# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

This Chapter presents a brief review of the terminology and the chemistry of geopolymers and the past studies on geopolymer concrete. The available published literature on geopolymer technology is also briefly reviewed.

## 2.2 Environmental Issues

The production of Portland cement requires a large input of energy and at the same time produces a large quantity of $CO_2$ as a result of the calcination reaction during the manufacturing process. According to Lawrence (2003) the calcination of $CaCO_2$ to produce 1 ton of Portland cement releases 0.53 tons of $CO_2$ into the atmosphere and, if the energy used in the production of Portland cement is carbon fuel, then an additional 0.45 tons of $CO_2$ is produced. Therefore, the production of 1 ton of Portland cement releases approximately 1 ton of $CO_2$ into atmosphere. There are 80% to 90% less green house gas emissions released in the production of fly ash (Duxson et al 2007 and Mehta, 2001). Therefore a 100% replacement of OPC with GGBS or fly ash would have a significant impact on the environment. The climate change is attributed not only to the global warming, but also to the global dimming due to the pollution present in the atmosphere. Global dimming is related to the reduction of the amount of sunlight reaching the earth due to pollution particles in the air blocking the sunlight. With the effort to reduce the air pollution that has been taken into implementation, the effect of global dimming may be reduced; however, it will increase the effect of global warming (Fortune 2005). From this view, the global warming phenomenon should be considered more seriously and action to reduce the effect should be given more attention and effort.

## 2.3 Fly ash

Fly ash is a by-product of the combustion of finely ground coal used as fuel in the generation of electric power. A dust collection system removes the fly ash as a fine particulate residue from combustion gases before they are discharged into the atmosphere. The ash content of coal used by thermal power plants in India varies between 25% and 45%. Coal with an ash content of around 40% is mostly used in India for thermal power generation. As a consequence, a large amount of fly ash is generated in thermal power plants causing several disposal-related problems. In spite of initiatives taken by the government, several non-governmental organisations and research and development organizations, the total utilisation of fly ash is only about 50%. India produces 130 million tons of fly ash annually .This is expected to reach 175 million tons by 2012. Disposal of fly ash is a growing problem as only 15% of fly ash is currently used for applications like concrete, the remaining being used for land filling. Globally less than 25% of the total annual fly ash produced in the world is utilized. Fly ash has been successfully used as a mineral admixture component of Portland pozzolan blended cement for nearly 60 years.

Various technologies have been developed for the gainful utilisation and safe management of fly ash due to the concerted efforts of Fly Ash Mission of the Government of India since 1994. As a result, the utilisation of fly ash has increased to 73 million tons in 2010-12. Fly ash was moved from “hazardous industrial waste” to “waste material” category during the year 2000 and during November 2009, it became a saleable commodity.

Fly ash utilisation has started gaining acceptance. The present generation of fly ash from coal based thermal power plants in India is 131 MT/year and it is expected to increase to 300-400 MT/year by 2016-17 (Second international summit on fly ash utilisation, 2013). Fly ash used in this study was low-calcium (ASTM Class F 2001) dry fly ash from Ennore thermal power station, Chennai.

The anthracite and bituminous coals produce low calcium fly ash which possesses truly pozzolanic properties due to the high content of silica, while the lignite or sub-bituminous coals produce high calcium fly ash which is both a cementitious and pozzolanic material (it has lower silica and alumina but higher CaO content (Dhir,1986)). As per ASTM 618-08 there are two types of fly ash; class F which is low in calcium oxide (CaO) with a content of less than 10% and is derived from bituminous coals. Class C is high in CaO with greater than 10% content and is produced from sub-bituminous and lignite coals (Davidovits, 2008). ASTM C989 specifies typical class F fly-ash having 4.3% CaO and typical class C fly-ash having 27.4% CaO (Grace and Co-Conn, 2006).

Fly ash in concrete makes efficient use of the products of hydration of cement such as calcium hydroxide, which are otherwise a source of weakness in normal cement concretes and convert them into denser, stronger C-S-H compounds by pozzolanic reaction. The heat generated during hydration initiates the pozzolanic reaction of fly ash (ACI 1995). When concrete containing fly ash is properly cured, fly ash reaction products fill in the spaces between hydrating cement particles, thus lowering the concrete permeability to water and aggressive chemicals (Manmohan et al1995). Properly proportioned fly ash concrete mixes impart properties to concrete that may not be achievable through the use of portland cement alone. These mixes are more durable, economical, strong and also eco-friendly as it utilises an ecologically hazardous material.

The colour of fly ash can be tan to dark grey, depending upon the chemical and mineral constituents (Malhotra and Ramezanianpour 1994). Fly ash particles are typically spherical, finer than Portland cement and lime ranging in diameter from less than 1 μm to not more than 150 μm. The detail of fly ash production as of July 2012 is given in Table 2.1.

**Table 2.1 Worldwide Production of Fly ash**

| Name of Country | Production (Million Tons) | Utilisation (Million Tons) |
|---|---|---|
| Australia | 59 | <25 |
| China | >150 | 52 |
| Germany | 78 | 40 |
| India | >132 | 48 |
| Japan | 55 | 29 |
| Russia | 102 | 32 |
| South Africa | 78 | 57.9 |
| Spain | 58 | 26 |
| UK | 60 | 34 |

## 2.4 Uses of Fly ash in Concrete

Fly ash in the mix replaces Portland cement, producing big savings in concrete material cost. As a cement replacement, fly ash plays the role of an artificial pozzolan, where its silicon dioxide content reacts with the calcium hydroxide from the cement hydration process to form the calcium silicate hydrate (CS-H) gel.

The unique spherical shape and particle size distribution of fly ash make it a good mineral filler in Hot Mix Asphalt (HMA) applications and improve the fluidity of flowable fill and grout. The consistency and abundance of fly ash in many areas present unique opportunities for use in structural fills and other highway applications. For example, the construction of roads in India is implemented with 50% OPC replacement by the fly ash (Desai 2004). The use of High Volume Fly Ash (HVFA) in the place of ordinary portland cement in concrete shows excellent mechanical property and durability performance.

Phair and Van Deventer (2002) have carried out an experimental study on ‘Fly Ash-Based Geopolymeric Binders Activated with Sodium Aluminate’ and discovered that an aluminate activated geopolymer is mechanically superior to typical hydroxide and silicate activated geopolymers. The major conclusion of this paper is that an aluminate activator also reduced energy costs. Hou et al (2007) have suggested that the use of sodium hydroxide alone to activate the geopolymer results in a weak bond between the paste and aggregate. Results indicate that sodium hydroxide in combination with sodium silicate (liquid glass) is essential to ensure a stable bond between the paste and aggregate. Wong et al (1999) have investigated the effect of fly ash on strength and fracture properties of the interfaces between the cement mortar and aggregates.

During 1970s, the Structural Engineering Research Centre, Chennai has utilised fly ash in concrete as partial replacement for cement. Based on the research and development work at the centre, a two storied building measuring 300 square meter was constructed as early as in 1975 in Structural Engineering Research Center, Chennai. Fly ash was used as a partial replacement of cement in precast reinforced and prestressed concrete structural elements and in cement mortar for plastering and masonry in the construction of the building. This experimental building was constructed to demonstrate the use of fly ash in concrete construction with a view to effect savings in the use of cement and to study the long term performance of the building.

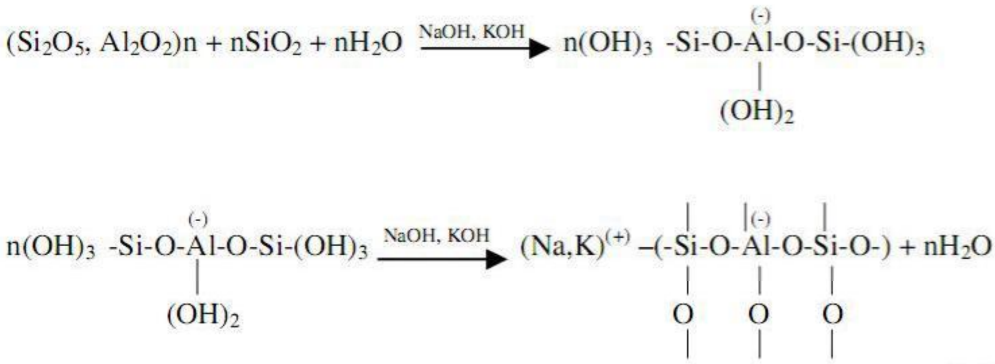
## 2.5 Geopolymer

Geopolymers are inorganic polymeric binding materials developed by Joseph Davidovits in 1970s. Geopolymerisation involves a chemical reaction between solid aluminosilicate oxides and alkali metal silicate solutions under highly alkaline conditions yielding amorphous to semi-crystalline three-dimensional polymeric structures, which consist of Si-O-Al bonds (Palomo et al, 1999). The polymerisation process involves a substantially fast chemical reaction under alkaline condition on Si-Al minerals, which results in a three dimensional polymeric chain and ring structure shown in equation (2.1) which consists of Si-O-Al-O bonds (Davidovits 1999).

$$M_n \, [-(SiO_2)\, z–AlO_2]_n . \, wH_2O \qquad \ldots (2.1)$$

where “z” is 1, 2 or 3 or higher up to 32; M is a monovalent cation such as potassium or sodium, and “n” is a degree of polycondensation (Davidovits 1984, 1988b, 1994a, 1999). Davidovits (1988b, 1991, 1994b, 1999) has also distinguished 3 types of polysialates, namely the Poly (sialate) type (-Si-O-Al-O), the Poly (sialate-siloxo) type (-Si-O-Al-O-Si-O) and the Poly (sialate-disiloxo) type (-Si-O-Al-O-Si-O).

The schematic formation of geopolymer material is given in Equations (2.2), (Van Jaarsveld et al (1997), Davidovits (1999)). These formations indicate that all materials containing mostly Silicon (Si) and Aluminium (Al) can be used to make the geopolymer material.



(2-2)

Hua Xu et al (2004) studied that the aluminium available for geopolymer reaction during synthesis appears to have a dominant effect in controlling setting time. Similarly increasing the $SiO_2/\ Al_2O_3$ ratio leads to longer setting times.

## 2.6 Source Material and Alkaline Liquid

The main constituents of geopolymer concrete are source material and alkaline liquid. The material that contains Silicon (Si) and Aluminium (Al) in amorphous form is a possible source material for the manufacture of geopolymer. 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 and type of application.

Low calcium (ASTM Class F) fly ash is preferred as a source material than high calcium (ASTM Class C) fly ash. The presence of calcium in big quantities may interfere with the polymerisation process and alter the microstructure (Gourley, 2003). Van Jaarsveld et al (1997, 1999) have identified the potential use of waste materials such as fly ash, contaminated soil, mine tailings and building waste to immobilise toxic metals. Swanepoel et al (2002), Phair et al (2001, 2002), Van Jaarsveld (2002a, 2002b) and

Bakharev (2005a, 2005b and 2005c) have also presented studies on fly ash as the source material to make geopolymers.

Calcined source materials such as fly ash, slag, calcined kaolin show a higher final compressive strength when compared to non-calcined materials such as instance kaolin clay, mine tailings, and naturally occurring minerals (Barbosa et al (2000)). Fly ash is considered to be advantageous due to its high reactivity that comes from its finer particle size than slag. The suitability of various types of fly ash to be geopolymer source material has been studied by Fernandez-Jimenez and Palomo (2003).

The alkaline liquids are from soluble alkali metals that are usually sodium or potassium based. Palomo et al (1999) have reported the study of fly ash-based geopolymers. A combination of sodium hydroxide with sodium silicate was used in the study and the results showed that alkaline liquid is a main factor affecting the mechanical strength and the combination of sodium hydroxide with sodium silicate produced high compressive strength.

Ammar Motorwala et al (2013) have conducted an experimental study that involves the observation of structural behaviour of fresh fly ash-based geo-polymer concrete. The main objective of this study was to find the effect of varied concentrations of alkaline solutions on the strength characteristics of the concrete. The test conducted, yielded certain important findings such as increase in the compressive strength with increase in the molarity. Curing under normal sunlight yielded strength of 16 $N/mm^2$ and curing when done by wrapping with plastic bag showed better compressive strength as it preserves the moisture. In the rate analysis carried, fly ash based concrete is more expensive than cement concrete and hence not economical. However, in the broader picture considering carbon credit, waste disposal and limited availability of non-renewable resources, geopolymer concrete is sure to play major role in construction industry.

## 2.7 Durability of Geopolymer Concrete

Durability is defined as the capability of concrete to resist weathering action, chemical attack and abrasion while maintaining its desired engineering properties. Durability is not always an absolute property since different forms of concrete require different degrees of durability depending upon its use. The durability of concrete has been evaluated in this study through parameters related to the permeability and chemical attack. Djwantoro Hardijito et al (2004) have described the effects of several factors on the properties of fly ash based geopolymer concrete especially the compressive strength. The test variables included were: the age of concrete, curing time, curing temperature, quantity of super plasticizer, the rest period prior to curing and the water content of the mix.

Song et al (2005) have carried out an experimental study and has revealed many facts about the resistance of geopolymer concrete to sulphate and chloride attack. It has been found that, after being exposed to sulphuric acid solution, fly ash based geopolymer concrete was structurally inert except development of some fine cracks on the surface whereas OPC concrete shows sign of severe damage.

Olivia et al (2008) have investigated on the water penetrability of low calcium fly ash geopolymer concrete. The conclusion drawn is that fly ash geopolymer concrete exhibits low water absorption and sorptivity. Low water/binder ratio and a better grading are recommended in order to reduce the capillary porosity and the overall porosity of geopolymer concrete. Anurag Mishra et al (2008) have carried out an experimental study on the effect of concentration of alkaline liquid and curing time on strength and water absorption of geopolymer concrete. It has been reported that compressive strength increases with increase in concentration of NaOH from 8M to 16M. Increase in compressive strength was observed with increase in curing time and also tensile strength increased with increase in concentration of NaOH except for 72 hours curing time.

Ranganath et al (2008) have conducted an experimental investigation on effect of fly ash, water content, ratio of sodium silicate to sodium hydroxide solution by the mass and the duration of elevated temperature curing on the properties of fly ash based geopolymer concrete (GPC). It was found that as the water content increases the optimum fly ash content also increases to obtain maximum strength. In addition the given fly ash content increase in the alkaline solution content does not contribute additional strength. It has been found that long curing at elevated temperature increases the strength of geopolymer concrete; however elevated temperature curing beyond 20 hours does not contribute significant strength.

Andi Arham Adam (2009) has carried out an experimental investigation on the strength and durability properties of Alkali Activated Slag (AAS) and fly ash based geopolymer concrete in terms of chemical attack. Concrete has been tested for workability, compressive strength, depth of carbonation, rapid chloride permeability and chloride ponding. Microstructure studies were conducted using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDAX). The study concludes that AAS and fly ash based geopolymer concretes can exhibit comparable strength to OPC and slag-blended OPC concretes.

Deevasan et al (2010) have studied the development of environmentally friendly construction materials with particular attention to the utilisation of industrial waste materials in their manufacture for sustainable development.

Geopolymer concrete is a material obtained from binders made out of an industrial waste such as fly ash but activated by commercially available alkaline solutions. Relatively large quantities of alkali effluents are being produced from paper and other poly-fiber industries worldwide. This preliminary paper reports the development of a fly ash-based geopolymer concrete with the partial replacement of alkaline solutions with an industrial effluent that is a byproduct of the fiber industry. Initial test results showed that geopolymer concrete of the order of 50 MPa could be produced by using such an effluent that was strengthened by commercially procured sodium hydroxide flakes and sodium silicate solution.

Bhikshma et al (2011) have conducted an experimental investigation on the properties of geopolymer concrete. Test experiments have proved that fly ash based Geopolymer concrete has excellent compressive strength, suffers very low drying shrinkage, low creep, excellent resistant to sulphate attack and good acid resistance. The workability of the concrete in terms of slump and compacting factor are observed to be excellent. The geopolymer concrete in fresh state has been observed to be highly viscous and good in workability.

Raijiwala et al (2011) have reported the progress of the research on making geopolymer concrete using the thermal power plant fly ash, (Ukai) Gujarat, India. The project aims at making and studying the different properties of geopolymer concrete using this fly ash and the other ingredients locally available in Gujarat. Potassium Hydroxide and sodium Hydroxide solution were used as alkali activators in different mix proportions. The effects of various salient parameters on the compressive strength of low-calcium fly ash-based geopolymer concrete are discussed by considering the ratio of alkaline solution to fly ash (by mass) 0.35 constant. The specimens were cured at two different temperature 25$^{o}$C and 60$^{o}$C for 24 hours in the oven. The main parameters studied were the compressive strength, curing temperature, effect of wet-mixing time, influence of handling time on compressive strength, effect of super plasticizer on compressive strength, effect of super plasticizer on slump of concrete, effect of water-to-geopolymer solids ratio by mass on compressive strength, stress-strain relation of geopolymer concrete in compression. Experimental results indicate that the compressive strength of GPC increased over controlled concrete by 1.5 times and split tensile strength of GPC increased over controlled concrete by 1.45 times. The flexural strength of GPC increased over controlled concrete by 1.6 times. In pull out test GPC increases over controlled concrete by 1.5 times.

Reddy et al (2011) have conducted an experimental study to evaluate the durability characteristics of low calcium fly ash-based geopolymer concretes subjected to the marine environment, compared to ordinary Portland cement concrete with similar exposure by means of accelerated corrosion testing of the reinforcing steel. In order to achieve this goal 8 molar geopolymer, 14 molar geopolymer and Ordinary Portland Cement Concrete (OPC) mix were prepared and tested for exposure in seawater. The test results indicate that the GPC shows excellent resistance to chloride attack with a longer time to corrosion cracking compared to ordinary portland cement concrete. Results conclude that the electrical resistivity and permeability of the low calcium fly ash-based GPC were not significantly affected by the severe marine environment in view of reduced cracking.

Bhosale et al (2012) have conducted an experimental investigation in the processing of geopolymer using fly ash and alkaline activator with the geopolymerization process. The factors that influence the early age compressive strength such as molarities of sodium hydroxide (NaOH) have been studied. Sodium hydroxide and sodium silicate solution were used as an alkaline activator. The study comprises the comparison of the ratios of $Na_2Sio_3$ and NaOH at the values of 0.39 and 2.51.The geopolymer paste samples were cured at 60$^{o}$C. The compressive strength was done at 7 and 28 days. The result showed that the geopolymer paste with NaOH concentration, compressive strength increases with increase in molarities.

Lohani et al (2012) have conducted an experimental study using fly ash sample collected from National Aluminum Company (NALCO) of Angul, Odisha having 0.5% carbon content. In this investigation an attempt has been made for preparing concrete of $M_{20}$ and $M_{25}$ grade. This clearly reflects an ambience towards reutilisation of industrial waste that creates environmental pollution to the society reducing the cost of concrete due to replacement of cement by fly ash. A comparative study through detailed technical parameters between cement concrete and geopolymerised concrete results with a conclusion that the geopolymer concrete (GPC) has better resistance to corrosion and fire (up to 2400$^{o}$F), high compressive and tensile strengths, rapid strength gain and lower shrinkage. As per recent researches conducted GPC reduces the cost of binding material as compared to standard cement.

Malathy et al (2012) have conducted an experimental investigation to determine the performance of geopolymer reinforced concrete. The compressive strength test was performed and an empirical formula was derived from the results. Vijaysankar et al (2013) have investigated the behaviour of fly ash based geopolymer concrete solid blocks and its durability. The bricks were cast with fly ash to river sand, M-sand and eco-sand (silica sand) with the ratio of 1:2.5 by weight. It was observed that the compressive strength of ambient-cured fly ash-based geopolymer M-sand blocks concrete of different sand mixes in which the M-Sand achieves the good compression test. In sulphate attack, the average percentage reduction by weight of M-sand solid block at 56th day is less when compared to other solid blocks.

Abdul Aleem et al (2012) have conducted an experimental investigation to find out an optimum mix for the geopolymer concrete. Concrete cubes of size 150 x 150 x 150 mm were prepared and cured under steam curing for 24 hours. The compressive strength was found out at 7 days and 28 days. The results are compared. The optimum mix is Fly ash: Fine aggregate: Coarse aggregate (1:1.5:3.3) with a solution (NaOH and $Na_2SiO_3$ combined together) to fly ash ratio of 0.35. The results conclude that high and early strength was obtained in the geopolymer concrete mix and geopolymer concrete was a workable mix. It was also observed that the increase in percentage of fine aggregates and coarse aggregates increased the compressive strength. This may be due to the high bonding between the aggregates and alkaline solution. The compressive strength was found reduced beyond the optimum mix. This may be due to the increase in volume of voids between the aggregates. The optimum mix is- Fly ash: Fine aggregate: Coarse aggregate are 1:1.5:3.3 with a solution (NaOH and $Na_2SiO_3$ combined together) to fly ash ratio of 0.35.

Rajamane et al (2013) have reported the overview of ‘geopolymeric cement concrete’ based on extensive works carried out and published information. The GPCs may be either self curing or high temperature curing, with compressive strength ranging from 20 to 75 MPa. A look at the properties of GPCs with reference to stress-strain curves, bond strength, corrosion and sulphate resistance, thermal conductivity and expansion coefficient, electrical resistance ultrasonic pulse velocity, flexure and shear behaviour indicates that the industrial waste based GPCs can possess satisfactory strength and durability related characteristics depending upon their formulations.

### *2.7.1 Acid Resistance*

Douglas (1992) has reported the changes in dynamic modulus of elasticity, pulse velocity, weight and length of sodium silicate-activated slag cement concrete after 120 days of immersion in 5% sodium sulphate solutions. The changes were smaller than those in the controlled specimens immersed in lime-saturated water.

Bakharev (2003) has investigated the durability of Alkali Activated Slag (AAS) concrete exposed to sulphate attack. AAS concrete was immersed in a solution containing 5% sodium, 5% magnesium and 5% sodium and magnesium sulphate solution. The main parameters studied were the compressive strength, products of degradation and micro structural changes. It was found that in AAS concrete the material prepared using sodium hydroxide had the best performance due to its stable cross-linked alumino silicate polymer structure.

The effect of geopolymer cement on the compressive strength of concrete and resistance to sulphuric acid was studied by Hewayde et al (2006). Experimental results indicate that use of geopolymer cement as partial replacement for Ordinary Portland Cement (OPC) effectively improves both the compressive strength and resistance to sulphuric acid. Replacement of 50% OPC by geopolymer cement increased the 28-day compressive strength by 50% and reduced the mass loss of concrete specimens subjected to eight weeks of immersion in sulphuric acid solutions with pH of 0.3 and 0.6 by 42% and 30%, respectively. A direct relationship between the ability of geopolymer modified concrete specimens to resist sulphuric acid and their normal 28-day compressive strength was found, but varied with the binder used.

Brock William Tomkins (2011) has evaluated the chemical resistance of Fly Ash based Geopolymer Concrete (FAGC) and Red Mud based Geopolymer Concrete (RMGC). The chemical resistance tests involve sodium hydroxide and sulphuric acid at $20^oC$ and $90^oC$. Results indicated OPC experienced some strength deterioration in both acid environment

(-24.9 to -25.6%) and alkaline environment (-2.2 to -13.3%). FAGC was found to have better acid resistance (+3.8 to -17.6%). RMGC exhibited a strength increase of 52.4% in sulphuric acid while also displaying strength enhancement of +50.5% in sodium hydroxide. This performance suggests that FAGC and RMGC are both suitable replacements.

Sreevidya et al (2012) have conducted an experimental study on the acid resistance of fly ash based geopolymer mortar specimens of size 50 x 50 x 50 mm with a ratio of fly ash to sand as 1:3. The ratios of sodium hydroxide and sodium silicate solution to fly ash were 0.376, 0.386, 0.396 and 0.416. After casting the specimens were subjected to both ambient curing and heat curing. Results obtained from the study indicate that geopolymers are highly resistant to sulphuric acid and hydrochloric acid.

Madhan Gopal and Naga Kiran (2013) have presented experimental data on the behavior of fly ash based geopolymer concrete exposed to a 5% acid solution. Geopolymer concrete was initially cured for 24 hours at $60^{o}$C. The results obtained were compared with the conventional concrete exposed to 5% acid solutions. The compressive strength of geopolymer concrete and conventional concrete of 150 mm cubes at an age of 28 days were 32 MPa and 48.5 MPa respectively. The percentage of weight loss by geopolymer samples after acid immersion in sulphuric acid for 7, 14 and 28 day is 1%, 1.7% and 2.2% respectively and the residual compressive strength was 14.5%, 19.7% and 27.5%. The results confirmed that Geopolymer concrete is highly resistant to acid when compared to conventional concrete. Suresh Thokchom et al (2009) have presented experimental on acid resistance of fly ash based geopolymer concrete. The results conclude that geopolymer has a very good resistance in acid media in terms of weight loss and residual compressive strength. Research reported by Mehta (1985) indicates that the presence of high alumina cement in concrete increase the resistance to acids.

Sadangi et al (2013) have conducted an experimental investigation to study the performance of fly ash based geopolymer specimens in sodium aluminium phosphate solution. High strength geopolymer is produced from coal combustion fly ash and sodium aluminium phosphate chemical which can be obtained by hydrated alumina powder reacting with ortho phosphoric acid and sodium hydroxide. The curing is done by both atmospheric and accelerated means. The performance of the specimens was evaluated in terms of visual appearance, change in compressive strength, phase development and micro-structural analysis over the exposure period of time. Evidence is provided with micro structural studies and mechanical strength properties on the presence of amorphous binding phase. Fly ash based geopolymer which is activated with phosphate bonded chemical activator shows a greater compressive strength compared to other activators. Accelerated cured geopolymer gives more strength and complete geopolymerization reaction compared to atmospheric cured geopolymer. 6% chemical activator solution gives an excellent result with a compressive strength of 23 MPa after 8 hrs of drying at 60$^{o}$C. Phosphate bonded geopolymers are greater suitable for ceramic application.

Rajamane et al (2012) have conducted an experimental investigation to study the resistance of geopolymer concrete to sulphates. Test specimens of typical GPCs and Portland Pozzolana Cement Concrete (PPCC) were submerged separately in 5% $Na_2SO_4$ and 5% $MgSO_4$ solutions for 90 days. The test results indicate that for 30 and 90 days exposure, there were small changes in weight, ranging from weight gain of about 2% to weight loss of about 2.4%. There were quite different significant losses of strength in the concretes the ranges being about 2% to 29% for GPCs as compared to 9% to 38% for PPCC depending upon the exposure time and type of sulphate. However GPCs were found to resist sulphate attack (both magnesium and sodium based) always better than PPCC as seen from their higher residual strengths after exposure to sulphates. Eco-friendliness of GPCs were examined by computing parameters such as ‘Embodied Energy’ and ‘Embodied Carbon’ or ‘Embodied $CO_2$ Emission’, per unit volume of concrete, Energy and $CO_2$ emission involved to produce unit strength in concretes. It was observed that GPCs were superior to PPCC in terms of these parameters also.

### *2.7.2 Water Permeability*

Olivia et al (2008) have carried out an experimental study on water penetrability properties, namely, water absorption, volume of permeable voids, permeability and sorptivity of low calcium fly ash geopolymer concrete. Seven mixes were cast in 100 x 200 mm cylinders and cured for 24 hours at 60$^{o}$C in the steam curing chamber. It is found that mix with aggregate grading (7, 10, 20 mm) shows low water permeability and void content. Results indicate that the low water/binder ratio and a well-graded aggregate have large influences on geopolymer concrete permeability.

Monita Olivia and Hamid Nikraz (2011) have conducted a study on the strength development, water absorption and water permeability of low calcium fly ash geopolymer concrete. Geopolymer mixtures with variations of water/binder ratio, aggregate/binder ratio, aggregate grading and alkaline/fly ash ratio were investigated. The result shows that the average water absorption of fly ash geopolymer was less than 5%, which can be classified as “low”. The overall percentage of Apparent Volume of Permeable Voids (AVPV) was less than 12% and was classified as “good”.

Antony Jeyasehar and Saravanan (2013) have evaluated the strength and durability of geopolymer bricks by conducting tests on the compressive strength, the split tensile strength and the flexural strength. To improve the quality of geopolymer mortar durability tests such as water absorption test and acid resistance test (HCl and $H_2SO_4$) were also conducted. The main focus of the investigation is on the optimum utility of the available fly ash and minimizing the water absorption and attaining high compressive strength. The results suggest that increase in curing temperature results in an increase in the compressive strength of the geopolymer mortar. Steam curing increases the compressive strength and the strength of stream cured bricks is more when compared to air curing. The percentage weight loss of geopolymer bricks when immersed in different concentration of $H_2SO_4$ and HCl is found to be very much lower when compared to other types of bricks. Further, the percentage weight loss increases with the increase in acid concentration. The increase in percentage of weight due to water absorption of geopolymer bricks is very small fraction when compared to that of other types of bricks.

## 2.8 Geopolymer Concrete Brick Prism

Abrams (1992) has investigated on the strength and durability of unreinforced masonry elements. Experimental results showed that unreinforced masonry can possess considerable capacity for inelastic deformation and need not be limited in strength by force which induced initial lateral flexure or diagonal tensile crack. It has been reported that the structural behavior and strength of reinforced geopolymer concrete beams and columns were similar to those made of Portland cement concrete.

Monjur Hossain et al (1997) have conducted an experimental investigation on clay bricks. The in-situ deformation characteristics of mortar and brick joint have been determined. The result shows that the strength and deformation characteristic of masonry constituents are more representative of the actual composite behavior of masonry. The property of brick and mortar joint was also found to be more appropriate. Mohamad et al (2005) have carried out experimental tests on masonry prisms subjected to compression. The failure mechanism of masonry depends on the difference of elastic modulus between brick unit and mortar. The mortar governed the non-linear behavior of masonry. Oliveira et al (2000) have carried out the tests on prisms under cyclic loading and the stress-strain behaviour of the brick prisms showed a bilinear pre-peak behaviour. Elizabeth et al (2001) have investigated the effect of deep rejointing behaviour of brick masonry subjected to axial compression. In all the specimen's typical vertical cracks due to compression appeared both along the length and the width of prisms. Maurenbrecher (1980) has described the effects of various factors on prism strength. The Canadian masonry design standard for buildings allow two methods of determining compressive strength of masonry, (i) tabular values based on unit strength and mortar type (ii) axially loaded prisms such as two-course block-work stacks.

Gumaste et al (2007) have studied the properties of brick masonry using table moulded bricks and wire-cut bricks from India with various types of mortars. The table moulded brick masonry using lean mortar failed due to loss of bond between brick and mortar. The wire-cut brick masonry exhibited a better correlation between mortar strength and masonry strength. Mosalam et al (2009) investigated the mechanical properties of masonry which was a heterogeneous composite in which brick units made from clay, compressed earth, stone or concrete were held together by mortar.

Hemant et al (2007) have studied the uniaxial monotonic compressive stress-strain behavior of unreinforced masonry. Based on the results of the study nonlinear stress-strain curves have been obtained for bricks, mortar and masonry and six "control points" have been identified on the stress-strain curves of masonry which are used to define the performance limit states of the masonry material. Using linear regression analysis a simple analytical model has been proposed for obtaining the stress-strain curves for masonry that can be used in the analysis and design procedures.

Freeda Christy et al (2013) have conducted a study on the compressive strength of brick masonry subjected to axial loading. The study focuses on the effect of the masonry components with different types of bonding on compressive strength. Short prisms have been tested under axial compressive load using clay brick and fly ash brick. The results shows that elastic modulus of the brick masonry can be determined with the prism strength and the equivalent homogenized elastic property of the masonry was derived with the elastic properties of brick, mortar and the reinforcement.

Cheema and Klingner (1986) have described the failure criterion curve for hollow prisms using the modular ratio between mortar/block and the failure type (by mortar crushing and transverse block splitting). Material non-linearity was accounted by using secant modulus and the strength of constituent materials was computed considering the effects of multiaxial stresses. An experimental investigation on blockwork masonry prisms was conducted by Khalaf et al (1994) to study the effect of different materials on the compressive strength. The conclusion of this work is that an increase of mortar strength of ungrouted prisms by 188% and 72% produced only an increase in the prism strength of about 20%.

Dattatreya et al (2011) have carried out an extensive study on the behaviour of reinforced GPC flexural members. A total of eighteen beams were tested in flexure. Three conventional concrete mixes and six GPC mixes of target strength ranging from 17 to 63 MPa and having varying combination of fly ash and slag in the binder phase were considered. The reinforcement was designed considering a balanced section for the characteristic strength. All the specimens were tested under two point static loading. The studies demonstrated that the load carrying capacity of most of the GPC beams was in most cases marginally more than that of the corresponding conventional ordinary portland cement concrete beams. The deflections at different stages including service load and peak load stage were higher for GPC beam. However, the ductility factor was comparable to that of OPCC beams. The study showed that conventional RC theory could be used for reinforced GPCC flexural beams for the computation of moment capacity, deflection and crack width with reasonable limits.

## 2.9 Inference from Literature Study

Review of literature indicates a big importance for geopolymer in the near future, in the construction sector. The use of fly ash in geo-polymer concrete is particularly important, as the disposal of this waste is a worldwide problem and based on the literature the following ranges were selected for the constituents of the mixture used in further studies described in chapter 4. Low calcium (ASTM Class F) fly ash was used with ratio of sodium silicate solution-to-sodium hydroxide solution by mass of 2.5. Molarity of sodium hydroxide (NaOH) solution was chosen in the range of 8M to14M. Ratio of activator solution-to-fly ash by mass was fixed to be 0.40. Curing at elevated temperatures was done in two different ways, i.e. curing at room temperature and in the laboratory oven at 60ºC.

## 2.10 Scope of the Research

Accumulation of unmanaged waste especially in the developing countries has resulted in increased environmental concern. Recycling of such wastes as building material appears to be a viable solution not only for problems like pollution but also to the problem of economical design of buildings. This research has utilized low-calcium (ASTM Class F) fly ash as the base material for making geopolymer concrete which was obtained from Ennore thermal power plant, Tamil Nadu, India. The property studied includes the physical, mechanical and the chemical properties of geopolymer concrete block. Consequently, the scope of this research is to conduct a study on the properties of geopolymer hollow block. A parallel study was also conducted to study the behavior of geopolymer brick prism of varying height. The potential for improving the performance of new concrete mixture has to be ascertained through experimental investigation. Hence a total investigation was comprehensively planned and conducted in a systematic procedure as shown in Figure 2.1.

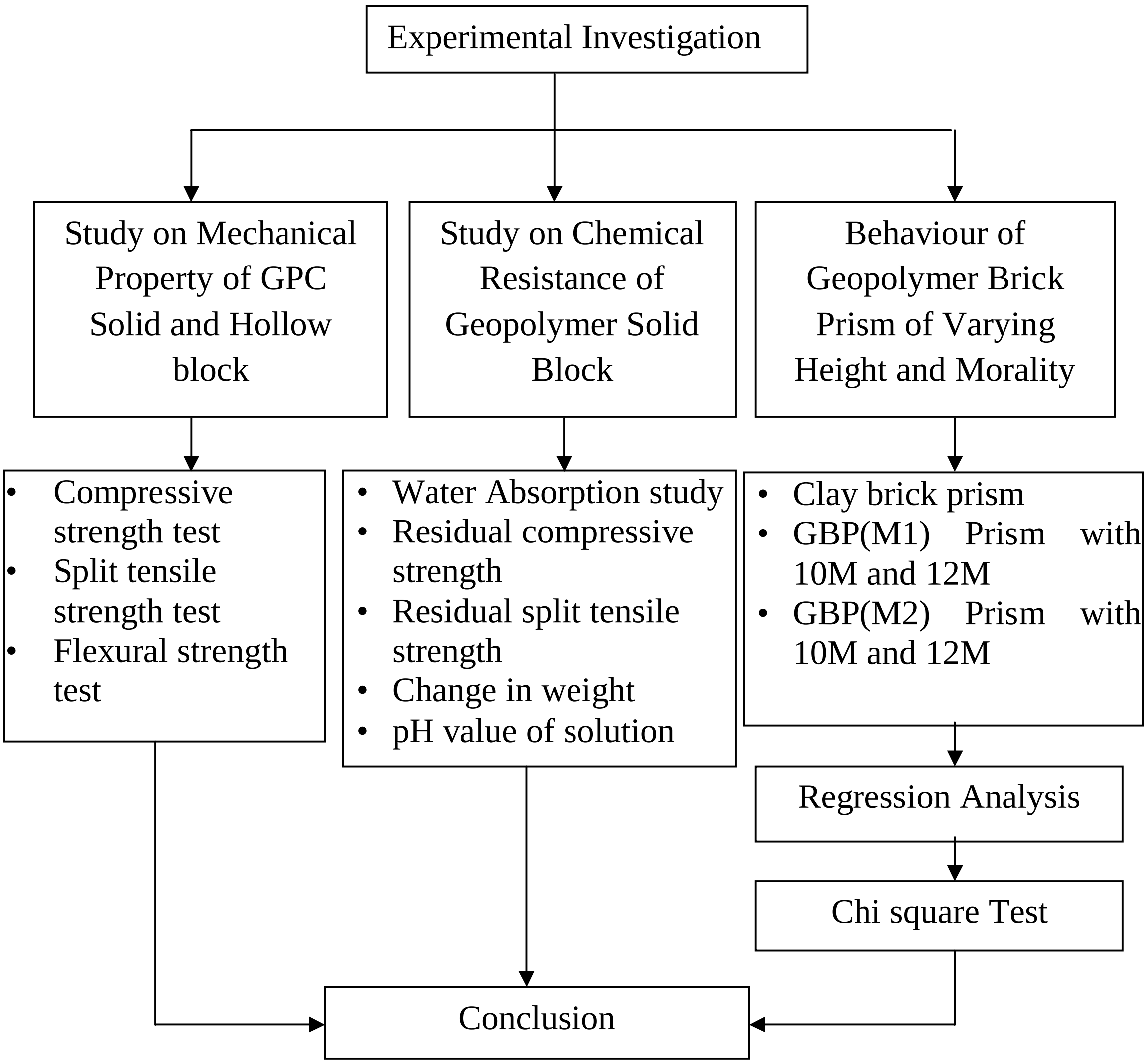



**Figure 2.1 Methodology of Total Investigation**