environmentally friendly, and need only moderate energy to produce. In geopolymer concrete, the geopolymer paste binds the coarse and fine aggregates, and any un reacted source material. Geopolymer concrete can be utilized to manufacture precast concrete structural and non-structural elements, to make concrete pavements, to immobilize toxic wastes, and to produce concrete products that are resistant to heat and aggressive environments.

Geo-polymers are based on alumino-silicates indicated by (Si-O-Al-O-)n. Therefore for geopolymerisation, minerals containing silica [SiO_2] & alumina [$Al_2 O_3$] are essential and to preserve chemical balance, mono-valent cations [such as Na+, K+] or di-valent cations [such as Ca_2+] are needed in the three dimensional arrangement of elements. Considering this, the industrial wastes such as fly ash (FA) and blast furnace slag powder (BFSP) can be expected to act as 'starting materials', since they essentially contain silica and alumina. But, these materials, conventionally used as 'mineral admixture' in Portland cement based concretes (IS 456-2000), consists of many other oxides such as Fe2O3, MgO, CaO etc. These oxides could affect the geo-polymerisation reaction rates and hence, a careful approaches to design a geopolymerisation process. In this regard, hydroxide-silicate based catalytic system of high alkalinity would be of significant utility.

Considering the above technical points, geopolymer (GP) have been developed for many special applications such as toxic waste [heavy metals] and radioactive waste containment, sealants, capping, barriers, etc [Jaarsveld, 1998 and 1999; Comrie, 1988]. Carbon fibre reinforced geopolymeric composites have been also developed for use in airports and aircraft industry. However, for civil engineering structures, adequate strength levels and sufficient durability characteristics are essential for geopolymeric composites. The geopolymer material can also be used in various application, such as fire and heat resistant fibre composites, sealants, concretes, ceramics, etc., depending on the chemical composition of the source materials and the activators. Geopolymer can also be used as waste encapsulation to immobilize toxic metals.

For the chemical designation of geopolymer based on silico-aluminates, poly (sialate) was suggested. Sialate is an abbreviation for silicon-oxo-aluminate. The sialate network consists of SiO4 and AlO_4 tetrahedra linked alternately by sharing all the oxygens. Positive ions (Na+, K+, Li+, Ca++, Ba++, NH_4+, H_3O+) must be present in the framework cavities to balance the negative charge of Al_3+ in IV-fold coordination. The amorphous to semi-crystalline three dimensional silico-aluminate structures were identified as:

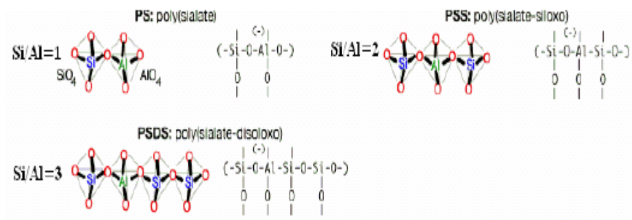


Figure: 1 Three basic forms of geopolymer.

Crystalline Polly (sialate) Mn-(-Si-O-Al-O)$_n$ and Poly (sialatesiloxo) Mn-(-Si-O-Al-O-Si-O)$_n$ result generally from hydrothermal setting conditions. Geopolymeric compounds involved in materials developed for industrial applications are non-crystalline (amorphous or glassy structure).

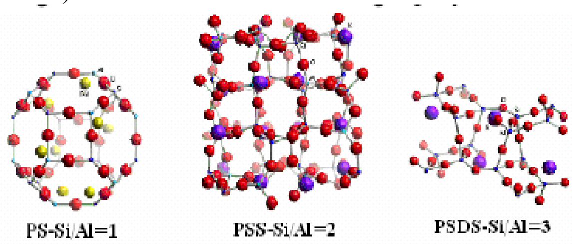


Figure: 2 Polymeric structures from polymerisation of monomers.

The strength of geopolymer depends on the nature of source materials. Geopolymers made from calcined source materials, such as metakaolin (calcined kaolin), fly ash, slag etc., yield higher compressive strength when compared to those synthesized from non-calcined materials, such as kaolin clay. The source material used for geopolymerisation can be a single material or a combination of several types of materials (Xu & van Deventer 2002). A combination of sodium or potassium siliate and sodium or potassium hydroxide has been widely used as the alkaline activator (Palomo, Grutzeck & Blanco 1999; van Jaarsveld, van Deventer & Lukey 2002; Xu & van Deventer 2000; Swanepoel & Strydom 2002), with the activator liquid-to-source material ratio by mass in the range of 0.25-0.30 (Palomo, Grutzeck & Blanco 1999; Swanepoel & Strydom 2002).

2. EXPERIMENTAL PROGRAMME

The experiments were carried out using four different ratios of Alkaline/Fly ash ratio. (0.30 to 0.45) with NaOH solution concentration of 10 molar solution. and different curing times. Compressive Strength Split Tensile Strength, Flexure Strength, and Modulus of Elasticity of Concrete. Tests were conducted at 24 hrs and 96 hrs. the curing temperature is being done at 60ºC and 100ºC respectively.

2.1 Materials

2.1.1 Fine Aggregate

Natural river and was used and tested as per IS: 2386.1970. The fineness modulus of sand used is 2.81 with a specific gravity of 2.6.

2.1.2 Coarse Aggregate

Crushed granite coarse aggregate of particle shape “average and cubic” was used for the present investigation. The specific gravity is 2.83 and fineness modulus is 6.4.

2.1.3 Fly ash

Fly ash that results from burning sub-bituminous coals is referred as ASTM Class C fly ash or high-calcium fly ash, as it typically contains more than 20 percent of CaO. On the other hand, fly ash from the bituminous and anthracite coals if referred as ASTM Class F fly ash or low-calcium fly ash. In consists of mainly an aluminiosilicate glass, and has less than 10 percent of CaO. The color of fly ash can be tan to dark grey, depending upon the chemical and mineral constituents The typical fly ash produced from Mettur power stations is light to mid-grey in colour, similar to the colour of cement powder. The majority of Mettur fly ash falls in the category of ASTM Class F, low calcium fly ash, and contains 80 to 85% of silica and alumina. In this Study the low calcium fly ash is used as binding material.

2.1.4 Catalytic liquid system

Analytical sodium hydroxide (NaOH with 98% purity) and sodium silicate solutions were used as the alkaline activators. In order to avoid the effect of unknown contaminants in the mixing water, the sodium hydroxide pellets were dissolved in distilled water. Even though it has been reported by several researchers that the activator solution was prepared at least one day prior to its use, in our present study, the catalytic system consisting of sodium hydroxide, sodium silicate and distilled water were mixed together approximately 24 hours before casting the specimens and kept for cooling under normal room temperature.

2.2 Preparation of Geopolymer Concrete

2.2.1 Preparation of solution

Separate solutions of NaOH and Na_2SiO_3 of required concentrations were prepared mixing together before 24 hours prior to casting.

2.2.2 Mixing

Weighed amount of fly ash, fine aggregate and coarse aggregate were dry mixed for 1 minute. After dry mixing, wet mixing was done for 2 minutes. Cubes of size 150 X 150 X 150 mm and Cylinders of size 150 X 300 mm and Prisms of size 100 X 100 X 700 mm were cast. Compaction was done by needle vibrator as in the case of Portland cement concrete.

2.2.3 Curing

After casting the specimens, they were kept in an oven. Then the specimens were demoulded at room temperature and kept at 60ºC for 24 hrs and 100ºC 96 hrs of the required curing time. After curing the specimens were kept at room temperature until the time of testing.

2.3 Design of Geopolymer Concrete Mix

Mixture proportion of heat-cured low-calcium fly ash-based geopolymer concrete mix design. Assume that normal density aggregates in SSD condition are to be used and the unit-weight of concrete is 2400 kg/m^3. Take the mass of combined aggregates as 77% of the mass of concrete, i.e. 0.77x2400= 1848 kg/m^3. The combined aggregates may be selected to match the standard grading curves used in the design of Portland cement concrete mixtures. For instance, the aggregates may comprise 277 kg/m^3 (15%) of 20mm aggregates, 370 kg/m^3 (20%) of 14 mm aggregates, 647 kg/m^3 (35%) of 7 mm aggregates, and 554 kg/SiO_2 to Na_2O ratio by mass of approximately 2, i.e., Na_2O = 14.7%, SiO_2 = 29.4%, and water = 55.9% by mass, is selected. The sodium hydroxide solids (NaOH) with 97-98% purity is purchased from commercial sources, and mixed with water to make a solution with a concentration of 8 Molar. This solution comprises 26.2% of NaOH solids and 73.8% water, by mass.

20 mm aggregates = 277 kg/m^3 , 14 mm aggregates = 370 kg/m^3, 7 mm aggregates = 647 kg/m^3, fine sand = 554 kg/m^3 , low-calcium fly ash (ASTM Class F) = 408 kg/m^3, sodium silicate solution (Na_2 O = 14.7%, SiO_2 = 29.4%, and water = 55.9 % by mass) = 103 kg/m^3, and sodium hydroxide solution (8Molar) = 41 kg/m^3 (30%) of fine sand to meet the requirements of standard grading curves. The fineness modulus of the combined aggregates is approximately 5.0. The mass of low calcium fly ash and the alkaline liquid = 2400 – 1848 = 552 kg/m^3. Take the

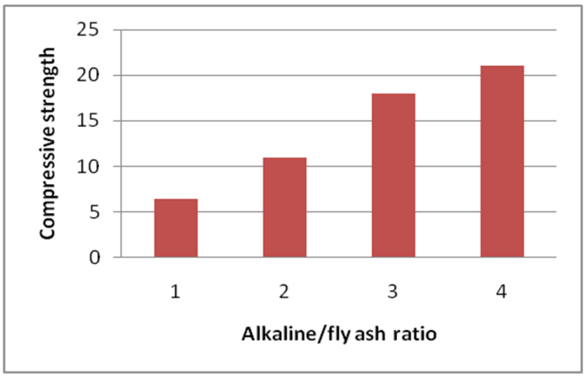
alkaline liquid-to-fly ash ratio by mass as 0.35; the mass of fly ash = 552/ (1+0.35) = 408 kg/m^3 and the mass of alkaline liquid = 552 – 408 = 144 kg/m^3. Take the ratio of sodium silicate solution-to-sodium hydroxide solution by mass as 2.5; the mass of sodium hydroxide solution = 144/ (1+2.5) = 41 kg/m^3; the mass of sodium silicate solution = 144 – 41 =103 kg/m^3.
Therefore, the trial mixture proportion is as follow: combined aggregates = 1848 kg/m3, low-calcium fly ash = 408 kg/m^3, sodium silicate solution = 103 kg /m^3, and sodium hydroxide solution = 41 kg/m^3.

2.4 Test performed
Compressive strength, Split tensile strength, Flexure strength and Modulus of elasticity of concrete tests were conducted

3. RESULTS AND DISCUSSIONS

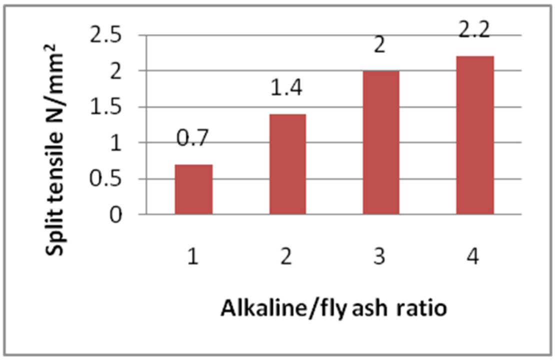
3.1. Compressive strength.
The compressive strength test was performed taking three cubes from each set after 24hrs and 96 hrs. The results of tests at 24hrs and 96hrs are given. Increase in compressive strength was also observed with increase in Alkaline/Fly ash ratio & Curing temperature from to 60ºC 100ºC.
Alkaline/Fly ash ratio = (0.30)
Sodium silicate/Sodium hydroxide ratio = (2.5)
Curing time = 24 hrs @ (60ºC)

Compressive Strength	
Alkaline/Fly Ash ratio = 0.30	4.36 N/mm^2



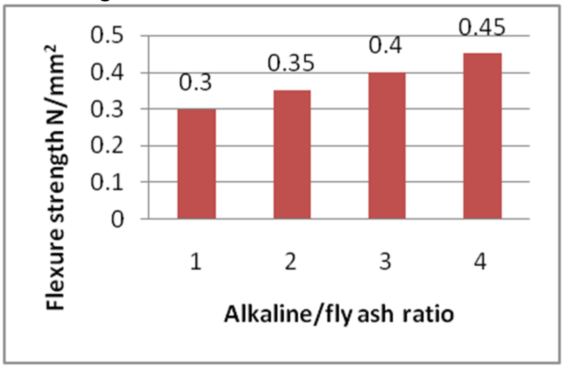
Variations of compressive strength in 4 Days with alkaline/fly ash ratio.

3.2. Split Tensile strength.
The split tensile strength test was performed taking cylinders from each set after 96 hrs. The results of tests at 96 hrs are given. Increase in split tensile strength was also observed with increase in Alkaline/Fly ash ratio & Curing temperature from 100 degree Celsius.



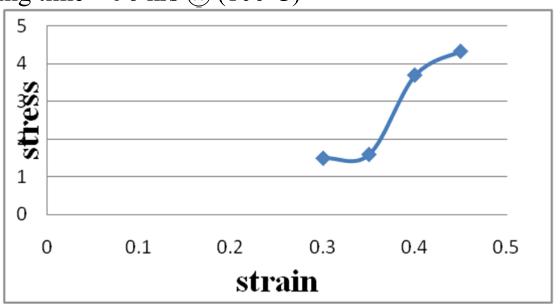
Variations in Split tensile strength of 4 days with alkaline/fly ash ratio.

3.3. Flexure Strength.
The Flexure strength test was performed taking Prisms from each set after 96 hrs. The results of tests at 96 hrs are given. increase in Flexure strength was also observed with increase in Alkaline/Fly ash ratio & Curing temperature from 100 degree Celsius.

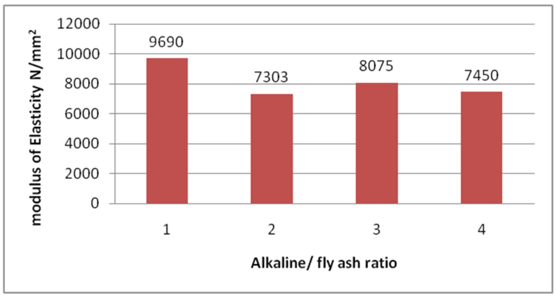


Variations in Flexure strength of 4 days with alkaline/fly ash ratio.

3.4. Modulus of Elasticity.
The Modulus of Elasticity of concrete test was performed taking cylinders from each set after 96 hrs. The results of tests at 96 hrs are given. Increase in Modulus of elasticity of concrete. It was also observed with increase in Alkaline/Fly ash ratio & Curing temperature from 100 degree Celsius.
Alkaline/Fly ash ratio = (0.30)
Sodium silicate/Sodium hydroxide ratio = (2.5)
Curing time = 96 hrs @ (100ºC)



Modulus of elasticity of concrete = 9690 N/mm^2



Variations of modulus of elasticity in 4 Days with alkaline/fly ash ratio.

4. CONCLUSIONS

Following conclusions were drawn from the study on geopolymer concrete, Geopolymer concrete is more environmental friendly and has the potential to replace ordinary cement concrete in many applications such as precast units. Compressive strength of Geopolymer Concrete increases with increase in concentration of NaOH from 8M to 16M. Increase in compressive strength was also observed with increase in curing time. However when curing time was increased from 24 hrs to 96 hrs, there is variation in compressive strength. The test results show that the compressive strength increases with increase in oven curing time from 24 hrs to 96 hrs. The Split Tensile strength increased with increase in Alkaline /fly ash ratio and increase in Curing time. The Flexural Strength also increases with increased in alkaline/fly ash ratio with increase in Curing time and temperature. The modulus of elasticity of concrete is Increasing and decreasing with the increasing alkaline/Fly ash ratio. The Sodium silicate/Sodium Hydroxide ratio should be further investigated with the increase in molar concentration of Sodium hydroxide solution.

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