JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

CONSTRUCTION ENGINEERING AND MANAGEMENT CHAIR

AN EXPERIMENTAL STUDY ON GEOPOLYMER CONCRETE USING LOW CALCIUM FLY ASH

A thesis submitted to the School of Graduate Studies, Jimma University, Jimma Institute of Technology, Faculty of Civil and Environmental Engineering in Partial fulfillment of the requirements for the Degree of Master of Science in Civil Engineering (Construction Engineering and Management)

By:
Agari Negash Garedew

January, 2020
Jimma, Ethiopia

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Main Advisor: Dr. Getachew Kebede (PhD)

Co-Advisor: Engr. Tashome Boja (MSc)

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Jimma, Ethiopia

DECLARATION

I declare that this research report entitled "AN EXPERIMENTAL STUDY ON GEOPOLYMER CONCRETE USING LOW CALCIUM FLY ASH" is my own work and has not been submitted requirement for any degree in any other University and all references material used while compiling this research paper are fully cited.

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As Master Research Advisors, we here by certify that we have read and evaluate this MSc research prepared under our guidance, by AGARI NEGASH GAREDEW entitled 'AN EXPERIMENTAL STUDY ON GEOPOLYMER CONCRETE USING LOW CALCIUM FLY ASH" and we recommend that would be accepted as a fulfilling requirement for Degree of Masters of Science in Construction Engineering and Management.

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ABSRACTS

Concrete is the widely used building material and cement is the main constituent in the manufacturing of concrete. In concrete production, ordinary Portland cement (OPC) is conventionally used as primary binder to produce concrete. In production of cement burning of lime stone take place which results in emission of carbon dioxide (CO2) gas into the atmosphere. So, it is important to find substitutes binders which have less carbon foot-print than cement, less natural resource depletion, less energy consumer and better strength. From many alternatives geopolymer binder is best alternative. In geopolymer concrete, a by-product material rich in silicon and aluminum such as low calcium fly ash, is chemically activated by a high- alkaline solution such as NaOH and Na_2SiO_3 to form a paste that binds the loose coarse and fine aggregates, and other unreacted in mixture.

In this study, fly ash sample is collected from Ayka Addis Textile and its oxides composition investigated in the laboratory of Dangote Cement factory Enterprise and physical properties (unity weight, specific gravity, water absorption, moisture content, fineness modulus and silt content) of coarse and fine aggregate, workability of fresh geopolymer concrete, density and compressive strength geopolymer concrete tests are conducted in laboratory of Jimma Institute of Technology.

*Experimental laboratory sample test has been made in this research work, C-25 with 0.5 of water to fly ash ratio and the slump of 25 to 50mm are used in geopolymer concrete mix design. Geopolymer Concrete cubes of size 150*150*150mm are prepared and placed in ambient temperature for a maximum of 28 days. Six different geopolymer concrete samples with ratio of 0.5 and 1.5 Na_2SiO_3 to NaOH and sodium hydroxide solution with concentration of 10M, 13M and 16M are prepared to make a concrete samples and one control OPC concrete. For each variable three sets of specimens are prepared for compressive strength tests conducted at the age of 7, 14 and 28 days.*

Test results revealed that the slump value of the geopolymer concrete with low calcium fly ash had shown a slight reduction as concentration of NaOH and ratio of Na_2SiO_3 to NaOH increases. In addition to that, density of the test specimens increased with an increase in concentration of NaOH but, less density than control OPC concrete and also the compressive strength of geopolymer concrete have shown improvement over the control OPC concrete with concentration of NaOH 10M, 13M and 16M and ratio of Na_2SiO_3 to NaOH of 1.5 at 28 day age. But, lesser compressive strength at age of 28 days with concentration of NaOH 10M, 13M and 16M and ratio of Na_2SiO_3 to NaOH of 0.5. So, geopolymer concrete with NaOH 10M, 13M and 16M and ratio of Na_2SiO_3 to NaOH of 1.5 suitable as construction material in construction industry.

Keywords: *Alkaline Solution, Compressive strength, density, Fly ash, Geopolymer, Sodium hydroxide, Sodium silicate, workability.*

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ACRONOMYS

AASHTO	American Association of State Highway and Transportation Officials
ACI	America concrete Institute
Al_2O_3	Alumina Oxide
ASTM	American Society for Testing and Materials
CA	Coarse Aggregate
CaO	Lime
CO_2	Carbon Oxide
EBCS	Ethiopia building code Standards
ES	Ethiopia Standard
FA	Fine Aggregate
FA	Fly ash
Fe_2O_3	Iron Oxide
GPC	Geopolymer concrete
KOH	Potassium Hydroxide
LOI	Loss on Ignition
M	Molarity
MgO	Magnesia
MPa	Mega Pascal
Na_2O	Sodium Oxide
Na_2SiO_3	Sodium Silicate
NaOH	Sodium Hydroxide
OPC	Ordinary Portland cement
SiO_2	Silicon Oxide
SO_3	Sulfur Trioxide
SSD	Saturated surface dry
W	Water

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Concrete is the most widely usable material globally, this is because of its strength suitability and availability of raw materials (ingredients) abundantly. Customarily, the common binding material in concrete production is ordinary Portland cement (OPC). Now a day, the demand for concrete and its ingredients are highly increase to meet infrastructure development especially in developing countries. Even if the concrete made by ordinary Portland cement as a binders is suitable (i.e. strength) and available, its well-known that cement production depletes significant amount of natural resources and releases large amount of carbon dioxide which increases environment pollution and global warming and use intense energy (Tabassum & Khadwal, 2015).

In the current era, the biggest problem to the human beings on this planet is environmental pollution and global warming. Environmental pollution means adding impurities to the atmosphere. Ecosystem is badly affected by this kind of pollution. This Pollution is caused by so many reasons. From many reason construction industry is listed as major one, Cement is the main ingredient for the production of concrete. But the production of cement requires large amount of raw material. During the production of cement burning of lime stone take place which results in emission of carbon dioxide (CO_2) gas into the atmosphere. There are two different sources of carbon dioxide (CO_2) emission during cement production. Combustion of fossil fuels to operate the rotary kiln is the largest source and other one is the chemical process of burning limestone. Concrete is used globally second to water. Due to increment of the demand of concrete there is increase in production of cement which results in increase in environmental pollution and global warming (Hardjito & Rangan , 2005).

So, it is important to discover an alternate binder which has less carbon foot-print than cement. Several efforts are in progress to supplement the use of Portland cement in concrete in order to address the global warming issues. These include the utilization of supplementary cementing materials such as fly ash, silica fume, granulated blast furnace slag, rice-husk ash and metakaolin, and the development of alternative binders to Portland cement (Davidovits, 1994).

The (Davidovits, 1994) Studied that one of the encouraging alternatives are using fly ash as part or total substitutions of cement in concrete. The total substitutions of cement has been made possible since the introduction of Geopolymer by Prof. Joseph Davidovits in 1979 proposed that an alkaline liquid could be used to react with the silicon (Si) and the aluminum (Al) in a source material such as low calcium fly ash to produce binders. Because the chemical reaction takes place in this case is a polymerization process, he coined the term 'Geopolymer' to represent these binders.

Geopolymer is an inorganic polymer. There are two main constituents of Geopolymer, namely the source material and the alkaline liquids. The source materials for geopolymer based alumina-silicate should be rich in silicon (Si) and aluminum (Al). These should be natural minerals such as kaolinite, clay, fly ash, 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 and combination of the source materials for making geopolymer depends on factors such as availability, cost, and type of application and specific demand of the end users. The alkaline liquids are from soluble alkali metals that are usually sodium and potassium based. The most common alkaline liquid used in geopolymerisation is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate and potassium silicate (Rangan, 2008).

1.2 Statement of the problem

Globally the use of concrete increases day to day due to the increment of the need of the modern infrastructure facilities which is mostly constructed by concrete. In concrete production, particularly in cement production depletion of natural resources which are used as raw material for concrete, releasing of large amount of carbon dioxide which is the main environmental impacting gases and usage of intense energy is the headache of construction industry. In order to produce environmentally friendly concrete (Mehta, 2002) stated that the use of fewer natural resources, less energy and less environmental impacts in short term and in long-term goal reducing the impacts of unwanted by-products of industry can be attained by lowering the rate of material consumption. So, reuse of fly ash as cement which is the by-product of coal combustion and cause of environmental impacts reduces natural resource depletion, carbon dioxide emission in cement production and usage of intense energy in addition to lessening environmental impacts of fly ashes (Davidovits, 2002).

The other problem in construction industry is getting the right compressive strength using OPC especially in structure require high compressive strength, it may require using admixture or changing the mix proportion or using the composite body which is un economical, resistance against aggressive environment and elevated temperature. To solve these problems of OPC concrete the geopolymer concrete is one solutions since it have better results in compressive strength (Hardjito & Rangan , 2005), improve durability (Liu & Chern, 2008) and better resistance against aggressive environmental condition and elevated temperature compared to normal concrete (Al Bakri et al., 2011).

In Ethiopia, a numbers of production industries uses coal as energy sources which generate huge amount of fly ashes as wastes where method of disposal of wastes are not good and mainly a causes of high environment impacts and even cause of conflict and public protest in general. So, reusing of fly ash as raw material for concrete production reduce all problems emerge in concrete production and environmental impacts due to fly ashes.

1.3 Research questions

1. What is the effect of sodium silicate to sodium hydroxide solution proportion and variation on concentration (molarity) of sodium hydroxide on the workability of fresh geopolymer concrete?
2. What are the effects of variation on concentration (molarity) of sodium hydroxide and ratio of sodium silicate to sodium hydroxide on the compressive strength and density of geopolymer concrete?
3. What is suitable proportion and concentration of alkaline solution for geopolymer concrete production?

1.4 Research Objectives

1.4.1 General Objective

The main objective of the study is to investigate the effects of sodium silicate and sodium hydroxide on the properties of geopolymer concrete using low calcium fly ash.

1.4.2 Specific Objective

- ✓ To study the effects of different molarity of sodium hydroxide solution and different ratio of sodium silicate to sodium hydroxide solution on workability of fresh geopolymer concrete.
- ✓ To examine the effect of different molarity of sodium hydroxide solution and different ratio of sodium silicate to sodium hydroxide solution on the compressive strength and density of geopolymer concrete.
- ✓ To identify suitable proportion of sodium silicate to sodium hydroxide solution and concentration of sodium hydroxide solution in geopolymer concrete production.

1.5 Significance of the Study

The Significance of this study was to provide helpful information to Construction industries stakeholders in decreasing greenhouses gases emission (particularly CO_2), depletion of natural resources (particularly cement), reducing the impacts of unwanted by-products of industry like, fly ash, to develop higher compressive strength concrete than conventional concrete and more resistance to aggressive environment. On the other hand, this research can be used as reference for Jimma Institute of Technology students and researchers those who want to carried out further study with respect to Geopolymer concrete. Thus new advanced technology are introduced in Construction industries which are environmental friendly and economical as well.

1.6 Scope and limitation of the study

This researcher utilized low calcium fly ash as the main ingredients and alkaline solution sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) with different proportion and concentration NaOH. Fly ash obtained from Ayka Addis Ethiopia. The technology and equipment currently used to manufacture OPC concrete are used to make geopolymer concrete.

The concrete properties studied include workability of fresh Geopolymer concrete, density of geopolymer, effects of different proportion of alkaline solution on compressive strength, effects of different concentration of NaOH compressive strength of concrete.

CHAPTER TWO

REVIEW OF RELATED LITERATURE

2.1 Concrete and Environment

The tremendous improvement in the civilization and industrialization brought us many fruitful benefits through science and technology for the mankind, out of many a huge growth in Construction industry is one. Many new technologies have evolved very rapidly to reduce different difficulties in the construction industry. Concrete is one of the most significant materials in a construction industry, among all the material used for construction purposes. The process of manufacturing of cement emits near about eight to ten percent of total world's carbon dioxide. The global warming gas is released when limestone and clays are crushed and heated to high temperatures. In recent year, the recycling of waste and industrial by products gaining popularity to make concrete environment friendly material and the concrete can be called as Green Concrete. Green concrete is defined as a concrete which uses waste material as at least one of its components, or its production process does not lead to environmental destruction, or it has high-performance and life cycle sustainability (Shekhar et al., 2017).

From the main component of concrete, use of Portland cement in concrete construction is under critical review due to high amount of carbon dioxide gas released to the atmosphere during the production of cement. So, new technology which does not require Portland cement as a binder should be emerge, Geopolymer concrete is a new material that does not need the presence of Portland cement as a binder. Instead, the source of materials such as fly ash, that are rich in Silicon (Si) and Aluminium (Al), are activated by alkaline liquids to produce the binder. Hence concrete with no Portland cement (Gupta & Chandrakar, 2017).

(Mishra et al., 2008) Conducted experiments on fly ash based geopolymer concrete by varying the concentration of NaOH and curing time. Total nine mixes were prepared with NaOH concentration as 8M, 12M, 16M and curing time as 24hrs, 48hrs, and 72hrs. Compressive strength, water absorption and tensile strength tests were conducted on each of the nine mixes. Results of the investigation indicated that there was an increase in compressive strength with increase in NaOH concentration. Strength was also increased with increase in curing time, Compressive strength up to 46 MPa was obtained with curing at 60^{o}C. The results of water absorption test indicated that % water absorption of cubes decreased with increase in NaOH concentration and curing time. Hence, geopolymar concrete has a great potential for utilization in construction industry as it is environmental friendly and also facilitates the use of fly ash, which is a waste product from coal burning industries.

(Liu & Chern, 2008) In construction industry usage of Supplementary cementing material (SCM), such as fly ash, ground-granulated blast-furnace (GGBF) slag, or silica fume, is one of the most sustainable construction materials because it;

- Recovers an industrial byproduct through beneficial use when incorporate into concrete,
- Avoids disposal of industrial byproducts,
- Reduces Portland cement content in concrete, resulting in decreased emission of greenhouse gas and decreased use of natural raw materials, and
- Increases structure service life by improving the durability of concrete.

2.2 Fly Ash

According to the American Concrete Institute (ACI) Committee 116R (2004), fly ash is defined as 'the finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gasses from the combustion zone to the particle removal system. Fly ash is removed from the combustion gases by the dust collection system, either mechanically or by using electrostatic precipitators, before they are discharged to the atmosphere. Fly ash particles are typically spherical, finer than Portland cement and lime, ranging in diameter from less than 1 µm to no more than 150 µm.

Fly ash is produced, in massive amount, as a waste material of burning fossil fuel (coal combustion) for the thermal generation of electricity. Currently about 900 million tonnes of fly ash produced, worldwide, annually and about 30-40% of this residue is being utilized for various purposes including in cement and concrete production. Disposing the remaining percentage is costly as it should be done carefully to avoid any environmental pollution, mainly groundwater contamination. There are different types of fly ash, including Class F and Class C, generated by burning black coal and brown coal respectively. Class F and Class C are being utilized in making building materials such as concrete, lightweight aggregate, bricks etc. Also fly ash is used as a material for road construction and earth filled dam construction (Gamage, *et al*., 2014).

The types and relative amounts of incombustible matter in the coal determine the chemical composition of fly ash. The chemical composition is mainly composed of the oxides of silicon (SiO_2), aluminium (Al_2O_3), iron (Fe_2O_3), and calcium (CaO), whereas magnesium, potassium, sodium, titanium, and sulphur are also present in a lesser amount. The major influence on the fly ash chemical composition comes from the type of coal. The combustion of sub-bituminous coal contains more calcium and less iron than fly ash from bituminous coal. The physical and chemical characteristics depend on the combustion methods, coal source and particle shape. The chemical compositions of various fly ashes show a wide range, indicating that there is a wide variations in the coal used in power plants all over the world (Malhotra & Ramezanianpour, 1994).

"*There are tradeoffs to anything; there is no perfect material. Fly ash, in a way, is still solving a symptom. In one sense, yes, you're using up this waste material. In another way it's justifying the burning of coal as a fuel source. Until we find better ways to produce energy. It is good use of the by-product*."
Daniel Hendeen, a research fellow at university of Minnesota center for sustainable building research

2.2.1 Classification of fly ash

According to ASTM C 618-99 Fly ash is classified into three as below
Class N-Raw or calcined natural pozzolans that comply with the applicable requirements for the class as given herein, such as some diatomaceous earths; opaline cherts and shales; tuffs and volcanic ashes or pumicites, calcined or uncalcined; and various materials requiring calcination to induce satisfactory properties, such as some clays and shales.

Class F-Fly ash normally produced from burning anthracite or bituminous coal that meets the applicable requirements for this class as given herein. This class fly ash has pozzolanic properties.

Class C-Fly ash normally produced from lignite or subbituminous coal that meets the applicable requirements for this class as given herein. This class of fly ash, in addition to having pozzolanic properties, also has some cementitious properties.

ASTM prescribes the total composition of silicon oxide (SiO_2) plus alumina oxide (Al_2O_3) plus iron oxide (Fe_2O_3) are minimum 70% (by weight) for class F fly ash and class N and 50% (by weight) for class C fly ash.

2.2.2 Use of fly ash in concrete

The (Bhatia, 2016) revealed that Coal fly ashes were plentiful industrial waste product, known to be a good pozzolanic material and has been used to increase the ultimate compressive strength and workability of fresh concrete. For this simple reason it is rapidly becoming a common ingredient in concrete all over the world; it is already present to some degree in half the concrete. The use of fly ash as a performance-enhancing ingredient in concrete is one of the most outstanding examples of industrial ecology-i.e., making effective use of waste resources, and ultimately eliminating the concept of waste altogether. The use of fly ash in concrete contributes the reduction of greenhouse emissions with negative impacts on the economy. It has been observed that 0.9 tons of CO_2 is produced per ton of cement production. Also, the composition of cement is 10% by weight in a cubic yard of concrete. To avoid the pollution and reuse the material, thus, concrete is an excellent substituent of cement as it is cheaper, because it uses waste products, saving energy consumption in the production. The trend is clear, Fly ash will soon be considered as a resource material and its potential will be fully exploited. Through development & application of technologies, Fly Ash has shifted from "Waste Material" category to "Resource Material" category. Thus fly ash management is a cause of concern for the future. Unfortunately, the millions of tons of fly ash and related-products have been generated. To overcome these problems, (Al Bakri et al., 2011) stated that fly ash was used in term of geopolymer to produce precast structure, non-structural elements, concrete pavements, concrete products and immobilization of toxic waste that are resistant to toxic waste that are resistant to heat and aggressive environment.

2.3 Geopolymer

According to Geopolymer Institute (2010) the name geopolymer was formed by a French Professor Davidovits in 1978 to represent a broad range of materials characterized by networks of inorganic molecules. The geopolymer depend on thermally activated natural materials like Meta kaolinite or industrial byproducts like fly ash or slag to provide a source of silicon (Si) and aluminum (Al). These Silicon and Aluminium is dissolved in an alkaline activating solution and subsequently polymerizes into molecular chains and become the binder (Geopolymer Institute, 2010).

Geopolymer is a material produced by inorganic poly-condensation, i.e., by so-called "geopolymerisation." The process comprises dissolution of aluminosilicate followed by condensation of free silicate and aluminate species to form a three-dimensional structure of silicon-aluminate structures (Al Bakri et al., 2011). The reaction of Fly Ash with an aqueous solution containing Sodium Hydroxide and Sodium Silicate in their mass ratio, results in a material with three dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds (Krishna & Prasad, 2017).

(Davidovits, 2013) Studied Geopolymer cement is an innovative material and a real alternative to conventional Portland cement for use in transportation infrastructure, construction and offshore applications. It relies on minimally processed natural materials or industrial byproducts to significantly reduce its carbon footprint and energy usage, while also being very resistant to many of the durability issues that can plague conventional concretes.

Geopolymer concrete, high-alkaline (K-Ca)-poly (sialate-siloxo) cement, results from an inorganic poly condensation reactions, a so called, geopolymerisation yielding three dimensional frameworks. Geopolymer cement hardens rapidly at room temperature and provides compressive strengths in range of 20MPa after only 4 hours at $20^{o}C$, when tested in accordance with the standards applied to hydraulic mortars. (Davidots, 1994) Their unique properties include high early strength, low-shrinkage, freeze thaw resistance, sulphate resistance and corrosion resistance, make them ideal for long them containment in surface disposal facilities ((Davidovits, 1994).

Table 2.1 Energy needs and CO2 emissions for 1 tonne of Portland cement and Rock-based (more energy consumer) Geopolymer cement, according to Professor Joseph Davidovits. (Davidovits, 2013) .

Energy needs(MJ/ton)	**calcination**	**crushing**	**Silicate sol.**	**total**	**reduction**
Portland cement	4270	430	0	4700	0
GP-cement, slag by-product	1200	390	375	1965	59%
GP-cement, slag manufacture	1950	390	375	2715	43%
CO_2 Emissions(tonne)					
Portland cement	1.000	0.020		1.020	0
GP-cement, slag by-product	0.140	0.018	0.050	0.208	80%
GP-cement, slag manufacture	0.240	0.018	0.050	0.308	70%

Geopolymer is a material resulting from the reaction of a source material that is rich in silica and alumina with alkaline solution. Geopolymer concrete is totally Portland cement free concrete. In geopolymer, fly ash act as binder and alkaline solution act as an activator. Fly ash and alkaline activator undergo geopolymerisation process to produce alumino silicate gel. Alkaline solution used for present study is combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SO_3) with ratio 2.5. Grades chosen for the investigation were M40.The mixes were designed for molarity of 12M, 14M and 16M. The test results have shown that compressive strength increases with increase in molarity (Kawade et al., 2014). Geopolymer concrete is an innovative construction material which shall be produced by the chemical action of inorganic molecules. Fly Ash, a by- product of coal obtained from the thermal power plant is plenty available worldwide. Fly ash is rich in silica and alumina reacted with alkaline solution produced aluminosilicate gel that acted as the binding material for the concrete. It is an excellent alternative construction material to the existing plain cement concrete. Geopolymer concrete shall be produced without using any amount of ordinary Portland cement (Aleem & Arumairaj, 2012).

In geopolymer concrete, a by-product material rich in silicon and aluminum, such as low-calcium (ASTM C 618 Class F) fly ash, is chemically activated by a high-alkaline solution to form a paste that binds the loose coarse and fine aggregates, and other unreacted materials in the mixture (Hardjito, 2004). Geo-polymer concrete utilizes an alternate material called fly ash as binding material instead of cement. Fly ash reacts with alkaline solution (e.g. NaOH) and Sodium silicate (Na_2SiO_3) to form a gel which binds the fine and coarse aggregates (Janani & Revathi, 2015).

2.3.1 Constituents of Geopolymer Concrete

2.3.1.1 Aggregates

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 (Hardjito & Rangan , 2005).

(Rangan, 2014) stated that Combined aggregate was used in Geopolymer concrete. Local aggregates comprising 20mm (0.78 inches), 10 mm (0.39 inches), 7mm (0.273 inches) coarse aggregates in saturated surface dry (SSD) condition were used. The coarse aggregate (CA) were crushed granite and basalt type aggregates Fine aggregates used are mostly locally available grit sand and river sand. Coarse and fine aggregate used by the concrete industry are suitable to manufacture Geopolymer concrete. Coarse and fine aggregate of approximately 75% to 80% of the entire mixture by mass used in geopolymer concrete mixture, this value is similar to that used in OPC concrete.

The coarse and fine aggregates in a geopolymer concrete mixture must neither be too dry to absorb water from the mixture nor too wet to add water to the mixture. In practical applications, aggregates may contain water over and above the SSD condition. Therefore, the extra water in the aggregates above the SSD condition must be included in the calculation of water-to geopolymer solids ratio (Rangan, 2008).

2.3.1.2 Source Materials

The source materials for geopolymer 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 (Rangan, 2008).

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. Therefore, huge quantities of fly ash will be available for many years in the future (Malhotra, 2006).

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%. The Hardjito, et al. studied that particle size distribution tests revealed that 80% of the fly ash particles were smaller than 50µm (Hardjito et al., 2005). The reactivity of low-calcium fly ash in geopolymer matrix has been studied (Fernández et al., 2006).

2.3.1.3 Alkaline liquid

1. Sodium Hydroxide Solution

In Geopolymer concrete making the commonly used alkaline activator is combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate. The type and concentration of solution affect the dissolution of fly ash. Leaching of Al^{+3} and Si^{+4} ions is generally high with NaOH solution compared to

KOH solution. Hence, alkali concentration is important factor in controlling the leaching of alumina and silica from fly ash particles subsequent geopolymerisation and the strength property of hardened geopolymer concrete. (Sathisha & Mamatha, 2015).

2 Sodium Silicate

Sodium Silicate is activators play important role in the geopolymerisation process. Reactions occur at high rate when alkaline activator contains soluble silicate (Sathisha & Mamatha, 2015).

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 (Rangan, 2008).

(Hardjito & Rangan , 2005)Studied 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%, Na_2O = 14.7%, and water = 55.9% by mass, is recommended. The sodium hydroxide with 97-98% 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. 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 8x40 = 320 grams of NaOH solids per litre of the solution, where 40 is the molecular weight of NaOH. The mass of NaOH solids was measured as 262 grams per kg of NaOH solution with a concentration of 8 Molar. Similarly, the mass of NaOH solids per kg of the solution for other concentrations was measured as 10 Molar: 314 grams, 12 Molar: 361 grams, 14 Molar: 404 grams, and 16 Molar: 444 grams (Hardjito & Rangan , 2005).

Figure 2.1 Sodium silicate and Sodium hydroxide pellets (alkaline activators) (Hamraj et al., 2016)

Table 2.2 physical & chemical properties of sodium silicate (Gupta & Chandrakar, 2017)

Chemical Formula	**$Na_2O.SiO_2$, Colourless**
Na_2O	9.5%
SiO_2	30.04%
H_2O	60.10%
Appearance	Liquid(Gel)
Color	Light Yellow Liquid (Gel)
Boiling Point	102 C For 40% Aqueous Solution
Molecular Weight	184.04
Specific Gravity	1.6

2.3.2 Mixture Proportions of Geopolymer Concrete

Geopolymer is a novel binding material produced from the reaction of fly ash with an alkaline solution. In Geopolymer mortar, Portland cement is not utilized at all. In this research, tests were carried out on 50 x 50 x 50mm cube Geopolymer mortar specimens. The test results revealed that as the concentration of alkaline activator increases, the compressive strength of Geopolymer mortar also increases. Specimens cured at temperature of 65^0C for 1 day showed the highest 28 days compressive strength. The mass ratio of activator/fly ash of 0.4 produced the highest 28 days compressive strength for the specimen. The obtained compressive strength was in the range of 32MPa-60MPa (Hardjito et al., 2008).

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.

(Gupta & Chandrakar, 2017) stated that the ratio of sodium silicate solution-to-sodium hydroxide solution, by mass, of 0.4 to 2.5, Molarity of sodium hydroxide (NaOH) solution in the range of 8M to16M and Coarse and fine aggregates of approximately 75% to 80% of the entire mixture by mass. This value is similar to that used in OPC concrete.

2.4 Chemical and Physical Properties Material

2.4.1 Physical and Chemical Properties of Fly Ash

Table 2.3 Physical & Chemical Composition of Fly Ash (Gupta & Chandrakar, 2017)

Particulars	Fly Ash	
Chemical Composition		
Constituents	Composition (%)	Requirements as Per Is 3812-2003
% Silica (SiO_2)	63.4	>35
% Alumina(Al_2O_3)	30.5	
% Iron Oxide (Fe_2O_3)	3	
%Lime (CaO)	1	<10
% Magnesia(Mgo)	1	<5
% Titanium Oxide(Tio_2)	0.62	
%Sulphur Trioxide(SO_3)	0.1	
%Sodium Oxide Na_2O	0.02	<1.5
Loss on Ignition	0.24	<5

According to study carried out by (Hardjito et al., 2005) revealed that the chemical composition of the fly ash, was determined by x-ray fluorescence (XRF) analysis method. The chemical analysis shows that fly ash is mainly composed of silicon dioxide (53.36%), aluminium oxide (26.49%) and iron oxide of (10.86%) with small amounts of calcium oxide (0.37%), magnesium oxide (0.77%) and sulphate (1.70%) and Loss on ignition of fly ash was 1.39% which were fulfill the criteria specified in ASTM C 618-00 which were total composition of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) present in fly ash was 90.71% ≥ 70 , Calcium oxide (CaO) < 10, Sulfur Trioxide(SO3) ≤ 5and loss on ignition ≤ 6 conforms to ASTM C 618-00 type 'F' fly ash.

Table 2.4 Chemical composition of fly ash according to ASTMC 618-99

Fly ash `			
Chemical composition	N	F	C
Silicon oxide (SiO_2) plus Aluminum Oxide Iron oxide (Fe_2O_3) min,%	70	70	50
Sulfur trioxide (SO_3), Max,%	4	5	5
Moisture content, Max, %	3	3	3
loss on ignition, Max, %	10	6	6

2.4.2 Physical Properties of Aggregate

2.4.2.1 Grading

ACI Education Bulletin E1-07 described Grading; Grading refers to the distribution of particle sizes present in an aggregate. The grading is determined in accordance with ASTM C 136, "Sieve or Screen Analysis of Fine and Coarse Aggregates." A sample of the aggregate is shaken through a series of wire-cloth sieves with square openings, nested one above the other in order of size, with the sieve having the largest openings on top, the one having the smallest openings at the bottom, and a pan underneath to catch material passing the finest sieve. Coarse and fine aggregates are generally sieved separately. That portion of an aggregate passing the 4.75 mm (No. 4) sieve and predominantly retained on the 75 µm (No. 200) sieve is called "fine aggregate" or "sand," and larger aggregate is called "coarse aggregate." Coarse aggregate may be available in several different size groups, such as 19 to 4.75 mm (3/4 in. to No. 4), or 37.5 to 19 mm (1-1/2 to 3/4 in.).

Table 2.5 Sieves commonly used for sieve analysis of concrete aggregate according to ACI Education Bulletin E1-07

Standard sieve designation (ASTM E 11)		Nominal sieve opening	
		mm	inch
Coarse sieves			
Standard	Alternate		
75	3 in	75	3
63	2 ½ in	63	2.5
50	2 in	50	2
37.5	1 ½ in	37.5	1.5
25	1 in	25	1
19	¾ in	19	0.75
12.5	½ in	12.5	0.5
9.5	3/8 in	9.5	0.375

Maximum size and nominal maximum size (ASTM definitions):-In specifications for aggregates, the smallest sieve opening through which the entire amount of aggregate is required to pass is called the maximum size. The smallest sieve opening through which the entire amount of aggregate is permitted to pass is called the nominal maximum size.

ACI Education Bulletin E1-07 stated that the maximum nominal size of aggregate that can be used is determined by the size and shape of the concrete member and by the clear spacing between reinforcing bars. In general, nominal maximum size should not be more than one-fifth of the narrowest dimension between sides of forms, one-third the depth of slabs, or three-fourths of the minimum clear spacing between reinforcing bars. Use of the largest possible maximum aggregate size consistent with placing requirements is sometimes recommended to minimize the amount of cement required and to minimize drying shrinkage of concrete.

A. Significance of Aggregate Grading

ASTMC 136 described that this test method is used primarily to determine the grading of materials proposed for use as aggregates or being used as aggregates. The results are used to determine compliance of the particle size distribution with applicable specification requirements and to provide necessary data for control of the production of various aggregate products and mixtures containing aggregates. The data may also be useful in developing relationships concerning porosity and packing.

According to ACI Education Bulletin E1-07 There are several reasons for specifying both grading limits and maximum aggregate size. Aggregates having a smooth grading curve and neither a deficiency nor excess of any one particle size generally produce mixtures with fewer voids between particles. Because cement costs more than aggregate and the cement paste requirement for concrete increases with increasing void content of the combined aggregates, it is desirable to keep the void content as low as possible. If there is not enough fine aggregate to fill the voids between coarse aggregate particles, the space must be filled with cement paste. Such under-sanded mixtures also tend to be harsh and difficult to finish. On the other hand, aggregate combinations with excessive amounts of fine aggregate or excessively fine sands may produce uneconomical concretes because of the larger surface area of finer particles, which requires additional cement.

Aggregate grading is an important element in concrete mixing and the resultant compression strength. An experiment was conducted to determine the effect of aggregate size on the compressive strength of concrete. The experiment had three treatments, which were the aggregate sizes (9.5 mm, 13.2 mm and 19.0 mm) and the control. A constant mix of 1:2:4 with a water/cement ratio of 0.5 was used throughout the experiment. Tests that were conducted included the slump and compressive strength tests. Fresh concrete batches were formulated from each of the coarse aggregate sizes and the slump test was conducted to test for workability. Three cubes (150 mm × 150 mm) were cast from each batch and the compressive strength was determined using a concrete load testing machine after 7 days curing. The results reflected that workability (slump) increased with increasing aggregate size. The concrete made from the 9.5 mm, 13.2 mm and 19.0 mm aggregate sizes had workability (slumps) of 10 mm, 13.5 mm and 20 mm, respectively. The mean compressive strength for the 9.5 mm, 13.2 mm, and 19 mm were 15.34 N/mm^2, 18.61 N/mm^2 and 19.48 N/mm^2, respectively. The 9.5 mm and 19.0 mm aggregates had compressive strengths that were significantly different ($P<0.05$; 0.034), while the 13.2 mm and 19.0 mm aggregate sizes had compressive strengths that were not significantly different ($P>0.05$; 0.585). It was concluded that concrete workability (slump) was directly proportional to aggregate size. The mean concrete compressive strength increased with increasing aggregates size (Vilane & Sabelo , 2016).

B. Types of Grade of Aggregates

1. Uniform Graded Aggregate

It refers to a gradation that contains most of the particles in a very narrow size range. In essence, all the particles are the same size. The curve is steep and only occupies the narrow size range specified.

2. **Open Graded Aggregate**

It refers to a gradation that contains only a small percentage of aggregate particles in the small range. This results in more air voids because there are not enough small particles to fill in the voids between the larger particles. The curve is near vertical in the mid-size range and flat and near-zero in the small-size range.

3. Gap Graded Aggregate

It refers to a gradation that contains only a small percentage of aggregate particles in the mid-size range. The curve is flat in the mid-size range. Some PCC mix designs use gap graded aggregate to provide a more economical mix since less sand can be used for a given workability.

- ✓ Missing middle sizes
- ✓ No grain-to-grain contact
- ✓ Moderate void content
- ✓ Moderate permeability
- ✓ Low stability
- ✓ Easy to compact

4. Dense Graded Aggregate

A dense gradation refers to a sample that is approximately of equal amounts of various sizes of aggregate. By having a dense gradation, most of the air voids between the materials are filled with particles. A dense gradation will result in an even curve on the gradation graph.

- ✓ Wide range of sizes
- ✓ Grain-to-grain contact

- ✓ Low void content
- ✓ Low permeability
- ✓ High stability
- ✓ Difficult to compact

C. Grading Curve

The grading of aggregates is represented in the form of a curve or an *S CURVE*. The curve showing the cumulative percentages of the material passing the sieves represented on the ordinate with the sieve openings to the logarithmic scale represented on the abscissa is termed as *Grading Curve.* The grading curve for a particular sample indicates whether the grading of a given sample conforms to that specified, or it is too coarse or too fine, or deficient in a particular size (Pawar et al., 2016).

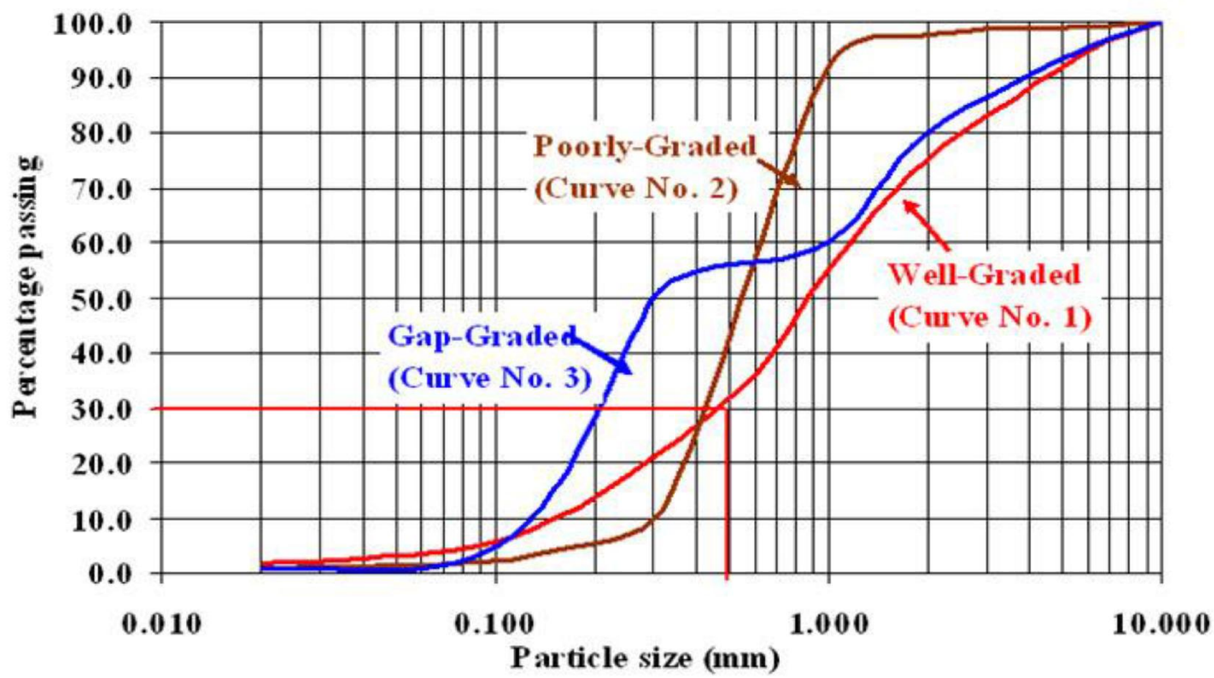


Figure 2.2 Types of Grade of Aggregates (Pawar et al., 2016)

D. Fineness modulus

ASTMC 125-00 defined Fineness modulus, (*n*): a factor obtained by adding the percentages of material in the sample that is coarser than each of the following sieves (cumulative percentages retained), and dividing the sum by 100.

Using the sieve analysis results, a numerical index called the fineness modulus (FM) is often computed. The FM is the sum of the total percentages coarser than each of a specified series of sieves, divided by 100. The specified sieves are 75.0, 37.5, 19.0, and 9.5 mm (3, 1.5, 3/4, and 3/8 in.) and 4.75 mm, 2.36 mm, 1.18 mm, 600 µm, 300 µm, and 150 µm (No. 4, 8, 16, 30, 50, and 100). Note that the lower limit of the specified series of sieves is the 150 µm (No. 100) sieve and that the actual size of the openings in each larger sieve is twice that of the sieve below. The coarse the aggregate, the higher the FM. For fine aggregate used in concrete, the FM generally ranges from 2.3 to 3.1 as called for in ASTM C 33.

ACI Education Bulletin E1-07 stated that Fineness modulus of coarse aggregates represents the average size of the particles in the coarse aggregate by an index number. It is calculated by performing sieve analysis with standard sieves.

The cumulative percentage retained on each sieve is added and divided by 100 gives the value of Fineness modulus aggregate. Higher the aggregate size higher the Fineness modulus hence fineness modulus of coarse aggregate is higher than fine aggregate.

Coarse aggregate means the aggregate which is retained on 4.75mm sieve when it is sieved through 4.75mm. To find fineness modulus of coarse aggregate we need sieve sizes of 80mm, 40mm, 20mm, 10mm, 4.75mm, 2.36mm, 1.18mm, 0.6mm, 0.3mm and 0.15mm. Fineness modulus is the number at which the average size of particle is known when we counted from lower order sieve size to higher order sieve. So, in the calculation of coarse aggregate we need all sizes of sieves.

2.4.2.2 Water Absorption and surface moisture

ACI Education Bulletin E1-07(2007) defined Mixing water and water-cementitious material ratio as: The various moisture states in which an aggregate may exist have been described previously. Two of these-oven-dry and saturated surface-dry-are used as the basis for calculations of specific gravity. Aggregates stockpiled on the job are seldom in either of these states. They usually carry some free or surface moisture that becomes part of the mixing water. Freshly washed coarse aggregates contain free water, but because they dry quickly, they are sometimes in an air-dry state when used, and they absorb some of the mixing water.

At this point, it is necessary to define the terms “mixing water” and “*w*/*c*.” The mixing water in a batch of concrete is all the water present in the concrete, with the exception of absorbed water within aggregate particles. Mixing water is the sum of the masses of free or surface moisture on the fine and coarse aggregate and the mass of water added separately, such as through a water meter or weigh batcher at the plant or through a truck mixer water system or added to the mixer in some other way. Mixing water is the water in freshly mixed sand-cement grout, mortar, or concrete exclusive of any previously absorbed by the aggregate.

The *w/c* is the mass ratio of mixing water to cementitious material. In the paste, this ratio was frequently expressed in gallons of water per sack of cement (usually portland cement). Today, most specifying agencies express required quantities of cementitious material (portland cement or blended cement plus any separately batched supplementary cementitious materials) and water in kg or lb, and *w/c* as a decimal fraction by mass, kg of water divided by kg of cementitious material, or lb of water divided by lb of cementitious material (ACI Education Bulletin E1-07, 2007).

ASTM C 125-00 defined that Absorption, **(***n*) is the process by which a liquid is drawn into and tends to fill permeable pores in a porous solid body; also, the increase in mass of a porous solid body resulting from the penetration of a liquid into its permeable pores.

Absorption: - the increase in the weight of aggregate due to water in the pores of the material, but not including water adhering to the outside surface of the particles, expressed as a percentage of the dry weight. The aggregate is considered "dry" when it has been maintained at a temperature of 110 ± 5°C for sufficient time to remove all uncombined water.

Significance of Water Absorption

According to (ASTMC 127- 88 (Reapproved 1993))

- ✓ Absorption values are used to calculate the change in the weight of an aggregate due to water absorbed in the pore spaces within the constituent particles, compared to the dry condition, when it is deemed that the aggregate has been in contact with water long enough to satisfy most of the absorption potential. and
- ✓ Absorption and specific gravity values are to be used in proportioning concrete mixtures.

2.4.2.3 Specific Gravity

According to ASTM C 125-00 Specific gravity (n) is the ratio of mass of a volume of a material at a stated temperature to the mass of the same volume of distilled water at a stated temperature.

ACI Education Bulletin E1-07 defined and described the specific gravity of an aggregate is the mass of the aggregate in air divided by the mass of an equal volume of water. An aggregate with a specific gravity of 2.50 would thus be two and one-half times as heavy as water. Each aggregate particle is made up of solid matter and voids that may or may not contain water. Because the aggregate mass varies with its moisture content, specific gravity is determined at fixed moisture content. Four moisture conditions are defined for aggregates depending on the amount of water held in the pores or on the surface of the particles.

1. Damp or wet: Aggregate in which the pores connected to the surface are filled with water and with free water also on the surface.
2. Saturated surface-dry: Aggregate in which the pores connected to the surface are filled with water but with no free water on the surface.
3. Air-dry: Aggregate that has a dry surface but contains some water in the pores.
4. Oven-dry: Aggregate that contains no water in the pores or on the surface.

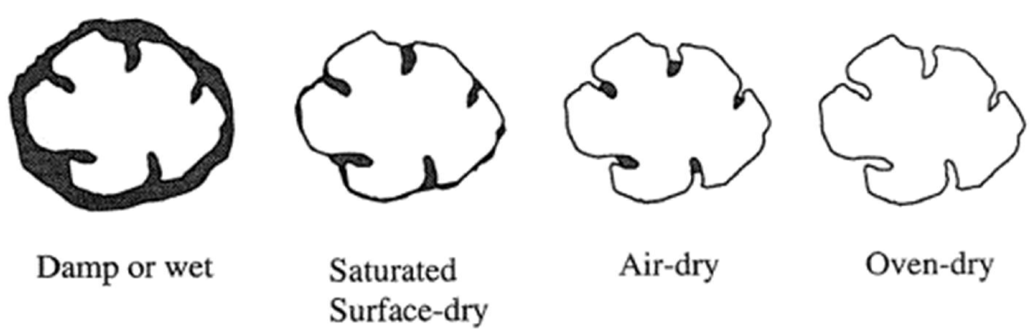


Figure 2.3 Specific gravity of aggregate

Significance of specific gravity: - The specific gravity of an aggregate is used in mixture proportioning calculations to find the absolute volume that a given mass of material will occupy in the mixture. Absolute volume of an aggregate refers to the space occupied by the aggregate particles alone; that is, the volume of solid matter and internal aggregate pores, excluding the voids between particles (ACI Education Bulletin E1-07, 2007).

Bulk specific gravity: - is the characteristic generally used for calculation of the volume occupied by the aggregate in various mixtures containing aggregate including Portland cement concrete, bituminous concrete and other mixtures that are proportioned or analyzed on an absolute volume basis. Bulk specific gravity is also used in the computation of voids in aggregate in test method of ASTM C 29 and the determination of moisture in aggregate by displacement in water in test method ASTM C 70. Bulk specific gravity determined on the saturated surface-dry basis is used if the aggregate is wet, that is, if its absorption has been satisfied. Conversely, the bulk specific gravity determined on the oven-dry basis is used for computations when the aggregate is dry or assumed to be dry.

Apparent specific gravity: - pertains to the relative density of the solid material making up the constituent particles not including the pore space within the particles that is accessible to water. This value is not widely used in construction aggregate technology.

2.4.2.4 Unit weight /Bulk Density

According to ASTM C 125 Unit weight, (*n*):- *of aggregate*, mass per unit volume. (Deprecated term-use preferred term bulk density).

The bulk density (previously "unit weight" or sometimes "dry-rodded unit weight") of an aggregate is the mass of the aggregate divided by the volume of particles and the voids between particles.

Factors affecting bulk density

Bulk density depends on the moisture content of the aggregate. For coarse aggregate, increasing moisture content increases the bulk density; for fine aggregate, however, increasing moisture content beyond the saturated surface-dry condition can decrease the bulk density. This is because thin films of water on the sand particles cause them to stick together so that they are not as easily compacted. The resulting increase in volume decreases the bulk density. This phenomenon, called "bulking," is of little importance if the aggregates for a concrete mixture are batched by mass, but must be taken into account if volumetric batching is used and moisture content varies. Other properties that affect the bulk density of an aggregate include grading, specific gravity, surface texture, shape, and angularity of particles.

Aggregates having neither a deficiency nor an excess of any one size usually have a higher bulk density than those with a preponderance (excess) of one particle size. Higher specific gravity of the particles results in higher bulk density for a particular grading, and smooth rounded aggregates generally have a higher bulk density than rough angular particles of the same mineralogical composition and grading. The rodded bulk density of aggregates used for normal weight concrete generally ranges from 1200 to 1760 kg/m3 (75 to 110 lb/ft^3).

Significance and Use

- This test method is often used to determine bulk density values that are necessary for use for many methods of selecting proportions for concrete mixtures.
- The bulk density also may be used for determining mass/volume relationships for conversions in purchase agreements. However, the relationship between degree of compaction of aggregates in a hauling unit or stockpile and that achieved in this test method is unknown. Further, aggregates in hauling units and stockpiles usually contain absorbed and surface moisture (the latter affecting bulking), while this test method determines the bulk density on a dry basis.
- A procedure is included for computing the percentage of voids between the aggregate particles based on the bulk density determined by this test method.

2.4.2.5 Silt Content

Silt consists of small particles or grains of soil and minerals that are easily carried and deposited by water. Each particle is smaller than a grain of sand but larger than a clay particle. When heavy rains pound the soil some of these fine granular particles are carried by the runoff water as silt. Silt carried by water runoff is deposited in lowlands, rivers or ponds as sediment (Bashir & Science, 2018). Also, studied that the Effect of silt fines on the durability properties of concrete according to the study Silt fines are fine aggregate particles smaller than the 75 μm (No. 2 00) sieve. The compressive strength, however, when silt fine content is small than 5%, increases only 1 MPa. But decreases from 3 MPa to 5 MPa when the silt content increases from 7% to 9%. Test results indicate a decrease in durability when the ratio of silt content to fine aggregate exceeds 5%. These results could serve as a reference in concrete production as well as quality control of fine aggregate containing a large amount of silt fines (Bashir & Science, 2018).

2.4.2.6 Bulking of Sand

The (Koirala & Joshi, 2017) studied that bulking process of sand is explained by moisture hulls or films which surround the sand particles. The contact moisture films, absorbed to the sand particles by moisture surface tension forces tend to cause the sand particles to occupy a large volume as compared to their dry state. When bulking of sand occurs, increases volume as the particle size of sand decreases. If further added moisture or water to the sand, reaches maximum increases its volume in a point in which inundation takes place because surface tension forces are neutralized and most of bulking vanishes. As a consequence the sand particles are rearranged into denser firm.

Sand particles are very small in size (0.075-4.75mm diameter) and hence of very light weight per single particles. As a result, they are easily held a part by free moisture on their surfaces and lose inter granular physical contact. This in turn results in an apparent increase in the volume of sand because the free moisture occupies some portion of the sand volume. The ease with which surface moisture pushes particles apart depends, largely, on how fine the sand particles are finer particles are more easily pushed apart than the coarser ones by surface moisture.

The apparent increase in volume of sand due to surface moisture is technically known as bulking of sand. Bulking of sand has to be determined in the laboratory or on site to calculate the correct volume of sand at hand (Dinku, 2002).

Table 2.6 Ranges in physical properties for normal weight aggregates used in concrete (ACI Education Bulletin E1-07, 2007)

Property	Typical ranges
Fineness modulus of fine aggregate	2.0 to 3.3
Nominal maximum size of coarse aggregate	9.5 to 37.5 mm
Absorption	0.5 to 4%

Bulk specific gravity (relative density)		2.30 to 2.90
Dry-rodded bulk density* of coarse aggregate		1280 to 1920 kg/m3
Surface moisture content	Coarse aggregate	0 to 2%
	Fine aggregate	0 to 10%

2.5 Mixture Proportion

Most of the reported works on geopolymer material to date were related to the properties of geopolymer paste or mortar, measured by using small size specimens. In addition, the complete details of the mixture compositions of the geopolymer paste were not reported.

(Palomo et al., 1999) studied the geopolymerisation of low-calcium ASTM Class F fly ash (molar Si/Al=1.81) using four different solutions with the solution-to-fly ash ratio by mass of 0.25 to 0.30. The molar SiO2/K2O or SiO2/Na2O of the solutions was in the range of 0.63 to 1.23. The specimens were 10x10x60 mm in size. The best compressive strength obtained was more than 60 MPa for mixtures that used a combination of sodium hydroxide and sodium silicate solution, after curing the specimens for 24 hours at 65^{o}C. (Xu and van Deventer, 2000) reported that the Proportion of alkaline solution to alumino-silicate powder by mass should be approximately 0.33 to allow the geopolymer reactions to occur. Alkaline solutions formed a thick gel instantaneously upon mixing with the alumino-silicate powder.

The specimen size in their study was 20x20x20 mm, and the maximum compressive strength achieved was 19 MPa after 72 hours of curing at 35^{o}C with stibnite as the source material. On the other hand, (van Jaarsveld, et al., 1998) reported the use of the mass ratio of the solution to the powder of about 0.39. In their work, 57% fly ash was mixed with 15% kaolin or calcined kaolin. The alkaline liquid comprised 3.5% sodium silicate, 20% water and 4% sodium or potassium hydroxide. In this case, they used specimen size of 50x50x50 mm. The maximum compressive strength obtained was 75MPa when fly ash and builders' waste were used as the source material.

As there are no code provisions for the mix design of geopolymer concrete, the density of geopolymer concrete is assumed as 2400 Kg/m^3. The rest of the calculations are done by considering the density of concrete. The total volume occupied by fine and coarse aggregate is adopted as 77%. The alkaline liquid to fly ash ratio is kept between 0.40 and 0.55. The ratio of sodium hydroxide to sodium silicate is kept as 2.5.The conventional method used in the making of normal concrete is adopted to prepare geopolymer concrete (Krishna & Prasad, 2017).

2.6 Mixing, Casting and Curing

It was found that the fresh fly ash-based geopolymer concrete was dark in colour (due to the dark colour of the fly ash), and was cohesive. The amount of water in the mixture played an important role on the behaviour of fresh concrete. When the mixing time was long, mixtures with high water content bleed and segregation of aggregates and the paste occurred. This phenomenon was usually followed by low compressive strength of hardened concrete. Davidovits (2002) suggested that it is preferable to mix the sodium silicate solution and the sodium hydroxide solution together at least one day before adding the liquid to the solid constituents. He also suggested that the sodium silicate solution obtained from the market usually is in the form of a dimer or a trimer, instead of a monomer, and mixing it together with the sodium hydroxide solution assists the polymerization process. When this suggestion was followed, it was found that the occurrence of bleeding and segregation ceased.

The (Hardjito & Rangan , 2005) studied that the effects of water content in the mixture and the mixing time were identified as test parameters. From the preliminary work, it was decided to observe the following standard process of mixing in all further studies.

- ✓ Mix sodium hydroxide solution and sodium silicate solution together at least one day prior to adding the liquid to the dry materials.
- ✓ Mix all dry materials in the pan mixer for about three minutes. Add the liquid component of the mixture at the end of dry mixing, and continue the wet
- ✓ Mixing for another four minutes.

In the geopolymerisation process of geopolymer concrete, water is given out during the chemical reaction and this water tends to vaporize as the specimens were subjected to heat during the curing process (Hardjito & Rangan , 2005).

(Rovnanik, 2010) studied that curing temperature has an important influence on hardening and geopolymerisation of rock-based geopolymer. At an ambience and higher temperature the specimen virtually set in the first 4 hours. On the contrary, the setting was further postponed for a period of 4 days when the mixture was handled at temperature of at most 10 °C, but this does not affect the grade and properties of solidified geopolymer product at the age of 28 days. Accelerated strength formation was observed on rock based geopolymer cured at 40 to 80°C. It is worth mentioning that the influence of temperature is relied on duration of curing. Curing for a shorter period in oven did not yield to significant changes in strength development, but extended curing process to at least 20 hours was the caused for a noticeable rapid rate of reaction rate and resulted in early strength gained. However, elevated temperature especially at the initial stage leads to the growth of larger pores in the specimen which eventually influenced the mechanical strength

(Yewale et al., 2016) studied that Concrete specimens are cured by four different methods by using oven, steam, water and room temperature curing respectively. In oven curing, the temperature of curing was varied at an interval of 20°C starting from 40°C up to 140°C for 24 hours inside oven and tested after a rest period of 7 and 28 days after demolding. While for steam curing the cubes were placed in a steam at 60° to 110°C for 18 hours at the same rest period. Similarly the specimens were cured in water as per conventional method and room temperature.

Experimental findings (Nurruddin et al., 2018) revealed that condition of curing has a good influence on the mechanical properties of geopolymer concrete. Conventionally, ambient temperature curing of geopolymer concrete results in low strength development at an early age, while higher temperature curing results in significant strength improvement. Similarly, extended curing time enhanced the geopolymerisation mechanism and achieved greater strength. However, longer duration of curing at an elevated temperature results in failure of the samples. The (Vairavan & Dharmar , 2017) Studied that heat curing is not suitable during construction and also uneconomical. To overcome these difficulties, we prefer the daylight curing. The results compared cement concrete and geopolymer concrete under daylight curing.

Figure 2.4 Geopolymer concrete Vs OPC concrete (Akbari et al., 2015) and Ambient curing of Geopolymer (Vinodhini et al., 2015)

2.7 Concrete Properties

2.7.1 Workability

According to engineering bulletin 001 workability is the ease of placing, consolidating and finishing freshly mixed concrete and the degree to which it resist segregation. Concrete should be workable but the ingredients should not separate during transport and handling. The degree of workability required for proper placement of concrete is controlled by the placement method, types of consolidation and types of concrete.

Workability can be assessed using numerous test methods, among which the slump test, compaction factor test and flow table test are widely used. In this study the slump test was used to assess the workability of the concrete mixes and the mixes were designed to result in low to medium workability levels were tested. When mixing was completed the workability of each mix was measured using slump test. A sample of freshly mixed concrete is placed and compacted by rodding in a mold shaped as the frustum of a cone. The mold is raised and the concrete allowed to subside, the distance between the original and displaced position of the center of the top surface of the concrete is measured and reported of as the slump of the concrete. Therefore the mixed concrete was checked for workability by filling the standard slump cone with three layers by rodding each layer with 25 times according to ASTM C 143-98. Standard Test Method for Slump of Hydraulic-Cement Concrete was used for geopolymer concrete.

Slump measurement was taken immediately after mixing each batch of concrete before casting them into specimen moulds. The moulds were coated with oil just before concrete casting. The concrete were cast in three layers into the moulds and each layer was tamped 25 times with 16mm diameter rod to removed entrapped airs present in the concrete. Excess concrete were cut away and the surface levelled with the trowel (Yalley & Sam, 2018).

Water-to-geopolymer binder ratio is the ratio of the total quantity of water (quantity of water present in solution and extra water added in the mix) to the geopolymer binder (quantities of fly ash, sodium silicate and sodium hydroxide solutions). It is observed that the flow increases with increase in water-to-geopolymer binder ratio by maintaining other parameters constant. At water to geopolymer binder ratio of 0.40, the mix was flow just like self-compacting concrete but after few minutes the slurry part separated out from rest of the mix due to presence of excess amount of water. Just after lifting the mould, all the concrete subside rapidly but spread for long time. One more thing was pointed out, is that the spread diameter of geopolymer concrete mix after jolting is similar to that of mix without jolting just after few minutes. At water-to-geopolymer binder ratio of 0.35 and 0.30, the mix was cohesive and viscous but flow slowly for long time. Before jolting, the geopolymer concrete mix was spread just like a self-compacting concrete but slurry part did not separated out and it takes more time than binder ratio of 0.40. At water-to-geopolymer binder ratio of 0.25, the mix was very viscous and takes more time for mixing. At water-to geopolymer binder ratio of 0.20, the mix was dry, and during mixing, fly ash stick to the surface of aggregate and form large size particles which separated out from each other so difficult to compact (Patankar et al., 2013).

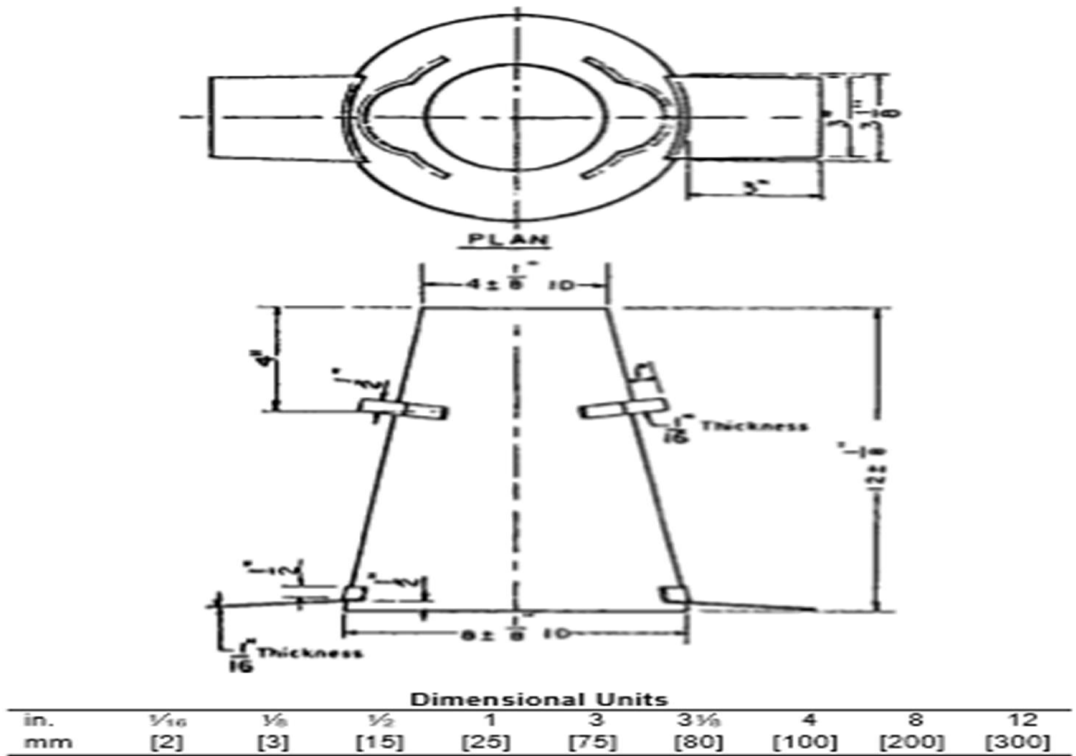


Figure 2.5 Standard Test Method for Slump of Concrete ASTM C 143-98

2.7.2 Density (unit weight)

Mass per unit volume (preferred over deprecated term (unit weight). The density of concrete primarily depends on the unit mass of aggregates used in the mixture. Because the type of aggregates in all the mixtures did not vary, the density of the low-calcium fly ash-based geopolymer concrete varied only marginally between 2330 to 2430 kg per m^3 (Hardjito & Rangan , 2005).

2.7.3 Compressive Strength

Engineering bulletin 001 stated that compressive strength defined as the maximum resistance of a concrete specimen to axial loading. It is generally expressed in Mega Pascal's (MPa) or pound per square inch (Psi) at age of 28 days, other test ages are also used; however, it's important to realize the relationship between the 28-day strength and other test ages. Seven-day strength is often estimated to be about 75% of the 28-day

strength and 56-day and 90-days strength is about 10% to 15% greater than 28-days strengths.
According to (kumar & Hanitha, 2016) compressive strength of a material is that value of uni-axial compressive stress reached when the material fails completely. The cubes are then tested between the loading surfaces of the compressive testing machine of capacity 2000KN in such a way that the smooth surface directly receives the load and it is applies until the failure of the load. It is determined by the ratio of failure load to the cross sectional area of the specimen.

According to ASTM C 39-99 compressive strength test method consists of applying a compressive axial load to molded cylinders or cores at a rate which is within a prescribed range until failure occurs. The compressive strength of the specimen is calculated by dividing the maximum load attained during the test by the cross sectional area of the specimen.

In addition to that Care must be exercised in the interpretation of the significance of compressive strength determinations by this test method according to ASTM C 39-99 since strength is not a fundamental or intrinsic property of concrete made from given materials. Values obtained will depend on the size and shape of the specimen, batching, mixing procedures, the methods of sampling, molding, and fabrication and the age, temperature, and moisture conditions during curing.
(Parthiban & Saravana, 2014) studied that an experimental investigation has been made to study the variation in the Compressive Strength Geopolymer concrete by varying the concentration of Sodium hydroxide as 10, 12, 14M and the ratio of alkaline solution (SiO_3^{2-} / OH^-) as 1.0, 1.5, 2.0. The compressive strength of the mixes was determined for their 3, 7, 14 and 28 days curing for studying there variation at different age of curing. The test results show that the compressive strength of the Geopolymer mixes increases with the increase in the NaOH concentration and alkaline ratio and geopolymer concrete properties significantly affected by curing approaches which are represented in curing time and temperature (Aliabdo et al., 2016).

(Nath & Sarker, 2017) stated that Geopolymer concretes were produced using low calcium fly ash with a small percentage of additive such as ground granulated blast furnace slag (GGBFS), ordinary Portland cement (OPC) or hydrated lime to enhance early age properties of geopolymer concrete since geopolymer concrete had low compressive strength at early age when cured at ambient temperature or sunlight curing.

According to (Al Bakri et al., 2011) Fly ash-based geopolymer is better than normal concrete in many aspects such as compressive strength, exposure to aggressive environment and exposure to high temperature.

Figure 2.6 Compressive strength test cubic specimen (kumar & Hanitha, 2016)

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Research Method and Design

The research work were conducted begins with literature review assessment about Geopolymer concrete and characteristics of low calcium fly ash. For investigation of the study, the objectives and problems were stated and reviewed. The method to solve the problems requires searching different journals related with the title and laboratory investigation. Data collection methods such as experiments and archival records are examined and used. Both primary data (collected personally) and secondary data from different journals were collected and used for analysis. Primary data were collected at controlled environments through testing in laboratories using electro mechanical equipment.

The research design was based on an experimental sampling process in which a sample of low calcium fly ash were collected and totally substituted cement with alkaline solution to made binder. The research was conducted by using experimental laboratory test method. Therefore, the methodology used in the research was a laboratory analysis of specimen, and analysis of the test results. The research work were include organizing a literature review of different previous published researches by reviewing different journals; studying physical and chemical properties of low calcium fly ash and geopolymer concrete made by using it and alkaline solution, studying chemical and physical properties of the ingredients as well as the mixed properties of geopolymer concrete at its fresh and dried stages.

The collected data were analysed qualitative and quantitative by detail investigation using the following procedures:

i. low calcium fly ashes exhausted to the environment were collected from an industry that uses coal as their source of energy.
ii. Delivery sand and naturally inert granular aggregate that used for test.
iii. The low calcium fly ash, sand and coarse aggregates were weighed and dry mixed together according to the mix proportion.

iv. The sodium silicate solution and sodium hydroxide solution with ratio of 0.5 and 1.5 (Na_2SO_3/NaOH = 0.5 and Na_2SO_3/NaOH = 1.5) with concentration of sodium hydroxide 10M, ,13M and 16M will be mixed at least twenty four hours before use.

v. Prepare three set of test samples for each mix proportion, for each trials record its change on the properties of concrete at both fresh and hardened state. (I.e. examine the effect of fly ash on workability and compressive strength of concrete.

vi. Make discussion based on the test results under varying sodium silicate solution and sodium hydroxide solution proportion and sodium hydroxide concentration.

vii. Finally prepare conclusion and recommendation depending on test results. Low calcium fly ashes used for the study have collected Ayka Addis Textile, which uses bitumen coal as the source of energy.

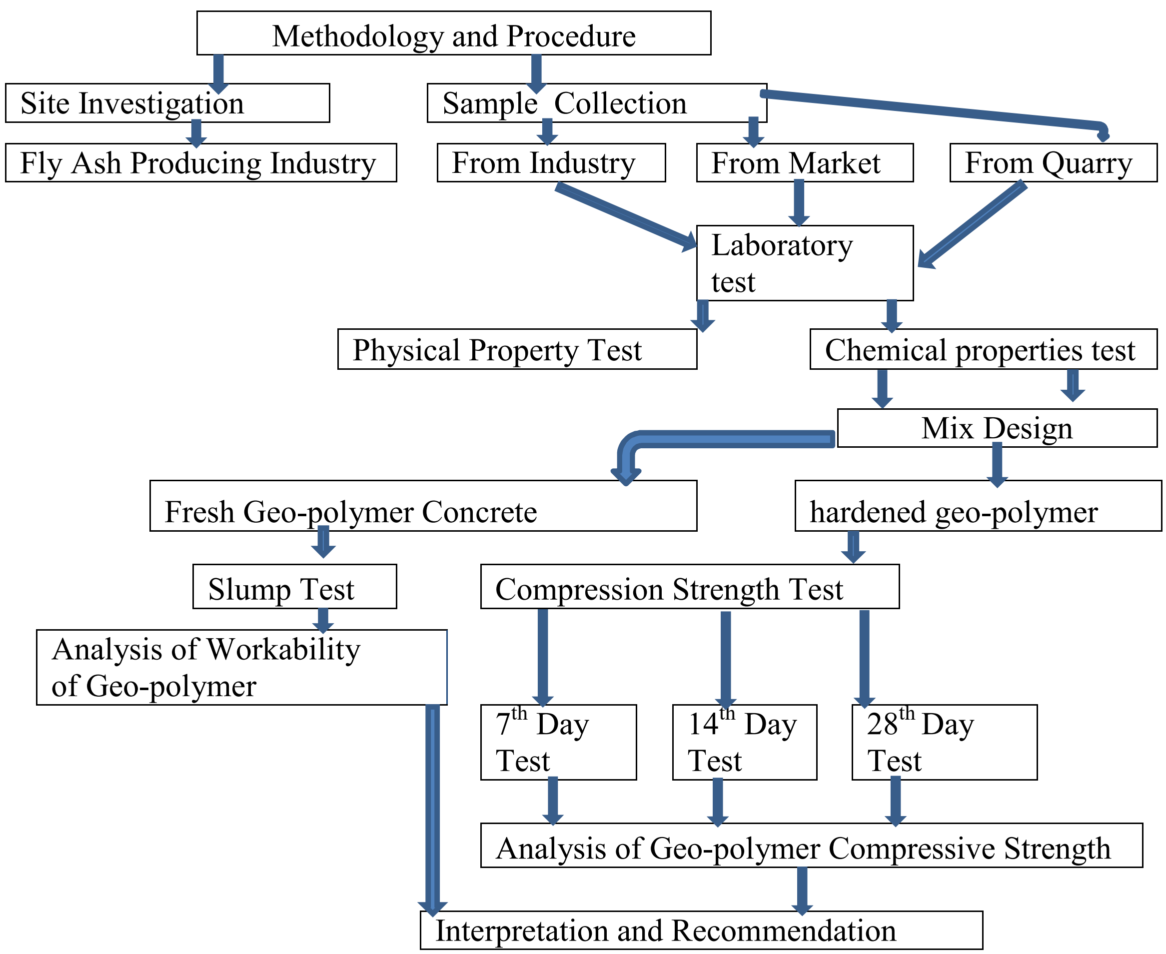


Figure 3.1 Method and procedure of the study

3.2 Data Source and Collection Process

In this study, the two methods of data collection applied were both descriptive and analytical. In descriptive method of data collection method, secondary sources of data from different literatures were collected. Primary data were collected from the test results of the experimental laboratory work.

3.3 Sampling Method

The sampling technique used for this research was according to ASTM standards and the aim or goal of the researcher to be achieved. The samples were collected and taken to Jimma Institute of Technology laboratory for investigation of physical properties and mixed properties of concrete. Also, the chemical properties of fly ash sample were examined in the laboratory of Dangote Cement Factory Enterprise.

3.4 Sample Size

The amount of ingredient, number of specimens and the number of test batches were dependent on ASTM C 192 standards, established practice and the nature of the test program. Guidance was given in the test method or specification for which the specimens were made. For this research three specimens with (150*150*150) mm^3 were molded for each test age and test variables. Test ages often used are 7 and 28 days for compressive strength tests, or 14 and 28 days for flexural strength tests. For this research work the test ages used were 7, 14 and 28 days for compressive strength and Six different geopolymer concrete mixing variables (M-1 (NaOH = 10M $ Na2SO3 /NaOH = 0.5), M-2 (NaOH = 10M $ Na2SO3 /NaOH = 1.5), M-3 (NaOH=13M $ Na2SO3 /NaOH = 0.5), M-4 (NaOH=13M $ Na2SO3 /NaOH = 1.5), M-5 (NaOH = 16M $ Na2SO3 /NaOH = 0.5), M-6 (NaOH = 16M $ Na2SO3 /NaOH = 1.5) and one controlling OPC Concrete. Numbers of layers and method of consolidations were 3 equal layers and rodding method of consolidation respectively.

3.5 Types of Ingredients in Geopolymer Concrete

Cement: **-** The cement used for this investigation was Dangote Ordinary Portland Cement (OPC) which is manufactured in Mugher, Oromia Regional State (control concrete only).

Coarse aggregate: - The coarse aggregate used for this study was basaltic crushed rock obtained from Agaro, Oromia Regional State of Ethiopia which is located at 46.1 Km from Jimma town.

Fine Aggregate: - The fine aggregate used for this investigation obtained from the local source, Worabe, Gurage Zone of the Southern Ethiopia which is located 343 Km from Jimma town were used to prepare the concrete samples.

Fly ash: - The Fly ash used for this investigation collected from Ayka Addis Textile and Investment Group PLC located at Ethiopia, Oromiya, Alemgena

Water: - The Drinkable water (potable water) used for this investigation obtained from JIT water supply.

Alkaline solution: Sodium hydroxide (pellets with 98% purity) and sodium silicate (Na_2O= 14.7%, SiO_2=29.4%, and water 55.9% by mass) activator obtained from Yehambasom trading PLC were used Addis Ababa, Ethiopia.

3.6 Names and types of tests on geopolymer ingredients and geopolymer concrete According to ASTM Standards

- Tests on coarse aggregate sieve analysis or gradation, water absorption, specific gravity, moisture content and unit weight according to ASTM C 136, ASTM C 127, ASTM C 29/ M29-97 and ASTM C 566-97 respectively.
- Tests on fine aggregate sieve analysis or gradation, water absorption, specific gravity, moisture content, unit weight, bulking of sand and Silt/Clay Test of Sand sample according to ASTM C 136, ASTM C 128, ASTM C 29/ M 29-97, ASTM C 566-97 and ASTM C 117 respectively.
- Tests on Fly ash Chemical composition and loss of Ignition according to ASTM C 618-99.

Table 3.1 Names and Types of Tests with standard specification

ASTM C 29/C 29M	Test Method for Unit Weight and Voids in Aggregate
ASTM C 33	Specifications for Concrete Aggregates
ASTM C 70 – 94	Standard test method for surface moisture in fine aggregate
ASTM C 117 – 95	Silt Content
ASTM C 125	Terminologies relating to concrete and concrete aggregates
ASTM C 127	Test method for specific gravity and absorption of coarse aggregate
ASTM C 128	Test Method for Specific Gravity and Absorption of Fine Aggregate
ASTM C 136	Test method for sieve analysis of fine and coarse aggregates
ASTM C 143/C 143M – 98	Standard Test Method for Slump of Hydraulic-Cement Concrete
ASTM C 192/C 192M –	Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory
ASTM C 70	Test Method for Surface Moisture in Fine Aggregate
ASTM C566	Test Method for Total Moisture Content of Aggregate by Engine Aggregate
ASTMD 75	Practices for Sampling Aggregates
ASTMC 566 – 97	Standard Test Method for Total Evaporable Moisture of Aggregate by Drying
ASTM C 618 – 99	Standard Specifications for Coal Fly Ash and Raw or Natural Pozzolan for Use as a Mineral Admixture in

3.7 Preparation of materials, properties o materials and Experimental Procedure

3.7.1 Preparation of materials

4 ***Temperature***: Before mixing the concrete, the concrete materials were brought to room temperature in the range of 68 to 86°F [20 to 30°C]. If a concrete temperature is specified, condition the materials to the temperature needed to obtain the specified concrete temperature.

5 ***Cement***: the cement Stored in a dry place, in moisture proof containers. The cement was thoroughly mixed to provide a uniform supply throughout the tests. It was passed through 850-µm [No. 20] or finer sieve to remove all lumps, remixed on a plastic sheet, and returned to sample containers.

6 **Fly Ash:** According to ASTM C 618-00 requirement the fly ash used in this research work were low calcium Fly ash with the summation of $SiO_2 + Al_2O_3 + Fe_2O_3 > 70$, $CaO < 10$, $SO_3 \leq 5$ and loss of ignition ≤ 6.

7 ***Aggregates***: granular material, such as sand, gravel, crushed stone, or iron blast-furnace slag, used with a cementing medium to form hydraulic-cement concrete or mortar or Geopolymer concrete. Physical properties of both coarse and fine aggregate were determined based on the procedure and steps on the ASTM standard.

8 **Alkaline solution:** Sodium hydroxide (pellets with 98% purity) and sodium silicate (Na_2O = 14.7%, SiO_2 = 29.4%, and water 55.9% by mass) activator were used.

3.7.2 Properties Materials

3.7.2.1 Chemical Properties of fly ash

The chemical composition of the fly ash was determined by x-ray fluorescence (XRF) analysis method in DANGOTE cement Ethiopia PLC, quality assurance department.

Figure 3.2 Accumulated fly ash in Ayk Addis Ethiopia

3.7.2.2 Properties of Coarse Aggregate

The size of coarse aggregate used for experimental investigation was a nominal maximum size of 20 mm diameter aggregate in all the concrete mix design to avoid any variations in concrete properties were not due to this material. The aggregate were supplied relatively clean and was dried in air. This aggregate type is commonly used in Ethiopia and particularly in the Jimma town and its surround. In this study the physical properties of coarse aggregate test results were performed according to ASTM standard.

1. Sieve Analysis (Grading)

According to ASTM C 136-96a, a sample of dry aggregate (air dry) of ten kilogram (10kg) mass is separated through a series of sieves of progressively smaller openings for determination of particle size distribution and calculated test result were shown on appendix table A1.1.

The calculation of fine modulus according to ASTM C 136-96a, Calculate the fineness modulus, by adding the total percentages of material in the sample that is coarser than each of the following sieves (cumulative percentages retained), and dividing the sum by 100:the sieve size used in calculation of fine modulus were 150-µm (No. 100), 300-µm (No. 50), 600-µm (No. 30), 1.18-mm (No. 16), 2.36-mm (No. 8), 4.75-mm (No. 4), 9.5-mm (3⁄8-in.), 19.0-mm (3/4-in.) and 37.5-mm (11⁄2-in.).

Figure 3.3 Sieve analysis of coarse aggregate

2. Unit Weight

ASTM C 29/C 29 M - 97 indicate that this test method covers the determination of bulk density ("unit weight") of aggregate in a compacted or loose condition, and calculated voids between particles in fine or coarse aggregates based on the same determination. This test method is applicable to aggregates not exceeding 5 inch [125 mm] in nominal maximum size.

The unit weight tests of the coarse aggregate samples were carried out according to ASTM C 29 and simply measured by filling a container of known volume and weighing it. Then, dividing the aggregate weight by the volume of the container provides the unit weight of the aggregate. This test method is often used to determine bulk density values that are necessary for use for many methods of selecting proportions for concrete mixtures and also may be used for determining mass/volume relationships for conversions in purchase agreements. The test results were shown on appendix table A1.2.

3. Moisture Content

According to ASTM C 566-97, the moisture content of coarse aggregate samples were determined by Oven drying the sample of 2000gm of coarse aggregate for about 24hrs with a temperature of 105 ± 5 °C and cooled sufficiently minimum for 1hour .Then, compute the moisture content by subtracting mass of dried sample from mass of original sample and dividing the weight difference by oven dry weight and multiplying by hundred. The result were computed according the formula on appendix Equation 5A

4. Specific Gravity and Absorption Capacity

According to ASTM C 127-88 (Reapproved 1993**)** A sample of 2kg aggregate was immersed in water for approximately 24hr to essentially fill the pores. It was then removed from the water, the water dried from the surface of the particles, and weighed. Subsequently the sample was Weighed while submerged in water. Finally the sample is oven-dried and weighed a third time. Using the weights thus obtained and formulas in this test method, it is possible to calculate three types of specific gravity and absorption capacity of aggregate. The result were computed according the formula on appendix

Equation 1A, 2A and 3A for bulk, saturated dry surface and apparent specific gravity respectively and water absorption according to equation 4A.

Figure 3.4 Unit weight, moisture content and specific gravity

3.7.2.3 Properties of Fine Aggregates

ASTM C 33-99a defined Fine aggregate shall consist of natural sand, manufactured sand, or a combination thereof. ASTM C 125-00 defined Fine aggregate as aggregate passing the 3⁄8-in. (9.5-mm) sieve and almost entirely passing the 4.75-mm (No.4) sieve and predominantly retained on the 75-μm (No. 200) sieve; or that portion of an aggregate passing the 4.75-mm (No. 4) sieve and retained on the 75-μm (No. 200) sieve).

1. **Sieve Analysis (Grading)**

According to ASTM C 136-96a, The size of 2kg test samples after drying, separated through a series of sieves of progressively smaller openings was used for determination of particle size distribution and fineness modulus of fine aggregate. The results were computed according to the table on appendix table A1.5.

Figure 3. 5 Figure 3.3 Sieve Analyses of Fine Aggregates

2. Unit Weight

ASTM C 29/ C 29M -97 This test method covers the determination of bulk density ("unit weight") of aggregate in a compacted or loose condition, and calculated voids between particles in fine, coarse, or mixed aggregates based on the same procedure. Unit weight was determined simply by filling a fine aggregate a container of $0.01m^3$ of known volume and weighing it. Then, divided the aggregate weight by the volume of the container gives the unit weight of the aggregate. The results were computed according to the table on appendix table A1.6.

3. Moisture Content

ASTM C 566-97 indicate that the moisture content of fine aggregate samples were determined by Oven drying the sample of 500gm of fine aggregate for about 24hrs with a temperature of 105± 5 °C and cooled sufficiently minimum for 1hour. Then, compute the moisture content by subtracting mass of dried sample from mass of original sample and dividing the weight difference by oven dry weight and multiplying by hundred. The results were computed according the formula on appendix Equation 11A.

4. Specific Gravity and Absorption Capacity

ASTM C 128-97 stated that bulk specific gravity is the characteristic generally used for calculation of the volume occupied by the aggregate in various mixtures containing aggregate including Portland cement concrete, bituminous concrete and other mixtures that are proportioned or analyzed on an absolute volume basis.

According to ASTM C 127-88 (Reapproved 1993**)** A sample of 0.5kg fine aggregate is immersed in water for approximately 24hr to essentially fill the pores. It is then removed from the water, the water dried from the surface of the particles, and weighed. Subsequently the sample is weighed while submerged in water. Finally the sample is oven-dried and weighed a third time. Using the weights thus obtained and formulas in this test method, it is possible to calculate three types of specific gravity and absorption. The result were computed according the formula on appendix Equation 7A, 8A and 9A for bulk, saturated dry surface and apparent specific gravity respectively and water absorption according to equation 10A.

5. Silt content

According to ASTM C 117 - 95 Silt content covers determination of the amount of material finer than a 75-µm (No. 200) sieve in aggregate by washing. A sample of the aggregate was washed in a prescribed manner, using plain water. The decanted wash water, containing suspended and dissolved material, is passed through a 75-µm (No. 200) sieve. The loss in mass resulting from the wash treatment was calculated as mass percent of the original sample and was reported as the percentage of material finer than a 75-µm (No. 200) sieve by washing. According to the Ethiopian standard manual it is recommended to wash the sand or reject it if the silt content exceeds a value of 6%. The silt content results were computed according the formula on appendix Equation 6A.

6. Bulking of Sand

According to ES cited in Dinku (2002) the bulking of fine aggregate samples were carried out by taken sand sample in loose condition then filled in a box of measured height after that the box is then flooded with water and rodding was done to make the sand settle and consolidate. The fine aggregate was then leveled in the box and the drop in height was measured. So, the bulking percentages of the fine aggregate samples were simply divided drop height to initial height and multiply by 100. The result was computed according the formula on appendix Equation 12A.

3.7.2.4 Alkaline solution

Sodium hydroxide (pellets with 98% purity) and sodium silicate (Na_2O = 14.7%, SiO_2 = 29.4%, and water 55.9% by mass) activator obtained from Yehambasom trading PLC were used.

Figure 3.6 Preparation of Alkaline Solution

3.7.2.5 Water

Mixing water used for all the mixes in this research was drinkable water (potable water) obtained from JIT water supply.

3.7.3 Experimental Procedure

3.7.3.1 Concrete Mix Designation and Mix Proportion

In this research work, the ACI 211.1-81 Education Bulletin E1-07 (2007) The control concrete mix had a mix proportion of 360 kg/m^3 cement, 182kg/m^3 water, 739kg/m^3 sand and 1071.46kg/m^3 coarse aggregate. The Geopolymer concrete specimens were prepared by total exclusion (elimination) of cement and usage of fly ash with equal weight of cement, keeping the fine and coarse aggregates constant and using alkaline solution.

Workability, compressive strength and unity weight of concrete tests were also conducted for each mixes. For all the concrete mixes, the same W/FA ratios were used.

The quantity of concrete materials was calculated by using the physical properties values of the ingredients, the Standard cast iron molds of size 15x15x15cm are used in the preparation of concrete cubes for compressive strength tests and ACI mix design standards. In this mix the amount of sodium hydroxide were depend on the molarity of its concentration, for 10M (Molarity) = 40*10 = 400g of solid sodium hydroxide, for 13M=13*40 = 520g of solid sodium hydroxide and for 16M = 40*16 = 640g of solid sodium hydroxide, were 40 is the molar mass of sodium hydroxide. The final mix proportions for one cubic meter ($1m^3$) for C-25 the Geopolymer concrete grade are as shown in table below.

Table 3.2 Mix designation and Mix proportion

Mix No.	**Mix- designation**	**Cement (kg/m^3)**	**Fly Ash (kg/m^3**	**Fine Aggre (kg/m^3**	**Coarse Aggre. (kg/m^3)**	**NaOH Soln. (Kg/m^3)**	**NA_2SO_3 Soln. (Kg/m^3)**	**W/C**	**H_2O**
1	M-0 (Control)	360		739	1071.46			0.5	182
2	M-1 (NaOH = 10M)		360	739	1071.46	121.33	60.67	0.5	
3	M-2 (NaOH = 10M)		360	739	1071.46	72.8	109.2	0.5	
4	M-3 (NaOH = 13M)		360	739	1071.46	121.33	60.67	0.5	
5	M-4 (NaOH = 13M)		360	739	1071.46	72.8	109.2	0.5	
6	M-5 (NaOH = 16M)		360	739	1071.46	121.33	60.67	0.5	
7	M-6 (NaOH = 16M)		360	739	1071.46	72.8	109.2	0.5	

3.7.3.2 Mixing of Concrete

ASTM C 192-98 stated that Mix concrete in a suitable mixer in batches of such size as to leave about 10 % excess after molding the test specimens. A machine mixing procedure suitable for drum-type mixers is described. There was no variation in the mixing sequence and procedure from batch to batch since the effect of such variation was not under study. In this research machine mixing types was used.

Machine Mixing: According to ASTM C 192-98, the mixer size, working, clean and dampness was checked. The prior to starting rotation of the mixer the coarse aggregate was added, some of the mixing alkaline solution, and the some extra water, when required. The mixer was started, and then the fine aggregate, fly ash, and alkaline solution were added with the mixer running. Mix the concrete, after all ingredients were in the mixer, for 3 min followed by a 3-min rest, followed by a 2-min final mixing. Take precautions was taken to compensate for mortar retained by the mixer so that the discharged batch, as used, was correctly proportioned. To eliminate segregation, deposit machine-mixed concrete in the clean, damp mixing pan and remix by shovel or trowel until it appears to be uniform**.**

3.7.3.3 Workability of Geopolymer Concrete Tests

ASTM C 143/C 143M -98 indicated that workability of a sample of freshly mixed concrete determined by, sample of freshly mixed concrete was placed and compacted by rodding of three equal layers in a mold shaped as the frustum of a cone and padding the cone by rod 25 times then the mold was raised, and the concrete allowed subsided. The vertical distance between the original and displaced position of the center of the top surface of the concrete is measured and reported as the slump of the concrete. Standard test method for Slump of Hydraulic-Cement Concrete used was used Geopolymer concrete.

Figure 3.7 Sump Tests of Geo-polymer Concrete

3.7.3.4 Mould preparation, Casting and Curing of Geopolymer concrete

ASTM C 192/C 192M-98 stated that, Molds for specimens or fastenings there to in contact with the concrete shall be made of steel, cast iron, or other nonabsorbent material, nonreactive with concrete containing Portland or other hydraulic cements. Molds shall conform to the dimensions and tolerances specified in the method for which the specimens are required. Molds shall hold their dimensions and shape under all conditions of use.

Molded specimens as near as practicable to the place where they were stored during the first 24 hours. Molds placed on a rigid surface free from vibration and other disturbances. Jarring, striking, tilting, or scarring of the surface of the specimens avoided when moving the specimens to the storage place.

The concrete placed in the molds using a scoop, blunted trowel, or shovel. Each scoopful, trowel full or shovelful of concrete from the mixing pan was selected to ensure that it was representative of the batch. Concrete was remixed in the mixing pan with a shovel or trowel to prevent segregation during the molding of specimens. Around the top edge of the mold the scoop or trowel was moved. So, the concrete is discharged in order to ensure a symmetrical distribution of the concrete and minimized segregation of coarse aggregate within the mold. Further the concrete was distributed by use of a tamping rod prior to the start of consolidation. In placing the final layer the operator attempted to add an amount of concrete that was exactly fill the mold after compaction.

Curing temperature has an important influence on hardening and geopolymerisation of fly ash based geopolymer concrete. Ambient temperature (sunlight) curing method was used for geopolymer concrete and water curing for control ordinary Portland cement

Figure 3.8 Mould preparation, Casting and Curing of Geo-polymer concrete

3.7.3.5 Compressive Strength Testing of the Geopolymer concrete

ASTM C 39/C 39M-99 Indicate that this test method consists of applying a compressive axial load to molded cylinders or cores at a rate which is within a prescribed range until failure occurs. The compressive strength of the specimen was calculated by dividing the maximum load attained during the test by the cross-sectional area of the specimen. The load applied continuously and without shock. The load applied until the specimen fails, and the maximum load carried by the specimen during the test was recorded and express the result to the nearest 10 psi [0.1 MPa].

Figure 3.9 Cube Weighting, Compressive Strength Test and Reading

3.8 Data Analysis Techniques and Procedure

The quantity of fly ash, aggregates (fine and coarse) and Alkaline solutions needed for laboratory test were depends on the types of test requirement and test standards. For each tests weighting method were used for ratio proportioning.

Engineering properties of fresh and hardened state of geopolymer concrete (workability, density and compressive strength) were performed in laboratory tests. In processing all the design and analysis, literature review of the research and data gathered from laboratory test were evaluate to came up with the research output. The output of each laboratory tests were analysed with ASTM standard. Finally present the results of analysis according to the research objectives.

The output of the study was to compare the strength (compressive) and workability of the produced geopolymer concrete at different proportion and concentration of alkaline solution and that of conventional concrete. For this study the researcher had 7, 14 & 28 days testing age, six studying variables and one control as well as three numbers of trial test with total of sixty three (63) samples were needed for all proportioning. The analyzed data then were presented using charts, figures and tables.

3.9 Study Variables

There were two variables of the study, as listed below dependent variables and Independent variables.

3.9.1 Dependent Variables

The dependent variable of the study was response variable or output of the character that was change because of variations in the independent Variables.

The dependent variables of this study are:-

- Geopolymer Concrete properties

This was considering as dependent because its value depends upon the value of the independent variables. Hence, workability, density and compressive strength of geopolymer concrete were a factor which were observed and measured depending on the effects of independent variables

3.9.2 Independent Variables

Independent variables cause change on dependent variables. In this study factors that affects production of Geopolymer concrete such as:

- ratio of Sodium silicate to Sodium hydroxide
- concentration(molarity) of Sodium hydroxide
- workability
- density
- compressive strength

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Chemical Composition of Fly Ash

Table 4.1 Chemical composition of Fly ash as tested in the laboratory of Dangote Cement Factory

Oxide types	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI
Percentage Composition	48.23	35.49	4.47	3.38	0.72	0 .17	3.97
ASTMC618-00 Requirement	If, $SiO_2 + Al_2O_3 + Fe_2O_3$ > 70 class "F", unless class "C"			If <10 class "F", Unless class "C"		Max 5.0	Max 6.0
Test Result	88.19			3.38	0.72	0.17	3.97

The chemical composition in table 4.1 indicated that the fly ash can be classified as a class F type Pozzolanic fly ash as per ASTM C 618-00 classification since it fulfilled the criteria to be classified as it. Such as the sum of SiO_2, Al_2O_3 and Fe_2O_3 content was greater than 70%, which was 88.19. the sulfur trioxide (SO_3) value was found to be 0.17% which was lower than that specified by ASTM C 618-00 maximum of 5, CaO is less than 10 which is 3.38 and The loss on ignition (LOI) value was found to be 3.97% which was less than the value specified by the standard as a maximum point of 6%. Fly ash used in this research work fulfilled the requirements of ASTM C 618 as pollozan or class F fly ash or low calcium fly ash. The use of Class F pozzolan containing up to 12.0 % loss on ignition may be approved by the user if either acceptable performance records or laboratory test results are made available.

Note: The LOI is measurement of the carbon content or unburned coal in the fly ash.

4.2 Physical Property of Aggregate

4.2.1 Coarse Aggregate

1. Gradation of Coarse Aggregate

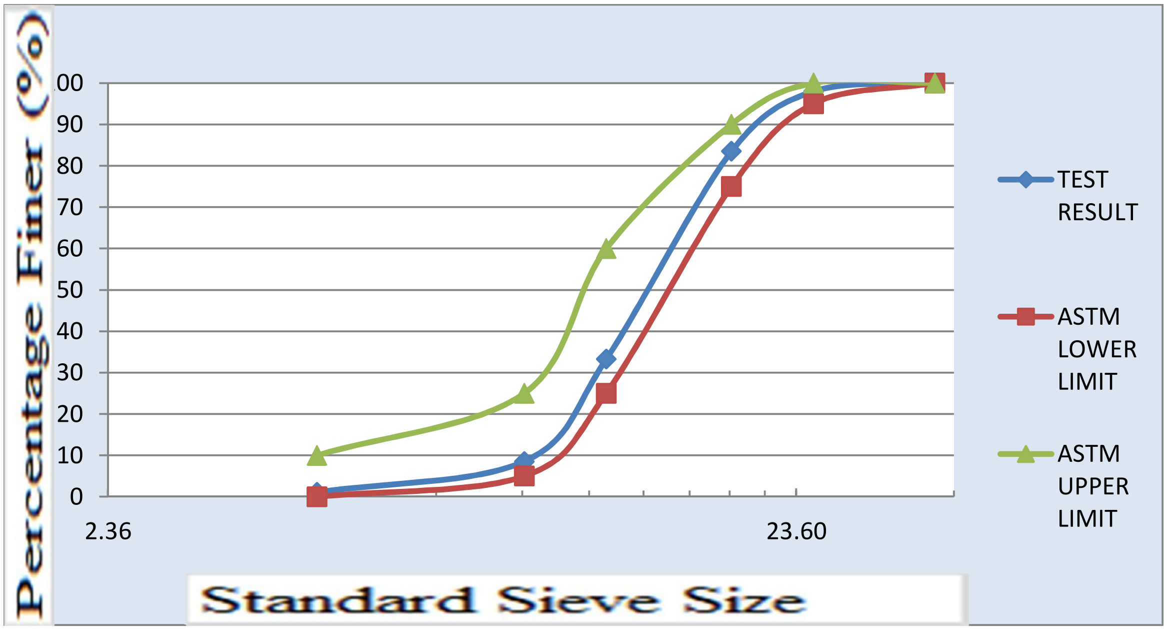


Figure 4.1 Sieve Analysis Result of Coarse Aggregate

Table 4.2 Summary of Test Result for Crushed Stone (Coarse Aggregate)

Material Type	Types of Test		Test Result
Coarse Aggregate	Unit Weight	Loose unit weight	1398.73 kg/m^3
		Compacted unit weight	1623.65 kg/m^3
	Bulk specific gravity	Oven-dry	2.75
		Saturated Surface dry	2.78
		Apparent	2.86
	Water Absorption Capacity		1.6 %
	Moisture Content		0.77 %
	Size of Aggregate	Max. Size	25 mm
		Nominal Max. Size	20 mm
	Fineness Modules		7.09

The summary of physical property test result on table 4.2 indicated that the coarse aggregate used for concrete making on study fulfilled ASTM requirement such as ASTMC 29, ASTMC 127, ASTMC 136 and ASTMC 33. All calculation and formulas used to found the result on table 4.2 were from ASTM standards. From the table the aggregate were well graded between upper and lower ASTM limit, (saturated surface dry) SSD of 2.78, Water absorption capacity of 1.6%, moisture content of 0.77%, maximum size of aggregate of 25mm, nominal maximum size of 20mm and with fineness modulus of 7.09 which indicated that the average size of particle of given coarse aggregate samples were in between 7th and 8th sieves, that is between 10mm to 20mm sieve size.

4.2.2 Fine Aggregate

Table 4.3 Sieve analysis result of fine aggregate

Sieve Size Sieve no	Mass Retained	% Retained	Cum. % Retained	cum. % Finer	ASTM Limits (%)		Remark
					lower	upper	
9.5 mm	0	0.00	0.00	100.00	100	100	OK
4.75 mm	12	0.60	0.60	99.40	95	100	OK
2.36 mm	114	5.73	6.33	93.67	80	100	OK
1.18 mm	439	22.06	28.39	71.61	50	85	OK
600 µm	780	39.20	67.59	32.41	25	60	OK
300 µm	391.5	19.67	87.26	12.74	10	30	OK
150 µm	205	10.30	97.56	2.44	2	10	OK
pan	48.5	2.44	0.00	0.00	0	5	OK
Total	1990		287.74				

FM = 287.74/100 = 2.8774 ≈ 2.9

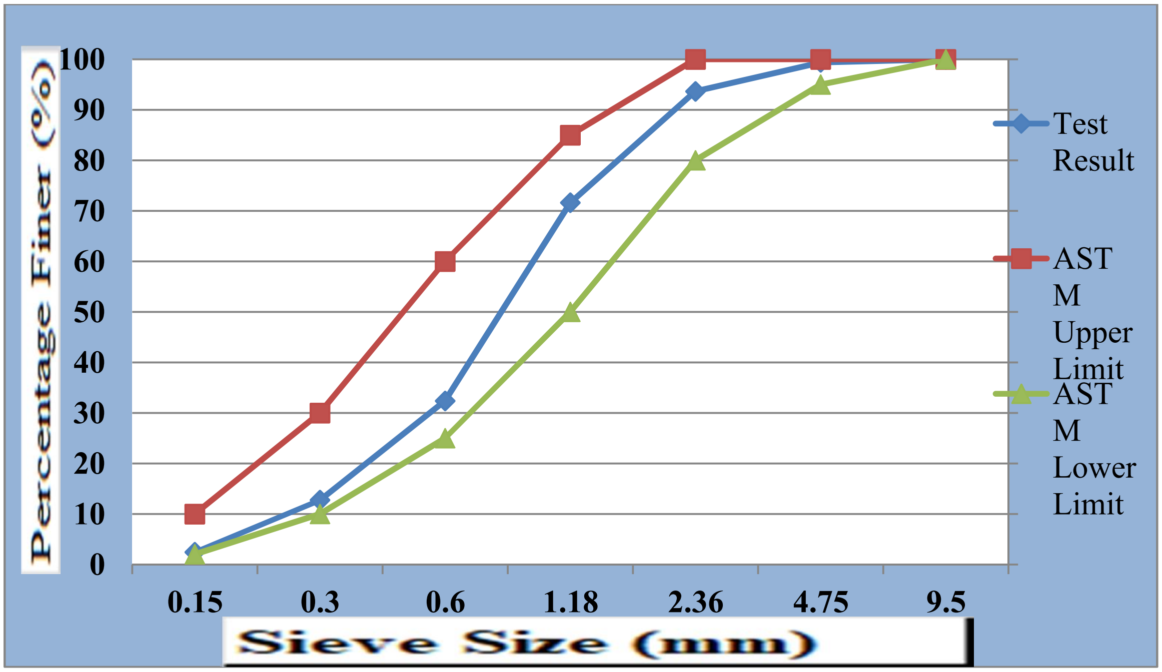


Figure 4.2 Sieve Analyses of Fine Aggregates

Table 4.4 Summarized of Test Results for Fine Aggregate

Material Type	Types of Test		Test Result
Fine Aggregate	Unit Weight	Compacted	1564.81 kg/m^3
		Loose	1485.8667 kg/m^3
	Bulk specific gravity	Oven-dry	2.405
		Saturated Surface dry	2.44
		Apparent	2.5
	Water Absorption Capacity		1.42 %
	Fineness Modules		2.9
	Moisture Content		1.18 %
	Silt/Clay Content before wash		7.53 %
	Silt/Clay Content after wash		3.92 %
	Bulking of Sand		4.02 %

The physical property test result on table 4.4 indicated that the fine aggregate used for concrete making on my study were according to ASTM requirement such as ASTMC 29, ASTMC 70, ASTMC 117, ASTMC 125, ASTMC 136 and ASTMC 33. The compacted unit weight, loose unit weight were 1504.81 and 1485.8667 respectively. Also, oven dry specific gravity, saturated surface specific gravity, Apparent specific gravity were 2.405, 2.44 and 2.5 respectively and water absorption capacity, fineness modulus, moisture content, silt content before wash, silt content after wash, and bulking of sand were 1.42, 2.9, 1.18, 7.53, 3.92 and 4.02 respectively. The test result indicate that FM was between 2.0 to 3.3, absorption capacity between 0.5 to 4% and surface moisture between 0 to 10% which fulfill the standard requirement of fine aggregate. The silt content of the fine aggregate indicates that it should be used after wash since the percentage of silt was greater than the standard requirement of 6% before wash.

4.3 Workability of Geo-polymer concrete

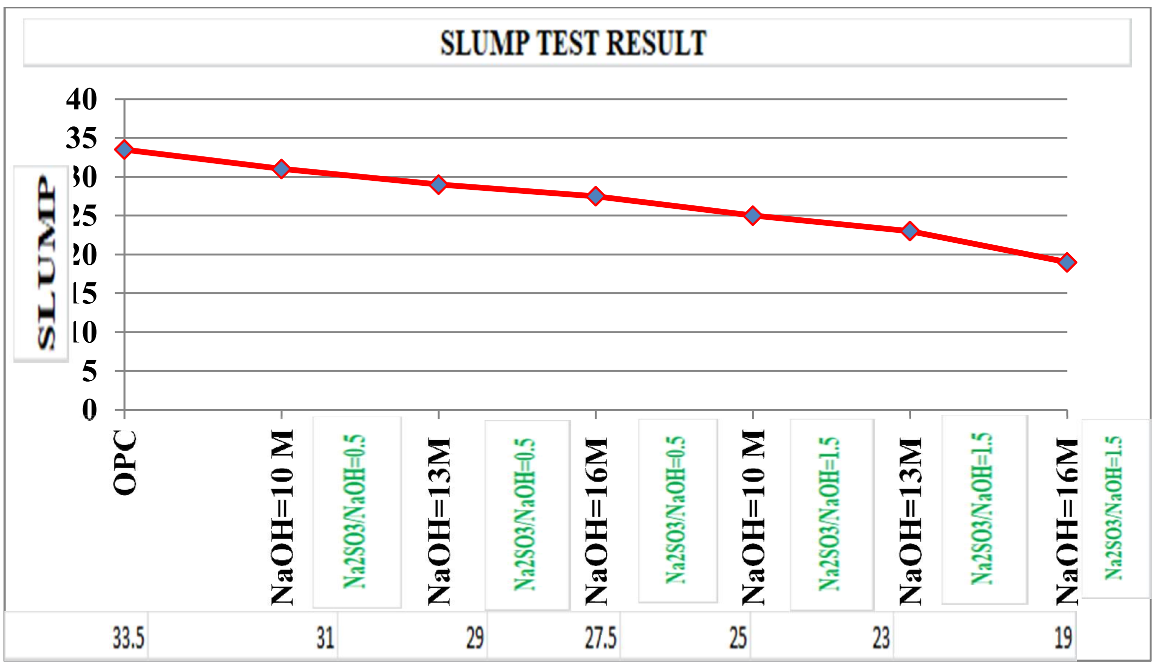


Figure 4.3 Workability of Fresh Geo-polymer Concrete

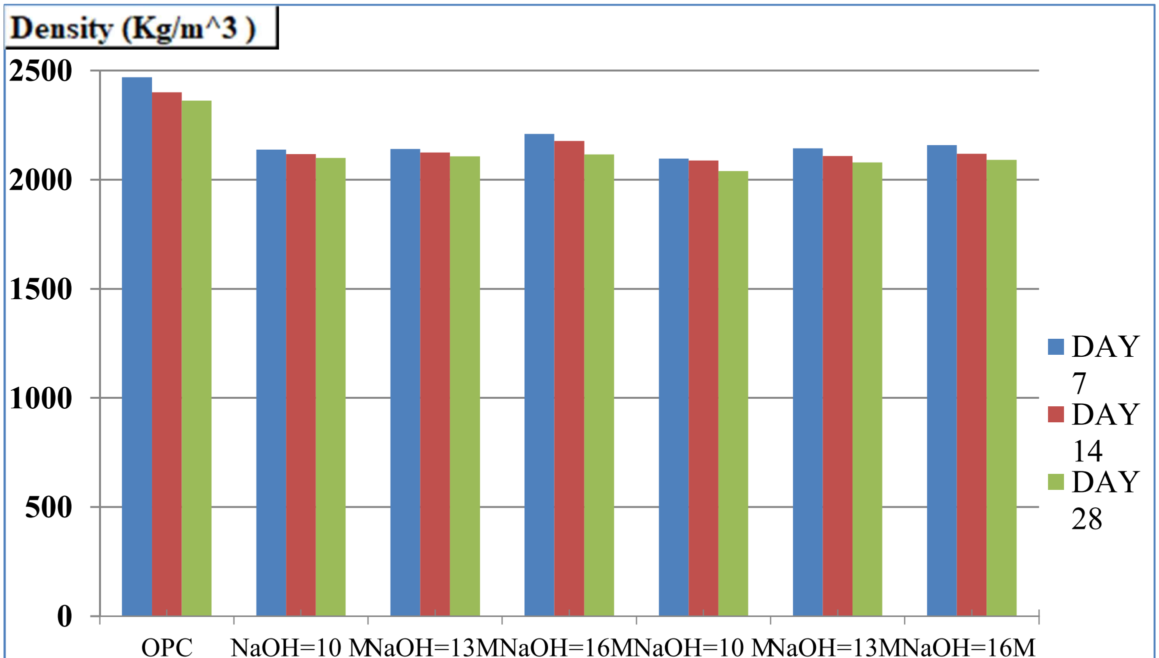
Workability test results indicated that the slump value of the geopolymer concrete with class F fly ash was less compared to ordinary Portland cement concrete and slightly reduction as the concentration of sodium hydroxide increases and the sodium silicate to sodium hydroxide proportion increases.

Table 4.5 Relationship between the concentration of sodium hydroxide, proportion of sodium silicate and sodium hydroxide to slump (Workability) of the fresh geopolymer concrete

Mix No.	Mix- designation	Observed Slump (mm)	Degree of Workability	Limit (mm)
1	M-0 (Control)	33.50	low	25-50
2	M-1 (NaOH = 10M)	31	low	25-50
3	M-2 (NaOH = 10M)	29.5	low	25-50
4	M-3 (NaOH = 13M)	27	low	25-50
5	M-4 (NaOH = 13M)	24.5	low	25-50
6	M-5(NaOH = 16M)	23	stiff	0-25
7	M-6(NaOH = 16M)	19	stiff	0-25

As figure and table above indicated that the concentration of sodium hydroxide and the proportion of the sodium silicate to sodium hydroxide were inversely proportion to workability as the concentration increase the were decreases smoothly and as proportion of sodium silicate to sodium hydroxide increases. The geopolymer concrete with less concentration and low proportion with sodium silicate had higher workability but less strength. This due to the amount of sodium hydroxide in high concentration was high in gram compared to the one with low concentration.

4.4 Density of Geopolymer Concrete



DAY	OPC	NaOH = 10 M	NaOH = 13M	NaOH = 16M	NaOH = 10 M	NaOH = 13M	NaOH = 16M
DAY 7	2469.94	2137.10	2140.31	2209.73	2096.89	2134.86	2157.93
DAY 14	2400.20	2117.04	2123.95	2177.88	2087.80	2109.04	2119.01
DAY 28	2361.48	2099.56	2106.57	2115.56	2039.31	2079.26	2091.21

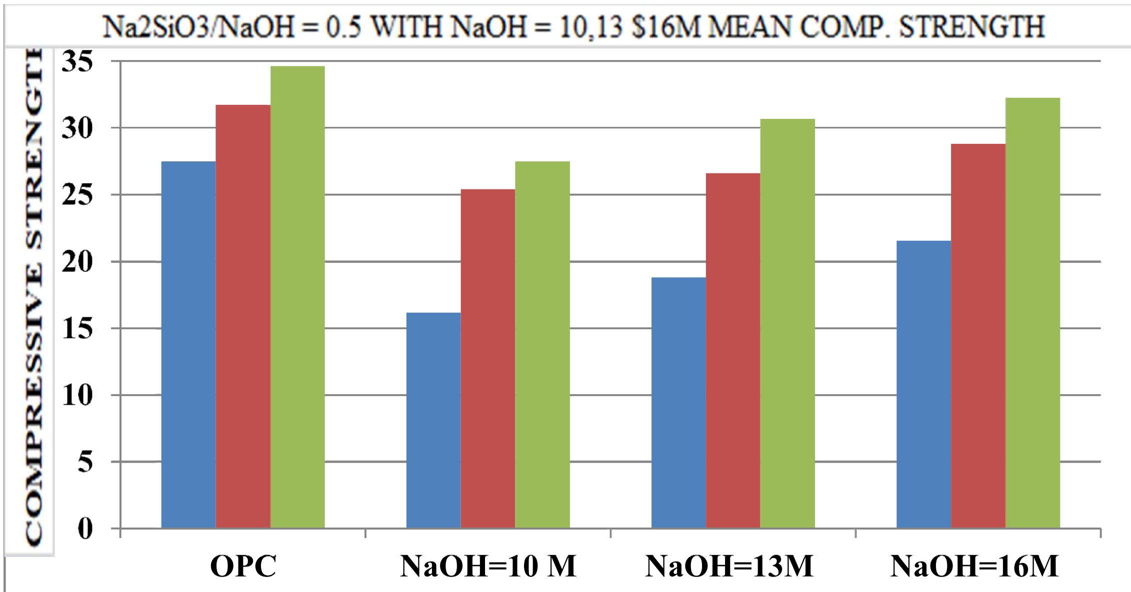
Figure 4.4 Density of fly ash based Geopolymer concrete

The experimental test result revealed that the unit weight of geopolymer concrete were less than the unit weight of ordinary Portland cement concrete used as control references , as described ASTM C 29 the unit weight of concrete were depend on the specific gravity or weight and unit volume of specimen. On this study the volume of specimen of study were kept the same which were 150mm*150mm*150mm. so, the unit weight of geopolymer concrete were less than the unit weight of OPC concrete because of the weight of fly ash were slightly lesser than cement.

As test results indicated that the density of the test specimens decreased slightly or almost the same with an increase in the curing age. Also the density of the test specimens as indicated on figure 4.4 depend on the concentration of alkaline solution, as alkaline solution concentration increases the density also slightly increases with small amount. In general the density of both OPC and Geopolymer concrete was between 2000 Kg/m^3-2500 Kg/m^3

4.5 Compressive Strength of Geo-polymer Concrete

4.5.1 Compressive Strength of Geo-polymer Concrete with $Na_2SiO_3/NaOH$ = 0.5



DAY	OPC	NaOH=10 M	NaOH=13M	NaOH=16M
DAY 7	27.47	16.17	18.83	21.56
DAY 14	31.73	25.40	26.59	28.81
DAY 28	34.62	27.50	30.66	32.26

Figure 4.5 Compressive Strength of Geo-polymer Concrete with $Na_2SiO_3/NaOH$ = 0.5

As the experiment results revealed that, the compressive strength of all hardened concrete increases with increase of curing age. As figure 4.5 revealed that, the compressive strength of hardened geopolymer concrete with sodium silicate to sodium hydroxide proportion of 0.5 increases as the concentration of sodium hydroxide concentration increases. But, less compared to OPC concrete used as control references.

The result of the test on the figure indicated that the compressive strength of Geopolymer concrete with $Na_2SiO_3/NaOH$ = 0.5 lesser (small) at ages of 7, 14 and 28 days of testing than control reference. Geopolymer compressive strength increases by great value from early age of 7 day to 14 day while OPC control not as such percentage increment. From the test result the increment of geopolymer concrete 16.17 to 25.40, 18.83 to 26.59 and 21.56 to 28.81 for NaOH = 10M, NaOH = 13M and NaOH = 16M respectively, the percentage of increment were 57.08%, 41.21% and 33.62% for NaOH = 10M, NaOH = 13M and NaOH = 16M respectively while 15.5% only for OPC concrete, but there was no visible variation in increment value from 14 days curing age to 28 day curing age which were 9.11%, 8.27%, 11.30% and 11.97% for OPC, NaOH = 10M, NaOH = 13M and NaOH = 16 respectively.

This result indicated that the compressive strength of geopolymer concrete highly effected by curing age, in addition to curing age the compressive strength also increase as the concentration of NaOH increases from 10M to 13M and 13M to 16M by 11.5% and 5.21% respectively but, less than of mean compressive strength of control of 33MPa and compressive strength OPC control of 34.62MPa by 20.56%, 11.44% and 6.82% at age of 28 days with NaOH = 10M, NaOH = 13M and NaOH = 16M respectively and $Na_2SiO_3/NaOH = 0.5$.

4.5.2 Compressive strength of geopolymer Concrete with $Na_2SO_3/NaOH = 1.5$

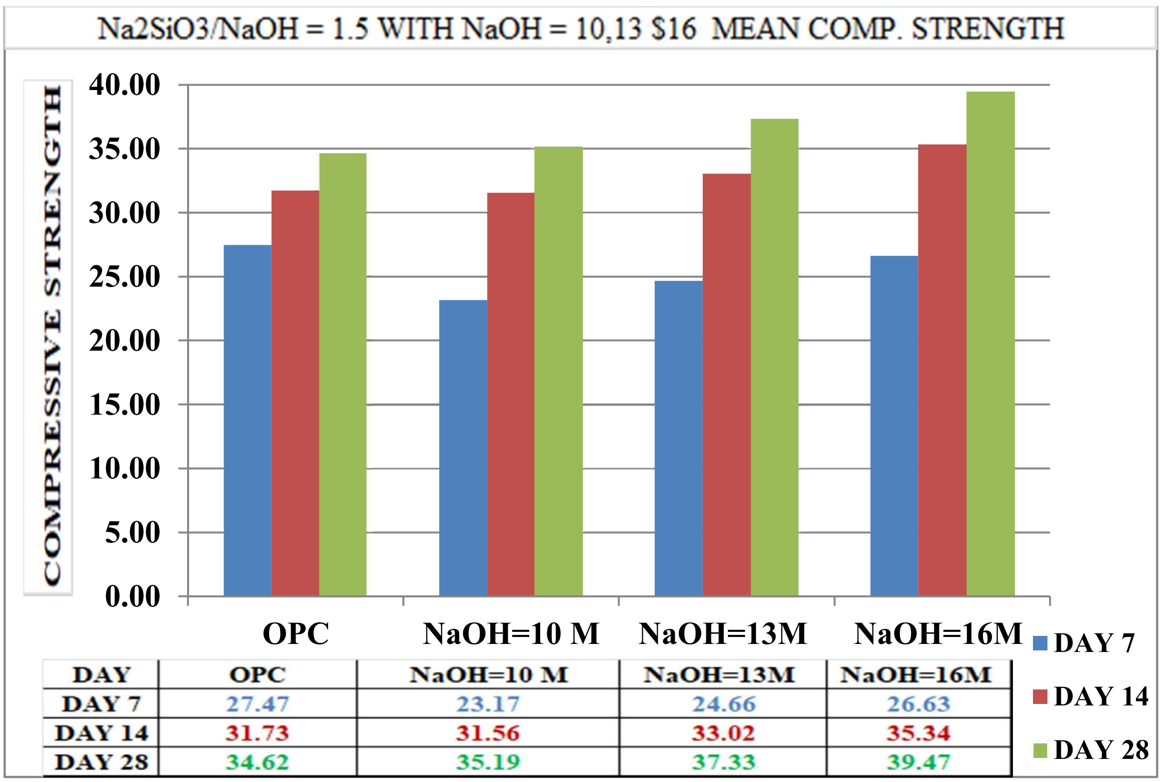


Figure 4.6 Compressive strength of geopolymer Concrete with $Na_2SiO_3/NaOH = 1.5$

The test result on figure 4.6 indicated that the compressive strength of geopolymer concrete with sodium silicate to sodium hydroxide proportion of 1.5 increase as the curing age increases, the increment level were different as shown on figure, the increment were high compared to OPC control at 14 and 28 days. At early age of 7 days the geopolymer concrete had lesser compressive strength compared to OPC control while at the age of 14 and 28 higher strength. Even if the compressive strength of geopolymer concrete at early age were lesser than the OPC concrete control but the geopolymer concrete compressive strength increases in high value from 7 day curing age to 14 day curing age than OPC concrete. That were 23.17 MPa to 31.56, 24.66MPa to 33.02MPa and 26.63MPa to 35.34MPa for NaOH = 10M, NaOH = 13M and NaOH = 16M respectively, which were in percent 36.21 %, 33.9% and 32.70% respectively were the proportion of sodium silicate to sodium hydroxide was 1.5.

Also, from the experimental test result revealed that the compressive strength were increases as the concentration of the sodium hydroxide increases that were 23.17MPa, 24.66MPa and 26.63MPa for NaOH = 10M, NaOH = 13M and NaOH = 16M at 7 day curing age, 31.56MPa, 33.02MPa and 35.34MPa for NaOH=10M, NaOH=13M and NaOH = 16M at 14 days curing age and 35.19MPa, 37.33MPa and 39.47MPa for NaOH = 10M, NaOH = 13M and NaOH = 16M for 28 days curing age respectively. The compressive strength of the geopolymer concretes were higher than the control OPC compressive strength in percentage of 1.646%, 7.83% and 14.01% with NaOH=10M, NaOH = 13M and NaOH = 16M respectively and Na_2SiO_3/NaOH = 1.5 at curing age of 28 days. Compressive strength of geopolymer concrete was increase as the proportion of sodium silicate to sodium hydroxide increase and as the concentration of the sodium hydroxide increases. But, on both figures the compressive strength at early ages of 7 days were less compared to the OPC control references.

4.6 Suitability of Geopolymer Concrete in Construction Industry

Geopolymer concrete is the advanced and modern technology to be used in construction industry. From the experimental laboratory tested results of the study geopolymer concrete is suitable in construction industry with proper mix proportion, curing time, curing temperature and at concentration of sodium hydroxide of 10M, 13M and 16M with proportion of sodium silicate to sodium hydroxide of 1.5. The test result revealed that the compressive strength of geopolymer concrete with 35.19MPa, 37.33MPa and 39.47MPa for 10M, 13M and 16M at 28 days curing age with proportion of sodium silicate to sodium hydroxide 1.5 were the most suitable in construction industry.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

Depending on the experimental laboratory test conducted on Geo-polymer concrete using low calcium fly ash conclusions and recommendations are forwarded on the workability, density and compressive strength of geopolymer concrete and on the effects of alkaline solution proportion, concentration and chemical and physical properties of low calcium fly ash.

5.1 Conclusions

Based on the research work results the following conclusions are drawn:

The fly ash oxide composition test indicated that, the fly ash from Ayka Addis Textile assigned as class F (low calcium) pozzolana as prescribed by ASTM C 618 which depends on percentage composition of SiO_2, Al_2O_3, Fe_2O_3, SO_3, CaO and loss of Ignition.

Workability test results indicated that the slump value of the geo-polymer concrete with class F fly ash was less compared to ordinary Portland cement concrete and smoothly decreases as the concentration of sodium hydroxide increases and the sodium silicate to sodium hydroxide proportion increases.

As the test results on compressive strength indicated that, the compressive strength of test specimens increases with an increase in curing ages; however, there were difference in increment value and in increment degree depending on the curing ages, concentration of sodium hydroxide and proportion of sodium silicate to sodium hydroxide. The compressive strength of geo-polymer concrete increases from 7 days to 14 days curing age in high range while it was low compressive strength at 7 days than OPC concrete, also the compressive strength increase from low concentration of 10M to high concentration of 16M sodium hydroxide and there was increment in compressive strength of geo-polymer concrete as proportion of sodium silicate to sodium hydroxide increases. In general the geo-polymer with high concentration of up to 16M and high proportion of the alkaline solution of 1.5 had high compressive strength and suitable to use as best construction material according to laboratory test result

5.2 Recommendations

Based on this research and an experimental laboratory study held on it, the following recommendations were given:

1. Geopolymer concrete mix design standard should be prepared to reduce ambiguity in mix proportioning or modification should be made on ACI mix design of OPC concrete.
2. Fly ash from Ayka Addis Textile Factory (Ethiopia) did not fulfill to fineness standard requirement of fly ash, to make it suitable for concrete production whether mechanical method of grinding fly ash or other method of fineness separation of fly ash should be applied during bag house collection technique.
3. High temperature curing method or blending with small amount of OPC were recommended to get high early strength of geopolymer concrete or in production of precast concrete to increase production speed
4. When workability of geopolymer concrete is became low using super plasticizer up to 2% is possible without effecting the compressive strength or addition of extra water is possible.
5. Precaution should be made while using alkaline chemicals in production of geopolymer concrete especially before mixing the solution together.

Finally the author of this research would like to recommend other researcher to study:-

- ✓ Curing temperature and curing time effect on Geopolymer concrete
- ✓ Effect of proportion of sodium silicate to sodium hydroxide greater than 1.5 on compressive strength and other properties of geopolymer concrete
- ✓ Tensile and flexural strength and other engineering properties of geopolymer concrete.

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APPENDICES 1

MATERIALS TEST RESULTS

1.1 Properties of Coarse Aggregate

1.1.1 Sieve Analysis

Table A1.1 Sieve analysis for coarse aggregate.

Sieve Size	Mass Retained	% Retained	Cumulative % retained	% Finer	ASTM Limits %		Remark
					Lower	Upper	
37.5	0	0	0	100	100	100	ok
25	201	2.03	2.03	97.97	95	100	ok
19	1436.5	14.48	16.51	83.49			
12.5	4984	50.24	66.75	33.25	25	60	ok
9.5	2452	24.72	91.46	8.54			
4.75	740	7.46	98.92	1.08	0	10	ok
pan	107	1.08	100.00	0.00			
Total	9920.5		275.66				

Fineness Modulus (FM) of coarse aggregates = sum (cumulative % retained) / 100 = (706.89/100) = 7.07. Therefore, Fineness Modulus was 7.09. It means that the average size of particle of given coarse aggregate samples were in between 7th and 8th sieves, by placing the sieve size according to their ascending orders which was between 10mm to 20mm sieve size.

Note: the cumulative percentage retained on only sieve size of (37.5 mm, 19 mm, 9.5 mm, 4.75 mm, 2.36 mm, 1.18 mm, 0.60 mm, 0.30mm and 0.150 mm are used in calculation of fineness modulus of coarse aggregate.

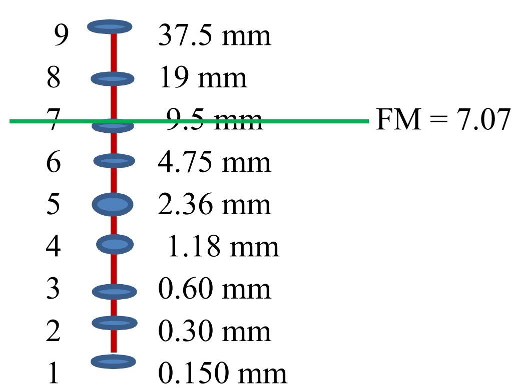

Figure A1.1 Average Size of Course aggregate.

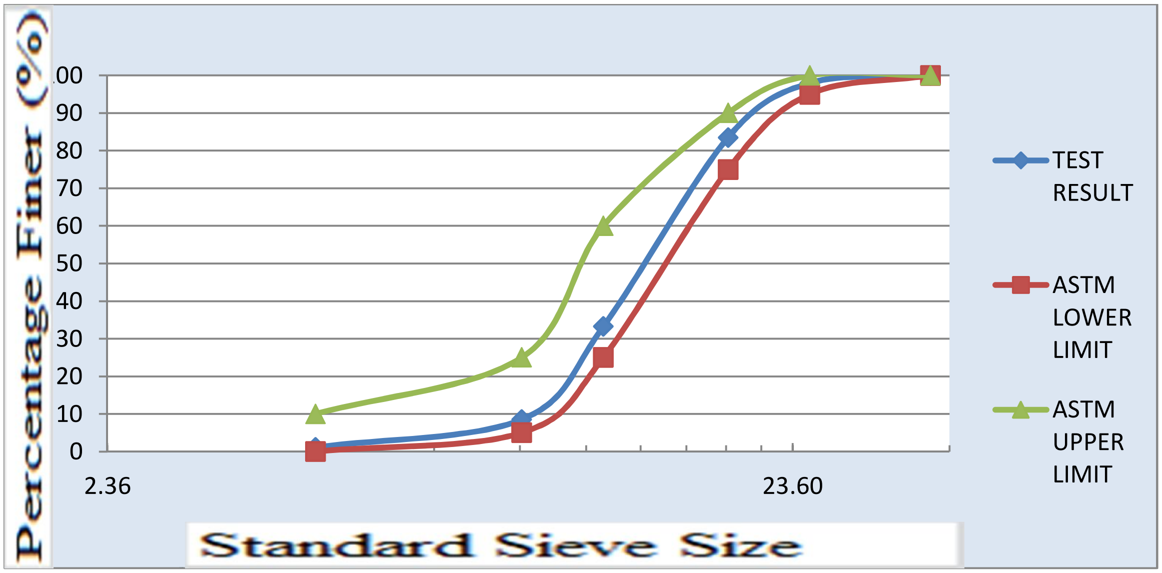

Figure A1.2 Coarse aggregate gradation chart.

1.1.2 Unit Weight

1.1.2.1 Compacted and Loose Unit Weight

Table A1.2 Compacted and Loose Unit weight coarse aggregate

Compacted Unity Weight Coarse Aggregate					
Sample	Wt. Of cylinder metal (Kg)	Wt. Of cylinder + Wt. Of sample(Kg)	Wt. Of sample (Kg)	Vol. Of cylinder (m3)	Unit Weight (Kg/m3)
1	1.675	17.3885	15.7135	0.01	1571.35
2	1.675	18.0835	16.4085	0.01	1640.85
3	1.675	18.2625	16.5875	0.01	1658.75
Mean					1623.65
Loose Unity Weight Coarse Aggregate					
1	1.675	15.7675	14.0925	0.01	1409.25
2	1.675	15.564	13.889	0.01	1388.9
3	1.675	15.6554	13.9804	0.01	1398.04
Mean					1398.73

1.1.3 Determine Specific Gravity of Coarse Aggregate

Initial sample mass=2kg

Weight of oven dry sample in air (mass A) = 1.9915 kg

Weight of saturated surface dry sample in air (mass B) = 2.007kg

Weight of saturated sample in water (mass C) = 1.3kg

Weight of sample and basket in water (mass D_1) = 1.723kg

Weight of empty basket in water (mass D_2) = 0.441kg

$C = D_1 - D_2$

= (1.723-0.441) kg

= 1.282kg

- **Bulk specific gravity:**

$$\text{Bulk sp. gr.} = \left[\frac{\text{A}}{\text{B} - \text{C}}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \ldots\ldots Equ.1A$$

$$= \left[\frac{1.9915}{2.007-1.282}\right] = \underline{2.75}$$

- **Bulk specific gravity (saturated surface dry basis):**

$$\text{Bulk sp gr (saturated } - \text{ surface dry basis)} = \left[\frac{\text{B}}{\text{B}-\text{C}}\right]. \ldots\ldots\ldots\ldots\ldots. Equ.2A$$

$$= \left[\frac{2.007}{2.007-1.282}\right] = \underline{2.77}$$

- **Apparent specific gravity:**

$$\text{Apparent sp gr} = \left[\frac{\text{A}}{\text{A}-\text{C}}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \ldots\ldots\ldots. Equ.3A$$

$$= \left[\frac{1.9915}{1.9915-1.282}\right] = 2.81$$

- **Absorption capacity:**

$$\text{Absorption capacity} = \left[\left[\frac{B-A}{A}\right] * 100\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equ.4A$$

$$= \left[\left[\frac{2.007-1.9915}{1.9915}\right] * 100\right] = \underline{0.77\%}$$

1.1.4 Moisture Content of the Coarse Aggregate

The moisture content of the coarse aggregates was performed by using Equ.5A. For instance, the moisture content of the coarse aggregate for sample-1 and for all sand samples followed the same procedure.

A = weight of original sample = 2kg

B= weight of oven dry sample = 1.985

MC= moisture content (%)

$$MC = \left[\frac{A-B}{B}\right] * 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Equ.5A$$

$$MC = \left[\frac{2-1.9848}{1.9848}\right]*100 = 0.764\%$$

Table A1.3 Moisture content of the coarse aggregate

Sample	Moisture Content of Coarse Aggregate		
	Weight of Sample before dry (gm.) (A)	Weight of Sample after oven dry (gm.) (B)	Moisture Content (%) MC
1	2000	1985.5	0.73
2	2000	1985	0.756
3	2000	1984	0.806
Mean			**0.764**

Table A1.4 Summary of physical properties of coarse aggregate

Material Type	Types of Test		Test Result
Coarse Aggregate	Unit Weight	Loose unit weight	1398.73 kg/m^3
		Compacted unit weight	1623.65 kg/m^3
	Bulk specific gravity	Oven-dry	2.75
		Saturated Surface dry	2.78
		Apparent	2.86
	Water Absorption Capacity		1.6 %
	Moisture Content		0.77 %
	Size of Aggregate	Max. Size	25 mm
		Nominal Max. Size	20 mm
	Fineness Modules		7.07

1.2 Properties of Fine Aggregate

1.2.1 Silt/Clay Content of Fine Aggregate

Percentage of material that is finer than 75µm (#200) sieve size (percentage of silt/clay content). This test was conducted in laboratory (using lab. Method)

A= Original dry mass before wash = 1kg

B= Dry mass of sample after washed = 0.93kg

$$\text{Silt Content Before wash } = \left[\frac{A-B}{B}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots Equ. 6A$$

$$\text{Silt Content Before wash sand} = \left[\frac{1-0.93}{0.93}\right] * 100 = 7.53\%$$

$$\text{Silt Content After wash sand} = \left[\frac{1-0.9623}{0.9623}\right] * 100 = 3.92\%$$

1.2.2 Sieve Analysis for Fine Aggregate

Table A1.5 Sieve Analysis of Fine Aggregate

Sieve Size Sieve no	Mass Retained	% Retained	Cum. % Retained	cum. % Finer	ASTM Limits (%)		Remark
					lower	upper	
9.5 mm	0	0.00	0.00	100.00	100	100	OK
4.75 mm	12	0.60	0.60	99.40	95	100	OK
2.36 mm	114	5.73	6.33	93.67	80	100	OK
1.18 mm	439	22.06	28.39	71.61	50	85	OK
600 µm	780	39.20	67.59	32.41	25	60	OK
300 µm	391.5	19.67	87.26	12.74	10	30	OK
150 µm	205	10.30	97.56	2.44	0	10	OK
pan	48.5	2.44	0.00	0.00	0	5	OK
Total	1990		287.74				

Fineness Modulus of Fine Aggregate

Fineness Modulus of Fine Aggregate = (cumulative % retained) / 100 = (287.74/100) = 2.9 Therefore, Fineness Modulus (FM) of fine aggregate is 2.9. It means the average size of aggregate is in between the **2nd** sieve size and **3rd** sieve size the sieve ordered according ascending order. It means that the average aggregate size is in between 0.3 mm to 0.6 mm as shown in below figure 3A.3

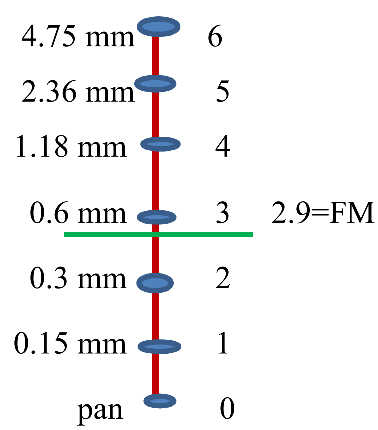

Figure A1.3 Average Size of Fine aggregate

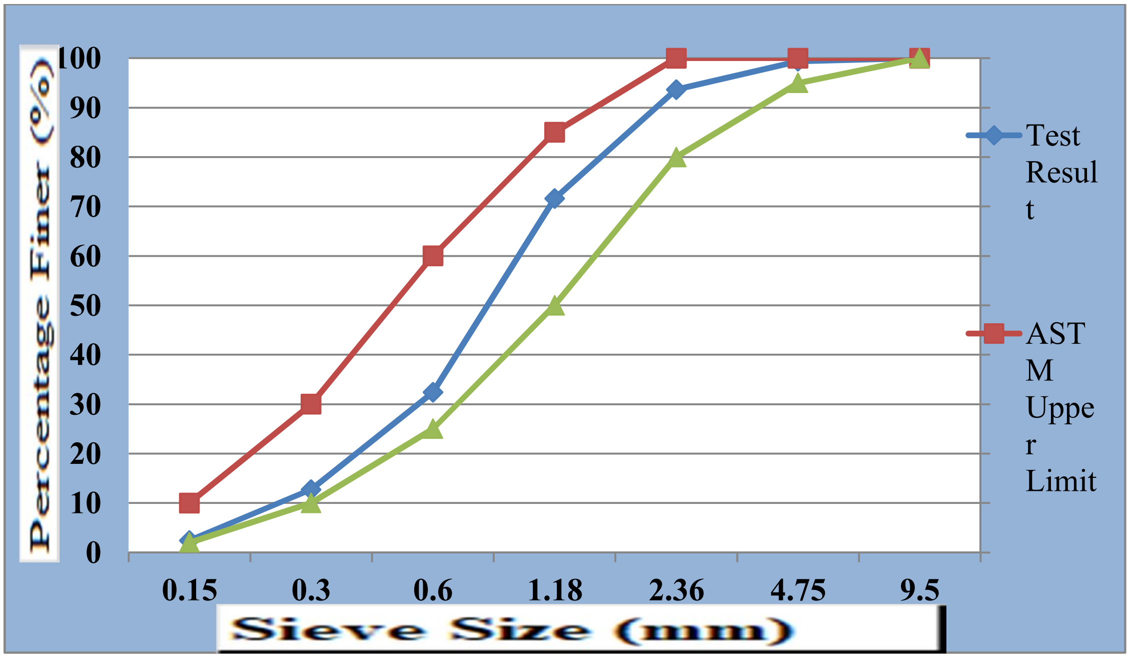

Figure A1.4 Gradation chart for fine aggregate according to ASTM Limitation

1.2.3 Unit weight

1.2.3.1 Compacted and Loose Unit weight of Fine Aggregate

Table A1.6 compacted and loose unit weight of Fine Aggregate

Loose Unity Weight of Sand					
Sample	Wt. of cylinder metal	Wt. Of cylinder + Wt. Of sample(Kg)	Wt. Of sample	Vol. Of cylinder (m3)	Unit Weight (Kg/m3)
1	1.054	8.471	7.417	0.005	1483.4
2	1.054	8.498	7.444	0.005	1488.8
3	1.054	8.481	7.427	0.005	1485.4
Mean					**1485.8667**
Compacted Unity Weight of Sand					
1	1.054	8.811	7.757	0.005	1551.4
2	1.054	8.912	7.858	0.005	1571.6
3	1.054	8.9112	7.8572	0.005	1532.2
Mean					1571.44

1.2.4 Determine Specific gravity of fine aggregate

Weight of saturated – surface dry sample (mass A) = 0.5 kg

Weight of pycnometer with sample and filled with distilled water (mass B) = 1.850kg

Weight of pycnometer filled with distilled water (mass C) = 1.555kg

Weight of oven-dry sample in air (mass D) = 0.493kg

- **Bulk specific gravity:**

$$\text{Bulk sp gravity (oven dry)} = \left[\frac{\mathrm{D}}{\mathrm{C+A-B}}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . Equ.7A$$

$$= \left[\frac{0.493}{1.555+0.5-1.850}\right] = \underline{2.405}$$

- **Bulk specific gravity (saturated surface dry basis):**

$$\text{Bulk sp gr (saturated − surface dry basis)} = \left[\frac{\mathrm{A}}{\mathrm{C+A-B}}\right] \ldots\ldots\ldots\ldots\ldots .. Equ.8A$$

$$= \left[\frac{0.5}{1.555+0.5-1.850}\right] = \underline{2.44}$$

- **Apparent specific gravity:**

$$\text{Apparent sp gr} = \left[\frac{\mathrm{D}}{\mathrm{C+D-B}}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. Equ.9A$$

$$= \left[\frac{0.493}{1.555+0.493-1.850}\right]$$

$$= \underline{2.50}$$

- **Water Absorption capacity:**

$$\text{Absorption capacity} = \left[\left[\frac{\mathrm{A-D}}{\mathrm{D}}\right] * 100\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. Equ.10A$$

$$= \left[\left[\frac{0.5-0.493}{0.493}\right] * 100\right] = \underline{1.42\%}$$

1.2.5 Moisture content of the fine aggregate

The moisture content of the fine aggregates was performed by using Equ.6A; For instance, the moisture content of the fine aggregate for sample-1 and for all sand samples followed the same procedure.

A = weight of original sample = 0.5kg

B= weight of oven dry sample = 0.495kg

MC= moisture content (%)

$$MC = \left[\frac{A-B}{B}\right] * 100 \ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots..\ldots\ldots\ldots\ldots. Equ. 11A$$

$$MC = \left[\frac{0.5-0.495}{0.495}\right]*100 = 1.18\%$$

Table A1.7 Moisture content for fine aggregate (sand) samples

Moisture content of Fine aggregate			
Sample	Weight of Sample before dry (kg) (A)	Weight of Sample after oven dry (kg) (B)	Moisture content (%) MC
1	0.500	0.494	1.2
2	0.500	0.495	1.01
3	0.500	493.5	1.32
Mean			**1.18**

1.2.6 Bulking of the fine aggregate (Sand)

Bulking of sand samples was determined as showed below:-

$$\text{percentage of bulking of sand} = \left[\frac{V1-V2}{V2}\right] * 100 \ldots\ldots\ldots\ldots\ldots.\ldots.\ldots Equ. 12A$$

For instance, the Bulking of the fine aggregate for sample-1 and for sample -2 followed the same procedure.

V_1 = volume moist of sand = 375 ml V_2= volume moist of sand = 349 ml

BS (%) = $\left[\frac{375-360.5}{360.5}\right]$*100 =4.02%

Table A1.8 Bulking of the fine aggregate

Sample of sands	Original volume (V1) ml	Volume after bulking of sand (V2) ml	% of Bulking (BS)
Sample -1	375	361	3.88 %
Sample -2	375	359	4.45 %
Sample-3	375	361.5	3.73 %
Average Bulking (%)			

Table A1.9 Summary of physical properties of fine aggregate

Material Type	Types of Test		Test Result
Fine Aggregate	Unit Weight	Compacted	1564.81 kg/m^3
		Loose	1485.8667 kg/m^3
	Bulk specific gravity	Oven-dry	2.405
		Saturated Surface dry	2.44
		Apparent	2.5
	Water Absorption Capacity		1.42 %
	Fineness Modules		2.9
	Moisture Content		1.18 %
	Silt/Clay Content before wash		7.53 %
	Silt/Clay Content after wash		3.92 %
	Bulking of Sand		4.02 %

APPENDICES 2

EXPERIMENTAL RESULTS

Table A2.1 Relationship between the concentration of sodium hydroxide, proportion of sodium silicate and sodium hydroxide to slump (Workability) of the fresh geopolymer concrete

Mix No.	Mix- designation	Observed Slump (mm)	Degree of Workability	Limit (mm)
1	M-0 (Control)	33.50	low	25-50
2	M-1 (NaOH=10M)	31	low	25-50
3	M-2 (NaOH=10M)	29.5	low	25-50
4	M-3(NaOH=13M)	27	low	25-50
5	M-4(NaOH=13M)	24.5	low	25-50
6	M-5(NaOH=16M)	23	stiff	0-25
7	M-6(NaOH=16M)	19	stiff	0-25

Table A2.2 Effect of concentration of sodium hydroxide and sodium silicate to sodium hydroxide proportion on the density of Geo-polymer concrete

Test no.	Mix- designation	unity weight (kg/m3)		
		7days	14days	28days
1	M-0 (Control)	2469.94	2400.20	2361.48
2	M-1 (NaOH=10M),R=0.5	2137.10	2117.04	2099.56
3	M-2 (NaOH=10M),R=1.5	2096.89	2087.80	2039.31
4	M-3(NaOH=13M),R=0.5	2140.31	2123.95	2106.57
5	M-4(NaOH=13M), R=1.5	2134.86	2109.04	2079.26
6	M-5(NaOH=16M), R=0.5	2209.73	2177.88	2115.56
7	M-6(NaOH=16M), R=1.5	2157.93	2119.01	2091.21

Table A2.3 Average compressive strength of Geopolymer concrete

Test No.	Mix Designation	Average Compressive Strength geopolymer conrete					
		7days		14days		28days	
		Load (KN)	Strengths N/mm2	Load (KN)	Strengths N/mm2	Load (KN)	Strengths N/mm2
1	M-0 (Control)	621.21	27.47	713.80	31.73	779.10	34.62
2	M-1 (NaOH=10M)	363.83	16.17	571.58	25.40	618.69	27.50
3	M-2 (NaOH=10M)	521.25	23.17	710.03	31.56	791.70	35.19
4	M-3(NaOH=13M)	423.68	18.83	598.28	26	689.93	30.66
5	M-4(NaOH=13M)	554.78	24.66	742.95	33.02	840.00	37.33
6	M-5(NaOH=16M)	485.10	21.56	648.23	28.81	725.85	32.26
7	M-6(NaOH=16M)	599.18	26.63	880.20	35.34	888.17	39.47

Table A2.4 Workability, Density and Compressive strength of Geopolymer concrete

Mix Designation	Test age days	Trial no.	Dimensions (m) L	W	H	w/c ratio	Slump (mm)	Weight (kg)	Volume (m^3)	Failure load (KN	Comp. Streng. (MPa)	Unit Weight (kg/m^3)
M-0	7	1	0.15	0.15	0.15	0.50	33.50	8.31	0.003375	624.46	27.76	2460.89
		2	0.15	0.15	0.15			8.31	0.003375	603.75	26.84	2462.96
		3	0.15	0.15	0.15			8.39	0.003375	635.42	27.80	2485.96
Mean										**621.21**	**27.47**	**2469.94**
M-0	14	1	0.15	0.15	0.15	0.50	33.50	8.01	0.003375	713.79	31.73	2372.74
		2	0.15	0.15	0.15			8.08	0.003375	714.70	31.77	2394.37
		3	0.15	0.15	0.15			8.21	0.003375	712.90	31.69	2433.48
Mean										**713.80**	**31.73**	**2400.20**
M-0	28	1	0.15	0.15	0.15	0.50	33.50	7.85	0.003375	782.97	34.79	2325.93
		2	0.15	0.15	0.15			8.01	0.003375	778.60	34.60	2373.33
		3	0.15	0.15	0.15			8.05	0.003375	775.72	34.48	2385.19
Mean										**779.10**	**34.62**	**2361.48**

Geopolymer Concrete												
M-1	7	1	0.15	0.15	0.15	0.50	31.00	7.24	0.003375	376.43	16.73	2145.63
		2	0.15	0.15	0.15			7.09	0.003375	355.50	15.80	2101.19
		3	0.15	0.15	0.15			7.31	0.003375	359.55	15.98	2164.47
Mean										**363.83**	**16.17**	**2137.10**
M-1	14	1	0.15	0.15	0.15	0.50	31.00	7.23	0.003375	567.68	25.23	2143.41
		2	0.15	0.15	0.15			7.19	0.003375	585.23	26.01	2130.37
		3	0.15	0.15	0.15			7.01	0.003375	561.83	24.97	2077.33
Mean										**571.58**	**25.40**	**2117.04**
M-1	28	1	0.15	0.15	0.15	0.50	31.00	6.88	0.003375	614.03	27.29	2039.70
		2	0.15	0.15	0.15			7.24	0.003375	629.55	27.98	2144.89
		3	0.15	0.15	0.15			7.14	0.003375	612.50	27.22	2114.07
Mean										**618.69**	**27.50**	**2099.56**
M- 2	7	1	0.15	0.15	0.15	0.50	29.50	7.01	0.003375	532.13	23.65	2077.04
		2	0.15	0.15	0.15			7.22	0.003375	511.43	22.73	2139.85
		3	0.15	0.15	0.15			7.00	0.003375	520.20	23.12	2073.78
Mean										**521.25**	**23.17**	**2096.89**
M-2	14	1	0.15	0.15	0.15	0.50	29.50	7.12	0.003375	702.68	31.23	2110.52
		2	0.15	0.15	0.15			7.02	0.003375	732.38	32.55	2078.81
		3	0.15	0.15	0.15			7.00	0.003375	695.03	30.89	2074.07
Mean										**710.03**	**31.56**	**2087.80**
M-2	28	1	0.15	0.15	0.15	0.50	29.50	6.73	0.003375	783.45	34.82	1993.78
		2	0.15	0.15	0.15			6.92	0.003375	801.90	35.64	2049.78
		3	0.15	0.15	0.15			7.00	0.003375	789.75	35.10	2074.37
Mean										**791.70**	**35.19**	**2039.31**
M-3	7	1	0.15	0.15	0.15	0.50	27.00	7.26	0.003375	435.38	19.35	2150.96
		2	0.15	0.15	0.15			7.10	0.003375	420.98	18.71	2103.70
		3	0.15	0.15	0.15			7.31	0.003375	414.68	18.43	2166.25
Mean										**423.68**	**18.83**	**2140.31**

M-3	14	1	0.15	0.15	0.15	0.50	27.00	7.28	0.003375	600.98	26.71	2158.22
		2	0.15	0.15	0.15			7.17	0.003375	585.90	26.04	2124.44
		3	0.15	0.15	0.15			7.05	0.003375	607.95	27.02	2089.19
Mean										**598.28**	**26.59**	**2123.95**
M-3	28	1	0.15	0.15	0.15	0.50	27.00	7.11	0.003375	675.00	30.00	2106.96
		2	0.15	0.15	0.15			7.09	0.003375	697.28	30.99	2100.15
		3	0.15	0.15	0.15			7.13	0.003375	697.50	31.00	2112.59
Mean										**689.93**	**30.66**	**2106.57**
M-4	7	1	0.15	0.15	0.15	0.50	24.5.00	7.18	0.003375	560.70	24.92	2127.11
		2	0.15	0.15	0.15			7.19	0.003375	564.75	25.10	2129.33
		3	0.15	0.15	0.15			7.25	0.003375	538.88	23.95	2148.15
Mean										**554.78**	**24.66**	**2134.86**
M-4	14	1	0.15	0.15	0.15	0.50	24.50	7.09	0.003375	749.48	33.31	2100.74
		2	0.15	0.15	0.15			7.10	0.003375	737.33	32.77	2102.81
		3	0.15	0.15	0.15			7.17	0.003375	742.05	32.98	2123.56
Mean										**742.95**	**33.02**	**2109.04**
M-4	28	1	0.15	0.15	0.15	0.50	24.50	7.06	0.003375	832.50	37.00	2091.85
		2	0.15	0.15	0.15			6.82	0.003375	855.23	38.01	2020.74
		3	0.15	0.15	0.15			7.17	0.003375	832.28	36.99	2125.19
Mean										**840.00**	**37.33**	**2079.26**
M-5	7	1	0.15	0.15	0.15	0.50	23.00	7.53	0.003375	474.98	21.11	2231.56
		2	0.15	0.15	0.15			7.46	0.003375	496.13	22.05	2209.19
		3	0.15	0.15	0.15			7.39	0.003375	484.20	21.52	2188.44
Mean										**485.10**	**21.56**	**2209.73**
M-5	14	1	0.15	0.15	0.15	0.50	23.00	7.44	0.003375	636.08	28.27	2205.04
		2	0.15	0.15	0.15			7.28	0.003375	656.10	29.16	2155.85
		3	0.15	0.15	0.15			7.33	0.003375	652.52	29.00	2172.74
Mean										**648.23**	**28.81**	**2177.88**

M-5	28	1	0.15	0.15	0.15	0.50	23.00	7.04	0.003375	722.48	32.11	2087.11
		2	0.15	0.15	0.15			7.21	0.003375	712.58	31.67	2136.30
		3	0.15	0.15	0.15			7.17	0.003375	742.50	33.00	2123.26
Mean										**725.85**	**32.26**	**2115.56**
M-6	7	1	0.15	0.15	0.15	0.50	19.00	7.22	0.003375	605.25	26.90	2139.85
		2	0.15	0.15	0.15			7.35	0.003375	609.75	27.10	2176.30
		3	0.15	0.15	0.15			7.28	0.003375	582.53	25.89	2157.63
Mean										**599.18**	**26.63**	**2157.93**
M-6	14	1	0.15	0.15	0.15	0.50	19.00	7.22	0.003375	792.68	35.23	2137.78
		2	0.15	0.15	0.15			7.09	0.003375	782.55	34.78	2100.74
		3	0.15	0.15	0.15			7.15	0.003375	810.00	36.00	2118.52
Mean										**880.20**	**35.34**	**2119.01**
M-6	28	1	0.15	0.15	0.15	0.50	19.00	6.98	0.003375	880.27	39.12	2068.44
		2	0.15	0.15	0.15			7.10	0.003375	904.05	40.18	2103.11
		3	0.15	0.15	0.15			7.09	0.003375	880.20	39.12	2102.07
Mean										**888.17**	**39.47**	**2091.21**