EVALUATION OF THE PROPERTIES OF METAKAOLIN BASED GEOPOLYMER CONCRETE MADE WITH RECYCLED CONCRETE AGGREGATE

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DEPARTMENT OF BUILDING,
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MARCH, 2017

Declaration

I declare that the work in this dissertation report entitled EVALUATION OF THE PROPERTIES OF METAKAOLIN BASED GEOPOLYMER CONCRETE MADE WITH RECYCLED CONCRETE AGGREGATE has been done by me in the Department of Building, under the supervision of Dr. D. D. Dahiru. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation report was previously presented for another degree at any university.

Jacob Enejo Adejo (P13EVBD808)	________________ Signature	________________ Date

Certification

This is to certify that this dissertation entitled EVALUATION OF THE PROPERTIES OF METAKAOLIN BASED GEOPOLYMER CONCRETE MADE WITH RECYCLED CONCRETE AGGREGATE by Jacob Enejo Adejo, meets the regulations governing the award of the Masters of Science (MSc) degree in Construction Technology, Department of Building, Ahmadu Bello University, Zaria and is approved for its' contribution to knowledge and literary presentation.

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Dedication

This Dissertation is dedicated to my parent Dr. & Mrs. A. A. Adejo for their unrelenting effort and immeasurable guidance and to my siblings (Lydia, Celestine, Andrew and Blessing).

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List of Abbreviations

ACI	American Concrete Institute
ACPA	American Concrete Pavement Association
ACV	Aggregate Crushing Value
AIV	Aggregate Impact Value
ASTM	American Standard for Testing and Material
BRE	Building Research Establishment.
FHWA	Federal Highway Authority
GPC	Geopolymer Concrete
ITZ	Interfacial Transition Zone
$MgSO_4$	Magnesium Sulphate
NA	Natural Aggregate
NaOH	Sodium Hydroxide
Na_2SiO_3	Sodium Silicate
PCC	Portland Cement Concrete
RCA	Recycled Concrete Aggregate
SSD	Saturated Surface Dry
UN	United Nations
WBCSD	World Business Council for Sustainable Development
WCED	World Commission on Environment and Development

Abstract

Over the years, the construction industry consumes large amount of materials and produces waste in large quanties, this practice depletes natural resources like aggregates and causes problem of waste accumulation. In order to attain sustainability, emphasis is made on circular pattern of consumption as against the linear pattern of consumption. Recycled Concrete Aggregate (RCA) is an example of waste produced from construction and demolition activities. Efforts have been made to eliminate the problem associated with cement usage and its production by fully replacing cement with an environmentally friendly binder known as geopolymer. Many researchers utilized natural aggregates in the production of geopolymer concrete but few researches have been carried out producing geopolymer concrete using RCA. This research evaluates the properties of metakaolin based Geopolymer Concrete (GPC) containing RCA. Metakaolin and alkaline solution (sodium hydroxide and sodium silicate) is the binder used for concrete production in this research. A total of 336 specimens of 100mm x 100mm x 100mm cubes were cast with each sample containing 0%, 20%, 30% and 40% RCA. A total of 192 concrete specimens were tested for compressive and tensile strength, for absorption capacity and abrasion resistance, 96 concrete specimens was used while 48 concrete specimens were tested for its resistance to magnesium sulphate ($MgSO_4$) attack. GPC was produced and cured at 60^oC in the oven for 24hrs, after which they were cooled at room temperature in the laboratory and their properties evaluated after 7, 14, 28 and 56days of curing periods. The Portland Cement Concrete (PCC) was also tested after curing in water at the same curing ages. The average compressive strength obtained at 28 days of curing for PCC specimens with 0%, 20%, 30% and 40% RCA are 24.23N/mm^2, 21.09N/mm^2, 19.81N/mm^2 and 19.37N/mm^2,

while for GPC specimen with same replacement of RCA are 31.54N/mm^2, 31.17N/mm^2, 28.55/mm^2, 26.40N/mm^2 respectively. The result obtained showed that GPC specimen have better compressive strengths when compared to PCC. This is concluded herein that hardened GPC specimens with various replacement of RCA showed higher compressive strength than PCC specimens. This research recommends that metakaolin based geopolymer concete containing RCA up to 40% RCA could be used for structural concrete.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the Study

Concrete is one of the most widely used construction material in the world. It is a fundamental construction material used to fulfill the housing and infrastructural need of the society having the basic constituent of conventional fine and coarse aggregate, cement and water. It has proven to be a leading construction material for more than a century and it is estimated that the global production rate annually is at $1m^3$ (approximately 2.5 ton) per capita (Neville, 2003). However, high consumption of concrete results in high demand of cement. It was estimated that 125liters of fossil fuel and 118KWH of electricity is consumed in the production of 1tone of cement (Vazinram and Khodaparast, 2009). This means the production of cement requires the burning of fuel which results in significant release of large amount of carbondioxide (CO_2). Patricija, Aleksandrs and Valdemars (2013), noted that cement does not only consume energy during its production, it is also accountable for a substantial part of man-made CO_2 emission, which leads to global warming. During the manufacturing of 1 ton of cement, 1 to 1⅓ ton of earth resources like lime stone is used up and at the same time, an equivalent amount of CO_2 is released into the atmosphere (Srinivasan, Sathiya and Palanisamy, 2010). According to Jindal and Kamal (2015), production of Portland cement currently exceed 2.6 billion tons per year worldwide and it increases at 5% rate each year thereby generating nearly 7% of atmospheric carbon-dioxide (CO_2) which contributes largely to the global warming. Priya and Partheeban (2013), explain that the CO_2 constitute up to 65% of global warming. Because of these, efforts have been made by researchers to reduce the problem created when using Portland cement in concrete production whereby its quantity is partially replaced with supplementary cementing materials such as fly ash, ground granulated blast furnace slag, rice husk ash, metakaolin etc. Another way of developing alternative environmentally friendly concrete is to replace Ordinary Portland Cement (OPC) with a binder known as geopolymer which is presented herein.

Tavor, Wolfson, Shamaev and Shvarzman (2007), defined geopolymer as an amorphous polymer formed through the ionic bonding reaction between an aluminosilicate (Al - Si) materials and strong alkaline solution. It results into polycondensation of silica and alumina from a source material rich in silica (Si) and alumina (Al) like fly ash, metakaolin, silica fume and other pozzolana to attain structural strength instead of forming calcium-silicate-hydrates (CSH) as in the case of OPC (Rajamane, Lakshmanan and Nataraja, 2009). This binder shows a promising application for use in concrete production because according to Priya and Partheeban (2013), it could reduce CO_2 emission caused by cement industry by 80%. Metakaolin is used in this research as the source material and according to Sanjay, Anil and Subhash (2013), metakaolin is obtained by heat-treating of kaolin, a natural, finely divided, alumina silicecous mineral and it is abundant in Nigeria. According to Getso (2014), Kaolin can be obtained in abundance from the following states in Nigeria: Kastina, Plateau, Ogun, Imo, Rivers, Bauchi, Anambra, Kebbi, Ekiti, Kogi, and Akwa ibom. Matakaolin is produced under controlled temperature to refine its colour and remove inert impurities so that a much higher degree of purity and pozzolanic reactivity can be obtained (Sanjay *et al*., 2013).

Natural aggregates made up of coarse and fine aggregate, form the major component of concrete, occupying from 70% to 80% of the total volume of concrete mixtures (Verian, Whiting, Olek, Jain and Snyder, 2013). According to the American Concrete Pavement

Association (ACPA) (2009), though these Natural Coarse Aggregates (NCA) are vast, they are not finite because they are consumed in large quantities especially in urban areas; and with scarcity of it's sources, the cost is expected to rise. Therefore Recycled Concrete Aggregates (RCA) can be used as a viable substitute for NCA. Adejo (2012) described recycled concrete aggregates as aggregates that form the main component of old concrete. Recycling of these aggregates help in sustainable development by discouraging vast consumption of natural aggregates and reducing the disposal of demolished waste from old concrete, which makes it fit into present day notion of sustainability which is 'Reducing, Reusing, Recycling and Regenerating' as described by (Swapna, Sarkar and Rajamane, 2011). Significant researches have been carried out on RCA using Portland cement. According to Swapna *et al.*, (2011), RCA has lower specific gravity, higher water absorption, lower level of compressive strengths and durability when used to produce concrete. The presence of two kinds of Interfacial Transition Zones (ITZ) in concrete made with RCA is responsible for the decreasing trend of compressive strength and tensile strength with increase in the content of RCA (Verian *et al.*, 2013).

Various researchers have produced Geopolymer Concrete (GPC) using geopolymer binder with natural aggregate but limited research have been carried out as at the time of this work incorporating RCA in producing metakaolin based geopolymer concrete. In this research, metakaolin based geopolymer binder is used to produce concrete containing RCA and its properties evaluated.

1.2 Statement of Research

The construction industry is known to be a major consumer of materials in large quantities and at the same time produces large amount of waste (Valerie and Assia, 2013). This practice has led to the gradual decrease of natural resources like aggregate and also increase problem of accumulation of waste that occur through demolition of concrete structures. Due to this reason, focus is placed on environmental issues such as sustainable development and recycling (Benjamine and Natelie, 2013). According to Valerie and Assia (2013), if the vision of sustainable material flow is to be realized, it is imperative that the waste generated from construction activities be recycled. Over the years, the practice of producing Portland cement concrete (PCC) while utilizing RCA as partial or full replacement of natural coarse aggregate have been carried out, but George (2014) discovered that properties of concrete made using RCA is of lower quality when compared to conventional concrete and as a result, its application in the construction industry is limited.

As the demands for concrete continue to increase due to rapid infrastructural development, so is the demand of OPC. Liew, Kamarudin, Mustafa, Luqman, Khairul and Heah, (2011), explains the growing concerns on environmental impact caused by the extraction of raw materials for cement and CO_2 emission during cement manufacturing. In view of this, the concept of geopolymer which is environmentally friendly was developed to be used as an alternative to OPC in concrete production. Many researchers have utilized natural aggregates in the production of geopolymer concrete but few researches have been carried out producing geopolymer concrete using RCA. Result on the study of mechanical properties of geopolymer concrete containing RCA at different replacement shows that compressive and tensile strength and elastic modulus increases when compared to OPC concrete containing the same replacement of RCA. Increase in percentage replacement of RCA in GPC lead to decrease in mechanical properties of GPC. As Sodium Hydroxide (NaOH) concentration increase, compressive and tensile strength increases (Anuar *et al.*, 2011; Shuang *et al*., 2012; Posi *et al*., 2013; Seta *et al*., 2013). Currently very few researches have been carried out exploring the properties of metakaolin based geopolymer concrete containing RCA.

1.3 Justification of the Study

One way to help in achieving higher infrastructure sustainability is the development and use of new materials, deliberately designed with sustainability as a primary goal, in terms of improved social wellbeing, increasing economic prosperity, and reduced environmental impact (Mukherjee and Vesmawala, 2013). Therefore, the result of this research gives information on the integrity and suitability of metakaolin based geopolymer binder when used as an alternative binder to OPC in order to produce GPC containing RCA. It also conserves natural resources used in the production of cement like limestone and so on.

Dahiru *et al.*, (2009) in Gambo, Dahiru and Khalil, (2014) explained that one of the most serious problems confronting this present generation is waste. That is why the two basic actions toward achieving sustainability stated in general Rio Agenda 21 are; the minimization of total waste produced and the maximization of environmentally sound waste and recycling. Utilizing RCA in this work tend to reduce waste produced as a result of demolition activities. According to Ayangbade, Olusola, Ikpo and Ata (2004), the cost of materials in construction account for about two-third of the total construction cost. Thus, producing concrete containing RCA using metakaolin based geopolymer binder would help in reducing the cost for concrete materials.

1.4 Aim and Objectives

1.4.1 Aim

This research is aimed at assessing the properties of concrete made with RCA and metakaolin based geopolymer with a view to establishing an alternative usage for RCA.

1.4.2 Objectives

The research aim is achieved through the following objectives:

i. To assess the physical and mechanical properties of RCA and NCA.
ii. To determine the workability of fresh concrete specimens.
iii. To determine the mechanical properties of hardened concrete specimens.
iv. To evaluate the durability properties of hardened concrete specimens.

1.5 Scope and Limitation

1.5.1 Scope

This research focuses on the mechanical and durability properties of concrete specimen which include compressive and tensile strengths, absorption capacity, abrasion resistance and the resistance of concrete specimens to $MgSO_4$.

1.5.2 Limitation

In view of the non- availability of some vital apparatus/ equipment used in the evaluation of thermal conductivity, carbonation, thermal insulation and chlorine absorption, these properties were not accessed.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Portland Cement

Portland cement is obtained by mixing together calcareous materials like limestone or chalk and argillaceous materials such as shale or clay or other silica and iron oxide bearing materials burning them at a clinkering temperature and grinding the resulting clinker (Neville and Brooks, 2010). According to Shetty (2009) the manufacturing process of cement involves grinding of raw materials and mixing them thoroughly in a certain proportion which depend upon their purity and composition and burning them in a kiln at about 1300^{o}C – 1500^{o}C. At this temperature, the materials bond together and partly fused into clinker (Neville and Brooks, 2010). It is then cooled and ground to a fine powder with some gypsum added. The process of Portland cement manufacturing is grouped into two and according to Shetty (2009), they are the wet and dry process. In the wet process, limestone after crushing into small fragment is taken to a ball or tube mill where it is mixed with clay or shale and ground to a fine consistency of slurry with the addition of water. The slurry is pumped to a slurry tank or basin and kept in an agitated condition with the aid of rotating arms with chains or blowing compressed air from the bottom to prevent setting of lime stone and clay particle. In the dry process, the raw materials are crushed and fed in correct proportions into the grinding mill where they are dried and reduced to a very fine powder. The dry powder is then further blended and corrected for its right position and mixed by means of compressed air.

2.1.1 Chemical composition of Portland cement

Materials used in Portland cement manufacturing consist mainly of lime, silica, alumina and iron oxide. At high temperature, the materials interact with one another to form a more complex compound (Shetty, 2009). The proportions of oxide composition for Ordinary Portland Cement (OPC) are shown in Table 2.1.

Table 2.1: Oxide Composition Limit of Ordinary Portland cement

Oxide	Percentage Content (%)
CaO	60 – 67
SiO_2	17 - 25
Al_2O_3	3.0 - 8.0
Fe_2O_3	0.5 - 6.0
MgO	0.1 - 4.0
Alkalies (K_2O, Na_2O)	0.4 - 1.3
SO_3	1.3 - 3.0

Source: Shetty (2009)

2.1.2 Current energy use and carbon-dioxide (CO_2) emission

According to Mohammed, Collect and Sean (2012), every year 3.6 billion tons of Portland cement is estimated to be produced. It was estimated that for every 1kg of cement manufactured, it gives an approximate by-product of 0.9kg of CO_2 meaning that 3.24 billion tons of CO_2 per year is released into the air (Hendriks, Worell, de Jagar, Blok and Riemer, 2004). The World Business Council for Sustainable Development (WBCSD) (2012) in Mohammed *et al.,* (2012) estimated that 40% of CO_2 emissions are from the burning of fossil fuel to operate the kiln, 50% from the manufacturing process itself and the remaining 10% are indirect CO_2 emitted during transportation of the finished product and front-end production. The process of manufacturing Portland cement and the percentage of CO_2 emission is shown in Figure 2.1 as described by Mohammed *et al.,* (2012) as follows:

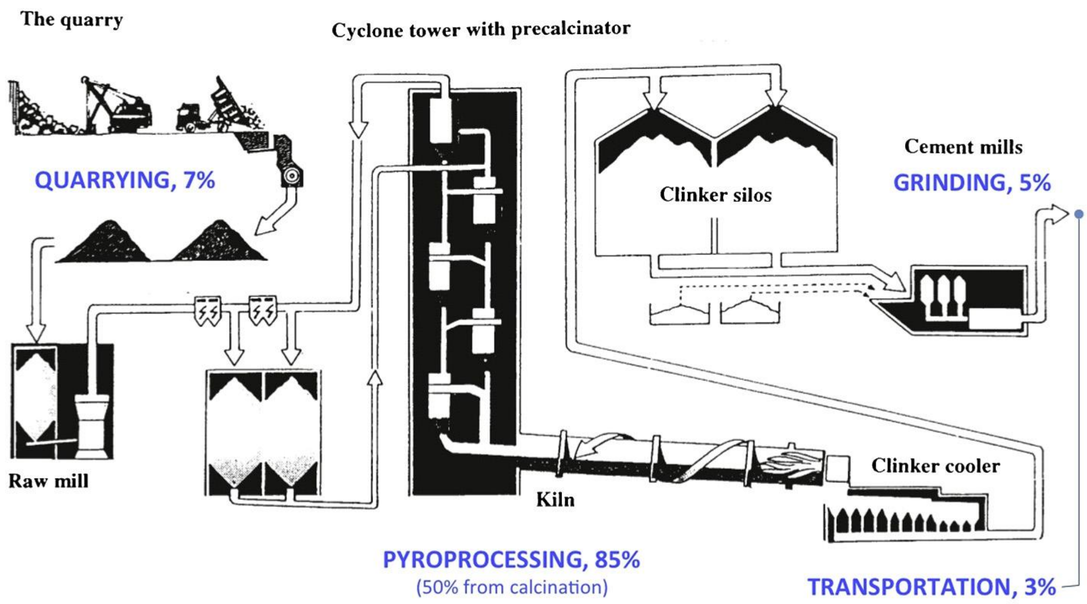

Figure 2.1: **Percentage emission of CO_2 during OPC production process**
Source: Mohammed *et al*., (2013)

i. Quarrying

This involves the drilling, blasting, excavating as well as crushing, screening and storing of raw materials such as lime stone used for cement production. During this process, the operation of machinery is responsible for CO_2 emission, which is about 7% of the total CO_2 emitted.

ii. Pyroprocessing

In this process, 85% of the total CO_2 is emitted. Material undergoes the process known as calcination inside the kiln after all moisture is evaporated out. The end product size ranges from dust to big lumps of calcium silicate or clinker. Temperatures used are generally around 1400^{o}C–1600^{o}C, and energy demand varies depending on the manufacturing process.

iii. Grinding

The lumps of clinker are ground up with calcium sulfate dihydrate ($CaSO_4.2H_2O$) or gypsum or active anhydrite to control the rate of hardening or the setting time. In the course of grinding the lump of clinker, 5% CO_2 is emitted. The final product, OPC is used in various ways; primarily to make mortar, concrete or cavity block.

iv. Transportation

It is recommended that cement production plants be located at or close to limestone quarries because the cost of transporting the raw materials greatly affects the cement production. About 3% of the total amount of CO_2 is emitted during transportation of cement.

2.1.3 Environmental impact of cement during manufacturing

According to Syed and Bhat (2013), cement kiln dust; a by-product of the final cement product, is usually stored as wastes in open-pits and landfills. These dusts contain heavy metals like chromium, nickel, cobalt, lead and mercury pollutants that are hazardous to the biotic environment thereby having great impact on vegetation, human health, animal health and ecosystem (Baby, Singh, Shrivastava, Nath, Kumar and Vievek, 2008). In areas filled with cement dust, people living there are badly affected by respiratory problems, gastro intestinal diseases etc (Adak, Adak and Purohit, 2007). Heather (2003) discovered that exposure to cement dust over a short period of time may not cause serious problem, but if the exposure prolonged, it will cause serious irreversible damage to plants and animals. Cement dust of sufficient quantities has been reported to have the tendency of dissolving leaf tissues and also irritate the skin (Ikli, Demir, Urer, Beker, Akar and Kalyoncu, 2003)

It has also been reported that cement dust on plants reduced growth, reduced chlorophyll, clogged stomata in leaves, cell metabolism disruption, interrupt absorption of light and diffusion of gasses (Syed and Bhat, 2013). According to Adak *et al.,* (2007), cement factories deteriorate the environment due to the exhaust gases and particulate matters of the dust exhausted from cement plants released into air which degrades the quality of air and thus creates considerable environmental pollution.

2.2 AGGREGATES

Duggal (2008) describe aggregates as materials basically used as filler with binding material in the production of mortar or concrete. According to Neville and Brooks (2010), they were initially viewed as an inert, inexpensive material dispersed in the cement paste to form concrete, but it is not altogether inert because the physical, thermal and in some cases chemical properties influence the performance of the concrete. Shetty (2005), explained that they occupy 70-80% of the total volume of concrete which makes them have considerable influence on the various characteristic and properties of concrete they are made up of. For this reason, it is of outmost importance that right type and quality aggregate be used to make concrete, they should be clean, hard, strong, durable and graded in size to achieve utmost economy from the paste (Duggal, 2008).

Aggregate materials as explained by Garba (2014), are used in concrete to increase strength, volume and durability, reduce creep, reduce shrinkage and reduce overall cost, thermal properties and impact sound, impact density and increase chemical resistance of the concrete. Examples of such materials include palm kennel shells, pumice, crush rock, recycled concrete, gravel, scrap iron, lead, iron shots, barites, crushed burnt bricks, etc.

2.2.1 Classification of aggregates

The classifications of aggregates include the following:

i. Based on their geological origin

Aggregate based on their geological origin can be classified into natural and artificial aggregates

a. Natural aggregate

According to Neville and Brooks (2010), they are formed by the process of weathering and abrasion or by crushing a larger part of their parent rock. Shetty (2005), explained that the parent rocks include Igneous rock which are made from the cooling of molten magma on the surface of the crust (trap and basalt), or deep beneath the crust (granite), Sedimentary rocks which are formed below the sea bed and lifted up, Metamorphic rocks are originally igneous or sedimentary rocks and they metamorphosed due to extreme heat and pressure. Many properties of the aggregates depend on the properties of their parent rocks e.g. chemical and mineral compositions, specific gravities, and hardness, physical and chemical stability etc, they influence the quality of fresh and hardened state of concrete (Neville and Brooks, 2010).

b. Artificial aggregate

Zongjin (2011), explains that these kinds of aggregates are manmade materials, resulting from products or by-products of industries. According to Faridah (2009), they produce light weight concrete of adequate strength and good heat insulation properties. Examples include blast furnace slag, expanded clay, etc., organic materials and by-products such as saw dust, wood chips, rice husk ask, palm kernel shells, periwinkle shells, etc.

ii. Classification based on size

According to Shetty (2005), factors influencing the maximum size of aggregates which can be used in any given condition include the following; thickness of section, spacing of reinforcement, clear cover to concrete element, mixing, handling and placing techniques. He also explained that the aggregates maximum size should be as large as possible within the limit specified, but should not in any case be greater than one-fourth of the minimum thickness of the member. On the basis of size consideration, aggregates can be classified as coarse and fine.

a. Coarse aggregate

According to Duggal (2008), they are obtained by natural disintegration or artificial crushing of rocks. Aggregates retained on 4.75 mm sieve are classified as coarse and their maximum size can be 80 mm.

b. Fine aggregates

They are obtained from natural sand deposited by rivers; crushed stone sand obtained by crushing stones and crushed gravel sand. They pass through 4.75 mm sieve and the smallest size of fine aggregates (sand) is 0.06 mm (Duggal, 2008).

iii. Classification based on shape and texture

The shape is an important characteristic since according to Zongjin (2011), aggregate shapes affects the workability of concrete due to the difference in surface area caused by different shapes. Factors influencing the shape of aggregates include the characteristic of the parent rock and also the type of crusher used (Shetty, 2005). Examples of aggregates shapes include Rounded, Irregular or partly rounded, flaky, angular, elongated etc. The texture of aggregate is the degree to which the aggregate surfaces are polished or dull, smooth or rough. According to Shetty (2005), factors influencing the surface texture of aggregates depend on the hardness, grain size, pore structure of the rock and the degree to which all the forces acting on the aggregates have smoothened or roughened surface. Example include honeycombed, crystalline, rough, granular, etc. Surface texture of aggregate have significant influences on the fluidity of fresh concrete and the bond existing between the aggregates and cement paste of the hardened concrete (Zongjin, 2011).

2.3 Recycled Concrete Aggregate (RCA)

The concept of sustainable development in construction have been gaining increasing attention and according to Sasha, Justin, Richard and Medhat (2009), one of the most obvious ways of achieving a sustainable construction is by conservation of natural aggregates and reusing construction and industrial wastes. Swapna *et al*., (2011) explained that (RCA) which is an example of common construction wastes, are obtained by crushing concretes from demolition of concrete structural components in many structures such as old buildings, concrete pavements, bridges, structures that have come to the end of their service life and utility, structures that deteriorated beyond the possibility of repairs, structures that turn into debris resulting from natural disasters (such as floods, earthquake, manmade disaster/war, etc), those structures not serving the needs in present scenario and old structures to be brought down to pave way for new construction for better economic growth. The most common method of managing the waste generated has been through its disposal in landfills until researchers began to incorporate this waste as aggregate to produce concrete. Akinkurolere, Aribisala, Oke, Ogundipe, (2013) explained that RCA is processed by crushing, screening, and washing of the aggregates to obtain proper cleanliness and gradation. Mirjana, Vlastimir and Snezana, (2010) categorize this production in two stages; that is, by crushing of the demolished concrete and by screening and removal of contaminants such as reinforcement, paper, wood, plastics and gypsum. Concrete made with recycled concrete aggregates (RCA) is called recycled aggregate concrete (RAC).

2.3.1 Properties of recycled concrete aggregate (RCA)

RCA is produced by crushing and sorting existing concrete to be used as aggregates in new concrete but according to Oikonomou (2005), working with RCA can be challenging since most often the specifics about the original concrete are unknown, this tend to make some of the properties of RCA differ from those of natural aggregates. The properties of RCA include:

i. Particle composition, shape and texture

Recycled concrete aggregates are comprised of reclaimed virgin aggregate, reclaimed mortar or both. However, Kou, Poon and Chen (2007), observed that the particle of RCA differ from those of natural aggregates (NA) because they are more angular in shape and have a rougher surface texture than those of natural aggregates. Roughly textured, angular, and elongated particles will require more water to produce a workable concrete than smooth, rounded compact aggregates.

ii. Absorption capacity

This is defined as the absorption rates of water by aggregates; it is determined by measuring the increase in mass of an oven dried sample when immersed in water for 24 hours. The old mortar that inherently cling to the aggregate during manufacturing of RCA creates a more porous system in the RCA and it is the primary factor that causes an increased absorption capacity leading to the decrease in specific gravity commonly associated with RCA as compared to NCA (Verian *et al.,* 2013). Table 2.2 gives details of results of absorption capacity from previous research. It was observed by Alexandra (2011), that the absorption rate not only affects the bond between the aggregates and cement paste, when the absorption capacity of the aggregate is high, it also decreases the workability of fresh concretes.

Table 2.2: Absorption capacity of RCA and NA from previous research

	Absorption Capacity (%)	
Author	**RCA**	**NA**
Xiao *et al.,*(2005)	9.25	0.4
Kou *et al., (2007)*	3.52 – 4.26	1.11 – 1.12
Ann *et al.,*(2008)	4.25	0.73
Abbass *et al., (2009)*	3.3 – 5.4	0.54 – 0.98
APCA (2009)	3.7 – 8.7	0.8 – 3.7

Source :Verian, *et al*., (2013)

iii. Specific gravity

Specific gravity or relative density is defined by American Standard for Testing and materials (ASTM) as the ratio of the density of a material to the density of distilled water at a stated temperature (James, 2009). ASTM C 128 is the procedure for obtaining specific gravity. According to Alexandra (2011), the specific gravity of an aggregate gives valuable information on its quality and properties and it is seen that the higher the specific gravity of an aggregate, the harder and stronger it is. Work carried out by various researchers as shown in Table 2.3 reported lower specific gravity for RCA than that of NA because of the old mortar attached to it.

Table 2.3: Specific gravity of RCA and NA from previous research

Author	Specific Gravity (Coarse Aggregate)	
	RCA	**NA**
Xiao *et al.*,(2005)	2.52	2.85
Kou *et al., (2007)*	2.49 – 2.57	2.62
Ann *et al.* ,(2008)	2.48	2.63
Abbass *et al., (2009)*	2.42 – 2.5	2.71 – 2.74
APCA (2009)	2.1 – 2.4	2.4 – 2.9

Source:Verian, *et al*., (2013)

iv. Abrasion resistance

Abrasion resistance is used as an index of aggregate quality and its ability to resist weathering and loading action. Sagoe-Crentsil, Brown and Taylor (2001), explain that abrasion resistance of RCA is twelve percent lower than that of virgin aggregate.

v. Mortar content

When producing RCA, some of the old mortar falls away but much of it inherently clings to the aggregate and becomes part of the RCA product. Verian *et al*., (2013) found that the presence of old mortar attached to RCA creates greater areas of aggregate-paste interfaces when used to produce new concrete. The aggregate-paste interface is known as Interfacial Transition Zone (ITZ). The interfacial transition zone occurs between aggregates and mortar in normal concrete, while in concrete made with RCA, the ITZ is weak because it occurs between aggregate-old mortar, aggregate-new mortar, and old mortar-new mortar (Verian *et al*., 2013).

2.3.2 Properties of concrete made with recycled concrete aggregates (RCA)

The properties of plastic and hardened concrete are usually affected by the characteristics of the Aggregates. The American Concrete Institute (ACI) (2001), explained that the difference in the properties of RCA when compared to natural coarse aggregates (NCA), could lead to differences in the properties of concrete containing RCA and that made from NCA. The difference in these properties is explored in both the plastic and hardened states and it includes:

i. Fresh concrete properties

a. Workability

Workability of concrete is usually determined using slump test in accordance with ASTM C 143. High slump means that the concrete is more workable, while a lower slump means it is a stiffer mix. Smith and Tighe (2008), report that RCA may have less workability than concrete produced with NCA at the same water/cement ratio, Roesler and Hunley (2008), attributed the decrease in workability of the concrete made with RCA to the angularity of the aggregates, aggregates sizes, shape and gradation, rough surface texture, higher absorption capacity and mixture proportion. Table 2.4 gives a report of various researches on workability of concrete made with RCA. According to Smith and Tighe (2008), the use of admixtures may be a way of achieving similar workability between concrete made with RCA and normal concrete when the same water/cement ratio is required.

Table 2.4: Workability of RAC from various Research

Author	Workability
Smith and Tighe 2008	Lower
ACPA (2009), FHWA (2007),ACI (2001)	Similar to slightly lower
Sturtevant et al. (2007)	Lower
Liu and Chen (2008)	Lower
Topcu et al. (2004)	Lower

Source :Verian, *et al.*, (2013)

b. Density and air content

Kou, (2006) found that concrete made with RCA will have a lower density because of the amount of old mortar that cling to the surface of the aggregates. The densities of RCA concrete may range from 5 – 15% lower than that of the concrete made with conventional aggregates. The air content of fresh concrete containing RCA is usually up to 0.6% higher than that of normal fresh concrete as explained by ACPA (2009). It was explained by Angulo, Carrijo, Figueiredo, Chaves and John (2009), that higher air content generally is assumed to be caused by the air that is entrained and entrapped in the reclaimed concrete mortar attached to the RCA.

ii. Hardened Concrete Properties

a. Compressive strength

Compressive strength is the ability to resist compression loads and in general, concrete produced using RCA decreases in compressive strength as compared to those of virgin aggregate (James, 2009).The extent of the decrease is related to parameters such as the type of concrete that the RCA is made of either high, medium or low strength concrete, replacement ratio, water/cement ratio and the moisture condition of the RCA (Akash, 2007). ACPA (2009) also discovered that the decrease in compressive strength of concrete with increased RCA content may be explained by the presence of two kinds of Interfacial Transition Zones (ITZ) in concrete made with RCA. The Interfacial transition zone represents the bond between aggregates and paste and is often weaker than either the aggregate or hydrated cement paste. According to Verian *et al*., (2013), the higher the percentage of RCA replacement in the concrete then theoretically the greater the potential reduction is in strength.

2.3.3 Benefits of using recycled concrete aggregates

Some of the benefits derived from using RCA include the following:

i. Reduced energy consumption in the production of virgin aggregates

According to Verian *et al.*,(2013), the production and even usage of virgin aggregate usually consumes a great deal of energy (either as motor fuel or electrical power). Each step of processing which includes: mining or extraction of the aggregate; the crushing, screening and washing; the stockpiling or transport to the job site, removal and disposal of material that is not recycled at the end of its period of utilization. But recycling can greatly reduce the need for mining or extraction, and can reduce haul distances and fuel consumption associated with both supply and disposal (ACPA 2009).

ii. Conservation of virgin aggregates.

The Federal Highway Authority (FHWA), (2004) found that another benefit derived from the usage of RCA in areas like the United States of America where the supply of virgin aggregate is becoming limited is that the use of recycled aggregates is beginning to serve as an environmentally friendly and economically viable solution. Also, some European countries have placed a tax on the use of virgin aggregates; this process is used as an incentive to recycle aggregates. According to FHWA (2004), several states have high levy for disposal of RCA, this is done to control landfill usage; thus increasing the reuse of RCA and conservation of the virgin aggregate.

iii. Reduce disposal costs

Reconstruction of urban streets and expressways results in an enormous amount of waste concrete being generated, which subsequently creates a massive disposal problem. The disposal of concrete rubble and other waste construction materials by dumping method or when it is buried is a less attractive and more expensive option (FHWA, 2004). Therefore recycling can alleviate some of these problems and offer savings to the owner in terms of material acquisition and disposal costs.

iv. Reduce construction cost

There may be considerable project savings by using RCA and less amount of virgin aggregates. According to ACPA (2009), some states estimated that 60% of savings is been realized by utilizing RCA as a replacement for natural aggregates. This saving is increased by the reduction of transportation and disposal costs. There are potentials for cost savings in many areas where aggregates are not locally available, and have to be hauled long distances.

2.3.4 Application of recycled concrete aggregate (RCA)

The application of RCA was explained by Dalhat (2010), to be in two forms which include:

i. Application without any processing include the following:

a. Many types of general bulk fills

b. Base or fill for drainage structures

c. Road construction

d. Noise barriers and embankment

ii. Application of RCA after processing include the following:

a. Structural grade concrete
b. Lean-concrete bases
c. New concrete for pavements, shoulders, sidewalks, curbs and gutter and bridge foundation.

2.4 GEOPOLYMER

According to Hadjito and Rangan (2005), Joseph Davidovite in I987 proposed that an alkaline solution could react with silicon (Si) and aluminum (Al) contained in a source material of geological or by-product; example of such are metakaolin, Fly Ash (FA), Rice Husk Ash (RHA), etc, to produce a binder which he termed geopolymer because of the polymerization process that takes place between them. Srinivas, Prathap and Prema (2015), explained that geopolymer are characterized by a three-dimensional aluminosilicate (Si-O-Al); they represent a broad range of materials characterized by a network of inorganic polymer. Geopolymer provides a comparable performance to traditional cementitious binder in a range of application with the added advantage of significantly reducing greenhouse gas (GHG) emission (Duxson, Fernandez-Jimenez, Provis, Lukey, Palomo, and Van-Deventer, 2007).

2.4.1 Terminology of geopolymer

Van Jaarsveld *et al*., (2002) in Wallah and Rangan (2006), recommended the use of the term Poly (sialate) as the chemical description of geopolymers because of its silico-aluminate content. The term sialate is an abbreviation used to represent silicon-oxo-aluminate while Poly(sialates) are defined as chain and ring polymer with Si^{4+} and Al^{3+} in IV-fold combination with oxygen. It ranges from amorphous to semi-crystalline with an empirical formula:

$$Mn\,(-(SiO_2)_Z - AlO_2)_n \,.\, wH_2O \text{ ---------------- } (2.1)$$

Where

z = a number from 1, 2 or 3 or higher up to 32

M = a monovalent cation such as potassium or sodium

n = is a degree of polycondensation or polymerization

w= the binding water amount

Davidovits (1999) in Wallah and Rangan (2006), categorized these Poly(sialates) as shown in Figure 2.2:

a. Poly(sialate) type (-Si-O-Al-O)

b. Poly(sialate-siloxo) type (Si-O-Al-O-Si-O)

c. Poly(sialate-disiloxo) type (-Si-O-Al-O-Si-O-Si-O-).

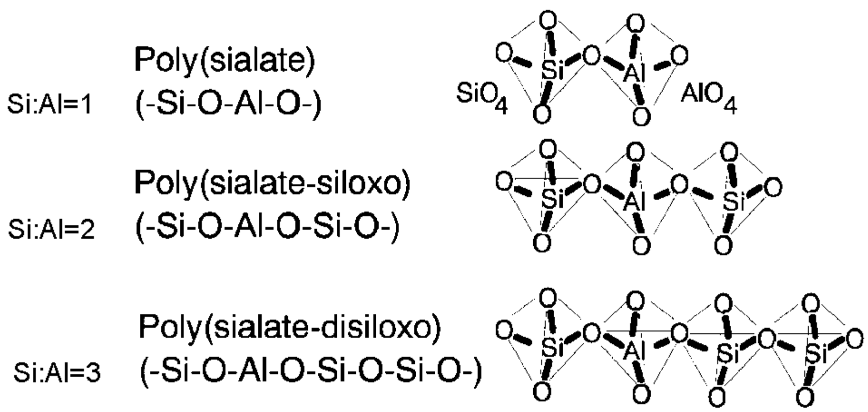

Figure 2.2: Schematic Structure of Polysialates
Source: Davidovits, (2002)

2.4.2 Geopolymer development

Geopolymer are developed through the following processes which include:

i. Dissolution of the Aluminosilicate Species within an Alkaline Environment

According to Jeffery, Ather and Michael (2012), this process occurs immediately the alkaline solution come in contact with the pozzolanic material; it gives room for ionic interface between the species and the breaking of covalent bonds between silicon, aluminium and oxygen atoms. The amount and composition of the ash and the pH of the activating solution determines the rate of dissolution (Xie and Xi, 2001).

ii. Polymerization of the dissolved minerals into short-lived structural gel

This process is a considerably fast chemical reaction under alkaline condition on Si – Al materials which result into a three-dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds (Skvara, Dolezal, Svoboda, Kopecky, Pawlasova, Lucuk, Dvoracek, Beksa, Myskova and Sulc, 2006). Xie and Xi (2001) explained that the gel product formed contain alkaline cations which balance the deficit charges associated with the aluminum-for-silicon substitution. In this case, an intermediate, aluminum-rich phase is first formed which then gives way to a more stable, silicon rich three-dimensional gel product. This is dependent upon curing conditions and activator type (Fernandez-Jimenez, Palomo, Sobrados and Sanz, 2006). Figure 2.3 gives the equation of the formation of geopolymer material.

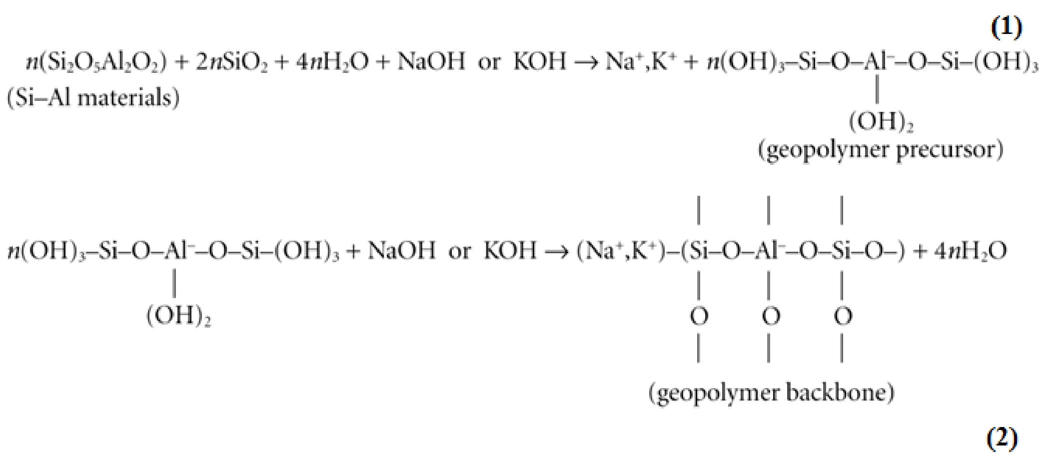

Figure.2.3: Formation of geopolymer material described using Equations (1) and (2).

Source:Rangan (2010)

According to Rangan (2010), in the second equation, the last term means water is released during the chemical reaction that occurs in the formation of geopolymers. The water expelled from the geopolymer matrix during curing and further drying process leaves behind nano-pores in the matrix. This means that water in a geopolymer mixture plays no role in the chemical reaction that takes place; it only provides the workability to the mixture during handling.

iii. Precipitation of formed hydration products similar to natural zeolite, final hardening of matrix by excess water exclusion and the growth of crystalline structures.

Slow growth of crystalline structure becomes obvious when the nuclei of the polymerized gel reach critical stage and the matrix crystallinity is relative to the rate by which precipitation occurs. Geopolymer cement are usually called zeolitic predecessor rather than the actual zeolite because the fast reaction that occurs between the alkaline and pozzolanic ash do not give time for growth of a well structured crystalline environment (Jeffery *et al*, 2012). Amorphous, semi-crystalline cementitious material is obtained as the final product of geopolymerization process. Figure 2.4 illustrates the development model for geopolymerization process.

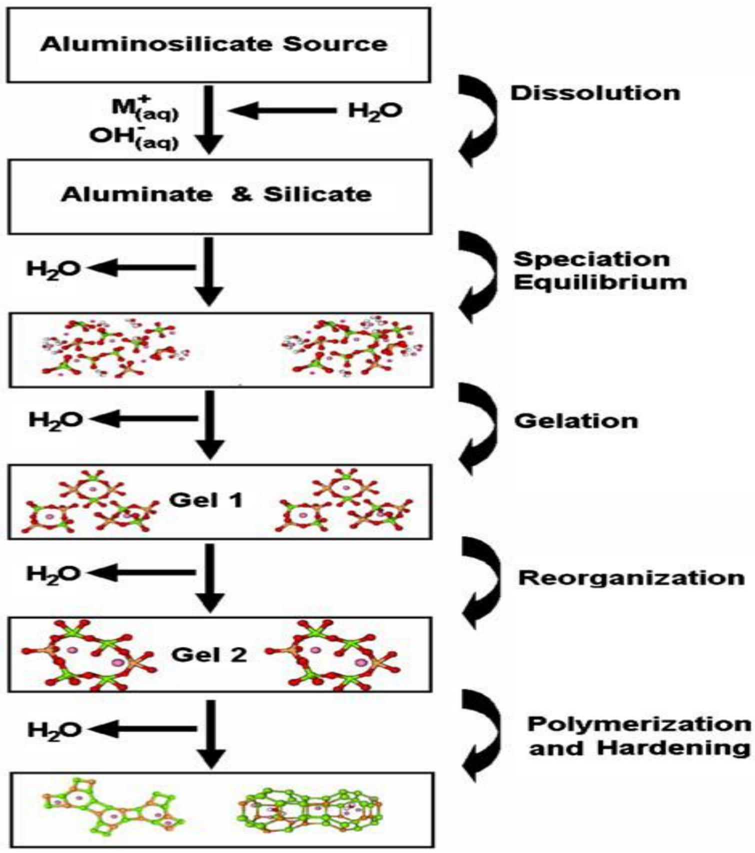

Fig.2.4: Geopolymer development model
Source: Duxson, *et al.*, (2007)

2.4.3 Constituent of geopolymer

The two main constituent used to make geopolymer binder are the source material and alkaline activator.

i. Source material

Materials rich in silica (Si) and Alumina (Al) are the primary requirement for geopolymerization to occur. According to Rangan (2014), source material with low calcium content is preferred compared to that with high calcium content, because the presence of calcium in high content interferes with the microstructure and hence compromises some benefits offered by geopolymer cement. Examples of materials for making geopolymer binder include fly ash, ground granulated blast furnance slag, metakaolin, etc. The choice for the selection of a source material for making geopolymer binder depends on factors such as availability, cost, and type of application and specific demand of the end user

(Rangan 2014). Examples of source materials include:

a. Commercial Fly Ash

Fly ash is an industrial by-product obtained from burning of bituminous coal; it is a material with low- calcium content and is considered suitable as a source material for geopolymer binder. According to Williams, Biernacki, Walker, Meyer, Rawn, Claudia and Bai (2002), fly ash is an acidic material containing acidic oxides such as Al_2O_3, SiO_2 and Fe_3O_2 which provide potentials for alkaline reaction. Most of the fly ash obtained from the burning of coal is made up of an in-homogeneous mix of aluminoslicate, silica glass with small amount of crystalline material such as mullite, quartz, hematite and magnetite (Song *et al.*, 2000). It was therefore suggested by Rangan (2005), that due to the degree of in-homogeneity, additional care should be taken to ensure optimal mix design and consistent final product.

Physical characteristics affecting the reactivity of fly ash include the particle size distribution and fineness of the particles. According to Chen and Brouwers (2007), the presence of reactive silica content in the fly ash is most influential from a chemical perspective; it increases the formation potential of the aluminosilicate gel which provides mechanical strength to geopolymers. The ability for a fly ash material to be alkaline-activated is driven by several other factors, which are the percentage of unburned material in the ash product that act as inert particles causes increase to the liquid/solid ratio and the content of its glassy phase (Jeffery *et al*., 2012). The aluminum content of a fly ash material is critical to the hardening properties of geopolymer. In the presence of alkali aluminosilicate slurries, the aluminum content is believed to be the chemical trigger for irreversible hardening (Rangan, 2005). Furthermore, the dissolution of solid Al_2O_3 regions by the activating solution controls the rate, stoichiometry and extent of solution phase reactions and it is dependent upon several variables including pH level, binder temperature, the Silica/Alumina ratio and alkali concentration (Rangan, 2005).

b. Metakaolin

Metakaolin can be described as a dehydroxylated pozzolanic product derived from the high temperature firing of raw kaolin. Kaolin or kaolinite ($Al_2Si_2O_5(OH)_4$) is a clay mineral which contain high amount of layered tetrahedral silicon atom connected via oxygen to octahedral aluminum atom (Jeffery *et al.*, 2010). ASTM C618 classifies metakaolin as a Class N (or natural) pozzolan. The Meta prefixes attached to kaolin connote change and the change that occurs in this context is the dehydroxylation. Dehydroxylation is the decomposition of kaolinite crystals to a partially disordered structure. According to Gabriel (2007), the isothermal firing results shows that dehydroxylation begins at 420^{o}C. Dehydroxylation of kaolin to metakaolin is an endothermic process because it requires large amount of energy say in excess of 550^{o}C and above to remove the chemically bonded hydroxyl ions which are strongly bonded to the aluminosilicate framework structure (Olawale, 2013; Sanjay *et al*, 2013).

The process of dehydroxylation is such that at approximately 500°C - 800°C, kaolinite loses most of its absorbed water and crystallinity, leading to the destruction of its hexagonal layer structure at this temperature. The original mineral structure therefore becomes disorganized, forming the material referred to as metakaolin. It is a partially ordered structure that cannot rehydrate in the presence of water (or does so very slowly). It is a white, armorphous and highly reactive aluminosilicate pozzolana forming stable hydrates after mixing with limestone in water and providing mortar hydraulic properties. The equation describing the process of kaolinite transformation to metakaoline according to Gabriel (2007) is given as

$$Al_2O_3.2SiO_2.2H_2O \rightarrow Al_2O_3.2SiO_2 + 2H_2O ---------(2.2)$$

Many advantages have been reported on the uses of metakaolin as raw material in the synthesis of geopolymer. Some of these advantages include; reduction of efflorescence (a whitish haze which is caused when a calcium hydroxide reacts with carbon dioxide in the atmosphere), increase or boost compressive and flexural strengths, mitigate against chloride and other permeability, increase resistance to acid attack and durability of the geopolymer (Olawale. 2013).

Source of Kaolin in Nigeria

Gabriel (2007), describes kaolin as a soft, lightweight and often chalk-like sedimentary rock that has an earthy odor with plate-like crystal morphology. It contains quartz and mica and less frequently feldspar, illite, montmorillonite, ilmenite, anastase, haematite, bauxite, zircon, rutile, kyanite, silliminate, graphite, attapulgite and halloysite (Gabriel, 2007). It can be found in abundance in many parts of Nigeria as shown in Table 2.5.

Table 2.5: Sources of kaolin in Nigeria and their chemical composition

Deposit	Chemical Composition (%)										
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	SO_2	L.O.I	Colour
Ozubulu	60	26	5	5	Trace	Trace	Trace	Trace	-	-	White, light grey and dark brown
Nahuta	47	32	1.3	2.4	Trace	Trace	Trace	Trace	0.55	12-18	White, Yellow, pink, grey and brown
Jagalwa River	50	30	1.4	2.4	Trace	Trace	Trace	Trace	-	-	-
Darazo	51.9	32.9	2.9	-	0.39	0.29	Trace	0.89	0.13	-	Orange, pink, brown and white grey
Kankara	43.3	36.7	0.21	Nill	Trace	1.49	Trace	0.7	-	11.10	Off-white with pink and patches
Onibode	43.1	36.1	3.1	1.9	Trace	Trace	Trace	Trace	-	12.65	-
Ifon	48	33.2	0.006	1.72	Trace	Trace	Trace	Trace	-	-	Pink
Okitipupa	50	29	-	-	-	-	-	-	-	10	-
Major Porter	45.6	35.2	2.7	-	Trace	Trace	Trace	Trace	-	-	-

Source: Alabi and Omojola, (2013)

Properties of metakaolin

The physical and chemical properties of metakaolin according to Sanjay *et al*, (2013) is as shown in Table 2.6 (a) and 2.6(b) which include the following

Table 2.6(a): Physical Properties of Kaolin

Physical Properties	**Description**
Specific Gravity	2.4 to 2.6
Physical Form	Powder
Colour	Off White, Gray to Buff
Brightness	80 – 82 Hunter L
BET	15 m^2/gram
Specific Surface	8 – 15 m^2/g.

Source: Sanjay *et al*., (2013)

Table 2.6(b): Chemical Properties of Kaolin

OXIDE	**COMPOSITION**
SiO_2	51 – 53%
Al_2SiO_3	42 – 44%
Fe_2O_3	< 2.20%
TiO_2	< 3.0%
CaO	< 0.20%
MgO	< 0.10%
Na_2O	< 0.05%
K_2O	.< 0.04%
SO_4	< 0.50%
P_2O_5	< 0.2%
L.O. I	< 0.50%

Source: Sanjay, *et al.*, (2013)

3 Alkaline activator

In producing good cementitious material through the process of polymerization, activation of the pozzolanic material selected by the alkaline activator is one of the most important factor (Jeffery *et al.*, 2010). This alkaline activator quickens the precipitation and crystallization of the siliceous and aluminious specie present in the solution. According to

Priya and Partheeban (2013), a combination of sodium hydroxide (NaOH) or Potassium hydroxide (KOH) and Sodium Silicate (Na_2SiO_3) or Potassium Silicate (K_2SiO_3) are commonly used as the alkaline activator. According to Jeffery *et al.,* (2010), the first step in geopolymerization reaction is stirred by the ability of alkaline solution to dissolve the pozzolanic materials and release the reactive silicon and aluminum into the solution. KOH attain higher mechanical strength when used at varying concentration because the K^+ ion is more basic compare to other activating ions. This allows it to have a higher rate of solublized polymeric ionization and dissolutions, which leads to a dense polycondensation reaction providing an overall network formation and an increased compressive strength of the matrix (Khale and Chaudhary, 2007). Although KOH is reliable to provide a greater extent of dissolution due to its higher level of alkalinity, NaOH as a matter of fact also possesses a greater capacity to liberate silicate and aluminate monomers (Rangan, 2005). It was also discovered by Fernandez and Palomo (2003) that NaOH in low concentration was the most effective chemical activator for low calcium fly ash. Nevertheless, irrespective of the type of alkaline activator selected, higher concentrations of alkaline activators yield greater mechanical strength values.

Palomo *et al.,* (1999) in Hardjito and Rangan (2005), concludes that in polymerization process, the type of activator used plays an important role because reactions occur at a high rate when the alkaline activator contains soluble silicate, either sodium or potassium silicate, compared to the use of only alkaline hydroxides. Xu and Van Deventer, (2000) explain that the addition of sodium silicate solution to the sodium hydroxide solution as the alkaline activator enhanced the reaction between the source material and the solution. Sodium silicate is the most suitable alkaline activator, because it contains dissolved and partially polymerized silicon which reacts easily, incorporates into the reaction products and significantly contributes to improving the mortar characteristics. (Komljenovi, Bascarevic and Bredic, 2010). The alkaline activators include the following:

a. Sodium Hydroxide (NaOH)

Sodium hydroxide also known as caustic soda is odorless and is commonly used as an activator when producing geopolymer binder. Rangan (2010), opines that although it does not maintain the level of activation as K^+ ion, sodium cations are smaller than potassium cations and can migrate throughout the paste network with much less effort thus promoting better zeolitization. The resulting geopolymer binder property is determined by the concentration and molarity of this activating solution (Jeffery *et al*., 2010). It was discovered that while high NaOH additions accelerate chemical dissolution, it depresses ettringite and carbon-hydrogen formation during binder formation, in higher concentration, it promotes higher strengths at early stages of reaction, but the strength of aged materials were compromised due to excessive OH^- in solution causing undesirable morphology and non-uniformity of the final products (Khale and Chaudary, 2007). It was also discovered by Garci-Loderio, Palomo and Fernandez-Jimenez (2004), that geopolymers activated with NaOH develop greater crystallinity, thus improving stability in aggressive environments of sulfates and acids. Also, the use of NaOH as an activator buffers the pH of pore fluids, regulates hydration activity and directly affects the formation of the main C-S-H product in geopolymer pastes (Chareerat, Lee-Anansaksiri and Chinaprasita, 2006). A detail of chemical properties of NaOH is presented in Table 2.7.

Table 2.7: Chemical composition of NaOH

Assay	97%	Min
Carbonate (Na_2CO_3)	2 %	Max
Chloride (Cl)	0.01%	Max
Sulphate (SO_2)	0.05%	Max
Lead (Pb)	0.001%	Max
Iron (Fe)	0.001%	Max
Potassium (K)	0.1%	Max
Zinc (Zn)	0.02%	Max

Source: Anuradha, *et al.*, (2011)

b. Sodium Silicate (Na_2SiO_3)

Sodium silicate is a compound of oxides of sodium and silica. It has a range of chemical formula of sodium oxide (Na_2O) and silicon dioxide or silica (SiO_2) contents or ratios. It is soluble in water and it is prepared by reacting silica sand and sodium carbonate at a high temperature ranging from 1200^oC to 1400^oC. Aqueous solution of sodium silicate is called water glass and the physical properties is presented in Table 2.8. According to Jeffery et al., (2010), water glass is rarely used as an independent activating unit, because it does not possess enough activation potential to initiate pozzolanic reaction alone. Rather, it is commonly mixed with NaOH or KOH as a fortifying agent to enhance alkalinity and increase overall specimen strength. Skvara, Dolezal, Svoboda, Kopecky, Pawlasova, Lucuk, Dvoracek, Beksa, Myskova, and Sulc (2006), explained that sodium silicate solution is commercially available in different grades, but according to Kong and Sanjayan (2008), powdered water glass leads to lower performance compared to the liquid form when used in geopolymerization process. For best results, Skvara *et al.*, (2006) opines that Na_2SiO_3 solution with SiO_2 to Na_2O ratio (by mass) of 2.0 mixed with 8–16 molarity activators (that is NaOH) for 24 hours prior to use is recommended. Fernandez - Jimenez and Palomo (2005), asserted that the most important property of this product is its mass ratio of SiO_2 to Na_2O, which is commercially available in the range of 1.5 to 3.2 (with 3.2 being the best suited for geopolymerization). Soluble silicates reduce alkali saturation in pore solution and promote greater inter-particle bonding with both geopolymer binders and the included aggregate material (Feng, Tan and Van-Deventer, 2004). It has been revealed through testing that activating solution made up of little or no soluble silicate produces significantly weaker compressive strengths of mortars and concretes than those activated with high dosage of soluble silicates (Feng *et al.*, 2004). The presence of such silicate material improves interfacial bonding between rock aggregates and geopolymer mortars.

Table 2.8: Physical properties of Na_2SiO_3

OXIDE	PROPERTIES
Na_2O	15.9%
SiO_2	31.4%
H_2O	52.7%
Appearance	Liquid (gel)
Colour	Light yellow liquid (gel)
Boiling Point	102^{o}C for 40%
Molecular	Aqueous solution
Weight	184.04
Specific gravity	1.6

Source: Anuradha, *et al.*, (2011).

2.4.4 Geopolymer concrete production

According to Jindal and Kamal (2015), GPC is a type of concrete which does not utilize any OPC as binder; rather the binding properties which bind the aggregate together are produced by the reaction of an alkaline liquid with a source material that is rich in silica and alumina. Geopolymer binders mixed with aggregates to produce GPC are excellent for building and repairing infrastructures and for precasting units. They have very high early strength, their setting times can be controlled and they remain intact for a very long time without any need for repair (Raijiwala, Patil and Kundan, 2012). It has good engineering properties and prospective to form a larger part of a sustainable construction industry by replacing conventional concretes. The processes of producing geopolymer concrete include the following:

i. Preparation of alkaline solution

A combination of sodium silicate solution (Na_2SiO_3) and sodium hydroxide (NaOH) solution can be used as the alkaline liquid; NaOH which is in pellets or flake form is dissolved in the water at the proportion of required molar concentrations. According to Rangan (2010), the Na_2SiO_3 solution is commercially available in different grades; it has a range of chemical formula varying in sodium oxide (Na_2O) and silicon dioxide or silica (SiO_2) contents or ratios. It is recommended that the alkaline liquid be prepared by mixing both solutions together at least one day prior to use because when the solutions are mixed together they begin to react and as such, there is release of large amount of heat (Rangan 2008).

ii. Molarity calculation for NaOH

Before using sodium hydroxide (NaOH) solids it should be dissolved in water with the required concentration, the concentration of NaOH solution can vary from 8 to 16 molar. According to Rangan (2011), the mass of NaOH solids in a solution varies depending on the concentration of the solution; for example, NaOH solution with a concentration of 8 molar consists of $8 \times 40 = 320$g, $10 \times 40 = 400$g, $12 \times 40 = 480$g, $14 \times 40 = 560$g and $16 \times$

40 = 640g of NaOH solids per liter of the solution, where 40 is the molecular weight of NaOH. The mass of NaOH solids was measured as 262g per kg of NaOH solution with a concentration of 8 molar, the mass of NaOH solids per kg of the solution for other concentrations has been measured as 10 molar for 314g, 12 molar for 361g, 14 molar for 404g, and 16 molar for 444 g (Hardjito and Rangan, 2005). It should also be noted that the mass of NaOH solids is only a fraction of the mass of the NaOH solution, and water is the major component

iii. Mixture proportion of geopolymer concrete

In geopolymer concrete silicon oxide (SiO_2) and aluminum oxides (Al_3O_2) in 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 concrete (Rangan, 2010). The aggregates occupy about 75 to 80% of the mass of geopolymer concrete just as it is in Portland cement concrete. The proportions and properties of the constituent materials that make up the geopolymer paste influences the compressive strength and workability of GPC (Rangan, 2010). In an experiment carried out by Hardjito and Rangan (2005), the result obtained showed that:

i. A higher concentration (in terms of molar) of the NaOH solution results in higher compressive strength of geopolymer concrete.
ii. The higher the ratio of Na_2SiO_3 to NaOH solution by mass, the higher the compressive strength of geopolymer concrete.
iii. The addition of naphthalene-sulfonate-based superplasticizer, up to approximately 4% of fly ash by mass, improves the workability of the fresh geopolymer concrete;

however, there is a slight degradation in the compressive strength of hardened concrete when the superplasticizer dosage is greater than 2%.

iv. The slump value of the fresh geopolymer concrete increases when the water content of the mixture increases.

v. As the H_2O/Na_2O molar ratio increases, the compressive strength of geopolymer concrete decreases.

vi. The effect of the Na_2O/Si_2O molar ratio on the compressive strength of geopolymer concrete is not significant.

According to Rangan (2010), the effect of the various parameters given above makes the compressive strength and workability of geopolymer concrete complex. Therefore, in-order to aid the design of fly-ash-based GPC mixture, a single parameter called water/geopolymer solid ratio by mass was devised. Where the total mass of water in this parameter is described as the sum of the mass of water contained in the Na_2SiO_3, water used to produce the NaOH solution, and mass of extra water, if any, is added to the mixture, while the mass of geopolymer solid is the sum of mass of fly ash, the mass of NaOH solids used to make NaOH, and the mass of solids in Na_2SiO_3 solution (that is, the mass of Na_2O and SiO_2). Hardjito and Rangan (2005), carried out a test to confirm the effect of water/geopolymer solid ratio by mass on the compressive strength and workability of concrete and discovered that the compressive strength decreases as the water/geopolymer solid ratio by mass parameter increases. The trend can be comparable to the well-known effect of the water/cement ratio on the compressive strength of OPC Obviously, as the water/geopolymer solids ratio increases; workability increases because the mixtures contain more water (Rangan, 2010).

iv. Mixing, casting, and compaction of geopolymer concrete

According to Rangan (2010), the conventional method used in manufacturing Portland cement concrete can also be used when producing geopolymer concrete. Rattanasak and Chindaprasirt (2009), in Mustafa, Kamarudin, Bnhussain, Khairul, Rafiza and Zarina (2012), proposed two types of mixing which include separate mixing and normal mixing. In the separate mixing, sodium hydroxide is mixed first with the fly ash for 10 minutes after which, sodium silicate is then added, while for the normal mixing, all the samples (that is fly ash, NaOH and Na_2SiO_3) were mixed at the same time. It was discovered that separate mixing gives a slightly stronger mortar than the normal mixing. It is believed by some researchers that the optimum mixing order for alkali-activated binders is as follows. First, solids are mixed (fly ash and aggregates), then the prepared activator is mixed with the solids, and the mixture is placed in molds (Swanepoel and Strydom, 2002; Cheng and Chiu 2003) in Mustafa *et al.*, (2012). According to Kong and Sanjayan (2010), compaction of the samples in molds is done in three equal layers using standard compaction and by using a rod and vibrating table.

v. Rest period prior to curing

The time taken from when casting of specimens is complete to the time which curing starts at an elevated temperature is known as rest period (Rangan, 2005). Rangan, (2005) noted that this may be important in certain practical applications, for example, in the case where fly ash-based GPC is produced in precast concrete industry, sufficient time must be provided between casting of products and sending them to the curing chamber. In order to determine the effect of rest period, Lloyd and Rangan (2010), carried out a research where they examined the impact of delayed steam curing (rest period) on the strength gain of three mixtures of GPC specimens. The trial mixtures produced had 75% aggregate by mass consisting of 20 mm and 7 mm coarse aggregates and fine sand, and varying quantities of added water and all mixtures were cured at 80^o C for 24 hours with or without a 24 hour delay or rest day before curing. The compressive strength results obtained showed that the inclusion of a 24 hour period before curing increased the compressive strengths of all the mixtures when compared with the mix without rest period.

vi. Curing of geopolymer concrete

The methods of curing GPC include the following:

a. Ambient Temperature Curing

According to Jeffery *et al.*, (2012), one of the challenges for successful GPC production is obtaining correct mechanics at ambient temperatures. Unlike Portland cement, geopolymer reaction is more easily achieved with the addition of an external heat source to promote alkaline reactivity of the pozzolanic material. According to Fernandez-Jimenez and Puertas (2002) there have been challenges in synthesizing fly ash based geopolymers at ambient temperatures, because research shows that GPC did not set at a temperature as low as 23^{o}C. Though it is possible to expose test specimens to elevated temperatures in a laboratory, but it would be difficult to expose them efficiently to heat during curing for a full scale pavement project (Jeffery *et al*, 2012). Rangan (2008) explained that heat-curing temperatures can be as low as 30 °C. According to Skvara *et al*., (2006), these could be attainable in tropical climate conditions. Jeffery *et al.*, (2012) opines that though ambient curing for full-scale project presents logistical difficulties, another option for field implementation would be thermal loading of pre-cast concrete sections prior to field delivery. This option could be a possible solution until a deeper understanding of ambient cured geopolymer is properly developed.

b. Elevated Temperature Cure

According to Skvara *et al.*, (2006) elevated temperature curing can be achieved through the use of steam or dry heat methodologies, but research has shown that dry heat gives a compressive strength increase of about 15% over the steam curing methods. It has been demonstrated through research that time and temperature greatly affects the mechanical properties of geopolymer binders. However, according to Rangan (2010), the limits for temperature do exist and when these limit are exceeded, the strength gain rate is extremely slow. The ranges between 50–80°C are the temperature values widely accepted for successful geopolymer hydration (Jeffery *et al*, 2012). In a research carried out by Hardjito and Rangan (2005), the curing time was varied from 4hr to 96hr (4 days) and they discovered that longer curing time improved the polymerization process, resulting in higher compressive strengths although the rate of increase in strength was rapid up to 24hr of curing time while beyond 24hr, the gain in strength was only moderate. Also, they indicated from their research that higher curing temperatures result in greater compressive strengths, but an increase in the curing temperature beyond 60°C did not increase the compressive strength to a large extent.

vii. Curing Duration

According to Jeffery *et al.*, (2012), geopolymer sets rapidly relative to Portland cement and attain a significant percentage of their total compressive strength value within the first few hours of reaction. Khale and Chaudhary (2007), stated that temperature is particularly important during the 2 to 5 hour interval; however, the strength increase for specimens cured beyond 48 hours was not significant. Skvara *et al.*, (2006) explained that the rate of increase in strength was rapid up to 24 hours of curing time and beyond this time, the strength gain was only moderate; meaning that in pzzractical application, the heated curing time need not be more than 24 hours.

viii. Binder – Aggregate Interface

In concrete, the weakest and most vulnerable part lies within the aggregate-binder interface or interfacial transition zone (ITZ) (Jeffery *et al*, 2012). According to Feng *et al.*, (2004), the ITZ maintains a higher porosity than the surrounding paste matrix and therefore, it allows easier penetration of harmful chloride species into the concrete structure. In Portland cement products, the ITZ consists of a higher concentration of the Portlandite ($Ca(OH)_2$) crystal and a lower concentration of calcium silicate hydrate (C-S-H) which is the main binding phase within the overall system (Fernandez-Jimenez *et al*, 2006). But in the case of GPC, no ITZ could be detected either morphologically or by direct measurement of the geopolymer product in the aggregate proximity (Jeffery *et al*, 2012).This is as a result of high soluble silicate content in the geopolymer mix, which reduces alkali saturation in the concrete pore solution and promotes greater inter-particle bonding within the geopolymeric binder as well as the aggregates mass (Feng *et al*, 2004). The increased bonding forms a denser, stronger ITZ and results in concrete of enhanced mechanical properties.

2.4.5 Properties of geoplymer concrete

Various studies have been carried out to determine the various properties of GPC some of which include:

i. Fresh geopolymer concrete.

a. Workability

Fresh GPC is highly viscous and cohesive with low workability, to improve the workability Mustafa, Mohammed, Kamarudin, Khairul and Zarina (2011), suggested that superplasticizers or extra water can be added to the fresh geopolymer concrete. The drawback with the suggestion was that though water when added to GPC improves its workability, it also increases its porosity due to its evaporation during curing process at elevated temperatures as explained by Sathia *et al*., (2008), in Mustafa *et al.*, (2011). Rattanasak and Chindaprasirt (2009) in Mustafa *et al.*, (2012), states that increases in NaOH and Na_2SiO_3 concentration reduces the flow of mortar. The use of superplasticizers also have an adverse effect on the strength of GPC, but Suresh and Manojkumar (2013), worked on factors influencing the compressive strength of GPC and discovered that the use of commercially available Naphthalene-based superplasticizers improved the workability of the fresh geopolymer concrete; but dosage of this admixture is limited to 2% by mass of fly ash because beyond this dosage, degradation in the compressive strength was observed. Reddy, Varaprasad and Reddy (2010), point out that with increases in molar concentration of the NaOH solution, the workability of geopolymer concrete decreases.

ii. Hardened geopolymer concrete

a. Compressive strength

Compressive strength is one of the most essential properties of concrete, the factors influencing it include curing temperature and curing time; for longer curing time and higher curing temperatures result to increases in compressive strength (Mustafa *et al*., 2011). It was also explained in a research carried out by Anuar, Ridzuan and Ismail (2011), that GPC produces a higher compressive strength due to the higher concentration of NaOH in the concrete. This makes good bonding between aggregates and the paste of the concrete. When GPC was compared with PCC, Rangan (2008), discovered that its compressive strength is about 1.5 times more than the compressive strength of OPC concrete. Bachhav and Dubey (2015), studied the effect of geopolymer on strength of concrete using fly ash as the source material and discovered that the compressive strength of geopolymer concrete is higher compared to that of PCC. The compressive strength increases with increases in the molarities of NaOH. An extensive study was carried out by Rangan (2008), on the fly ash based geopolymer concrete utilizing low calcium fly ash as the source material. The result obtained from the experimental investigation showed that fly ash-based geopolymer concrete has excellent compressive strength which is suitable for structural applications.

b. Split tensile

Hardjito and Rangan (2005) carried out tests to measure tensile strength of fly ash-based geopolymer concrete using concrete cylinders and the results obtained from the tests showed that the tensile splitting strength of gopolymer concrete was only a fraction of the compressive strength just as it was in the case of PCC. Preethy, Binu and Deepak (2015), carried out a research to assess demolished concrete as coarse aggregates in GPC using two types of RCA containing replacement of 60%, 65%, 70%, and 75% and sodium hydroxide concentration of 8M, 10M and 12M and discovered that the split tensile strength increases with increases in the molarity of sodium hydroxide as in the case of compressive strength. Higher concentrations of NaOH solution give higher split tensile strengths of GPC because higher concentrations of NaOH make good bonding between aggregates and pastes of the concrete. Also demolished concrete coarse aggregates type did not influence the split tensile strengths of GPC, if good quality RCA is used for the production of new GPC.

c. Water absorption

Suresh, Partha and Somnath, (2009), studied the effect of water absorption, porosity and sorpivity on durability properties of geopolymer mortars. They reported that geopolymer mortar specimens manufactured by activation with higher alkali content results in lower water absorption, apparent porosity and water sorptivity.

d. Abrasion

Various researches have been carried out to study the strength of GPC but the study of abrasion resistance is still limited (Shalika and Hemant, 2016). According to Shalika and Hemant (2016), the abrasion resistance of fly ash based GPC increases with increase in temperature. This was discovered after studying the abrasion resistance of geopolymer concrete at different temperatures that is 25^{o}C, 60^{o}C and 80^{o}C and at different curing times. Ramujee and Potharaju, (2014a) compared the abrasion resistance of GPC and OPC concrete by placing an abrasive charge on the surface of the specimens for the peddle to rotate at a required speed for every 12hrs duration. It was discovered that the depth of wear decrease for OPC concrete was 61% for 12hrs duration and 64% of 24hrs duration for GPC. This means GPC concrete has better abrasion resistance than OPC concrete, because the depth of wear for GPC is smaller than that of OPC concrete. Shuguang, Hongxi and Qingjing, (2008) calculated abrasion resistance of GPC in their work by using the formula.

$$\text{Ia} = (\frac{\text{R}}{\text{P}})^{1/2} ----------------------------(2.3)$$

Where

Ia = Grade of abrasion resistance,

R= Number of revolutions of grinding machine

P = Depth of grinding trace

e. Resistance to magnesium sulphate attack

Sulphates are chemical salts that are dissolved in water to form solution. According to Gupta and Gupta (2012), they are found in the soil as calcium, potassium, sodium and magnesium sulphate. In PCC, magnesium sulphate ($MgSO_4$) create more damage compared to other sulphates because it decomposes the hydrated calcium silicate as well as calcium hydroxide $Ca(OH)_2$ and hydrated tricalcium silicate (C_3A) to form hydrated magnesium silicate which has no binding properties (Gupta and Gupta, 2014). Wallah and Rangan (2006), exposed low calcium fly ash based geopolymer concrete to $MgSO_4$ for a period of 1 year and discovered that it has high resistance to sulphate attack because there was no damage to the surface after exposure, no change in its visual appearance nor in the compressive strength.

Rangan (2010), explains that geopolymer concrete is not susceptible to sulphate attack unlike Portland cement concrete because there is no gypsum or ettringite formation in the main product of geopolymerization. Thus as a result, there is no mechanism of sulphate attack in heat –cured fly ash based geopolymer concrete. The presence of high calcium in the pozzolana or in the aggregates will lead to the formation of gypsum and ettringite in GPC. Table 2.9 gives details of various exposure requirement of concrete to sulphate attack.

Table 2.9: Requirements of ACI 318-05 for concrete exposed to sulphate attack

Sulfate Exposure	**Water-Soluble Sulfate (SO_4) in soil**	**Sulfate (SO_4) In water**	**ASTM Cement Type**	**Maximum free W/C, normal-weight aggregate concrete**	**Minimum compressive strength, normal weight and lightweight concrete**
	% by mass	**Ppm or mg/liter**			MPa(psi
Negligible	0 to 0.1	0 to 150	-	-	-
Moderate (Seawater)	0.1 to 0.2	150 to 1500	II, IP(MS), IS(MS), P(MS), I(PM)(MS) I(SM)(MS)	0.5	28(4000)
Severe	0.2 to 2	1500 to 10,000	V	0.45	31(4500)
Very Severe	Over 2	Over 10,000	V plus pozzolan	0.45	31(4500)

Source: Gupta and Gupta, (2012)

f. Resistance to sulphuric acid

Past researches have considered resistance of GPC to sulfuric acid and with PCC in the same environment and discovered that geopolymeric materials performed significantly better in acid resistance compared to Portland cement (Gourley and Johnson, 2005). Thokchom *et al*., (2009) in Mustafa *et al.*, (2011) exposed geopolymer mortar to 10% sulfuric acid and discovered after 18weeks that the specimen was still intact with no recognizable change in colour. They went further to using an optical microscope to observe the exposed surface which revealed a corroded structure and it progresses with time. In terms of weight loss, the geopolymer showed better performance than OPC and in 18 weeks, specimen were fully de-alkalized by the sulfuric acid; but the residual compressive strength was still substantial.

2.4.6 Advantages and disadvantages of using geopolymer concretes

i. Advantages

Several advantages of GPC have been outlined, they include the following

a. Economic benefits

One of the benefits in the production of geopolymer binders is that it reduces the demand for costly production of the clinker required in Portland cements. The high cost of Portland cement production begins from the enormous amount of energy required to produce it. According to Fernandez-Jimenez and Palomo (2005), the extreme high temperature between (1400– 1500^{0}C) required makes Portland cement production a very costly and energy-intensive process. The pozzolanic materials used in geopolymer binders are readily available as by-products of industrial coal power plants, agricultural waste or of natural occurrences and are therefore inexpensive to obtain. According to Rangan (2014), the cost of one ton of fly ash or blast furnace slag when compared to the cost of one ton of Portland cement is only a small fraction. Recycling of these pozzolanic materials into commercial construction materials would not only be economically sound but beneficial to the environment as well (Jeffery *et al*, 2012).

b. Environmental Benefit

The environmental benefit derived when geopolymer binder is used to substitute OPC in concrete production is that the CO_2 emissions generated during Portland cement production would cease to exist. According to Skvara *et al*, (2006), the production of one ton of Portland cement emits approximately one ton of CO_2 into the atmosphere. Utilizing unclaimed pozzolanic by-products from power plants worldwide would prevent these materials from being disposed into the environment in their hazardous, raw state. The use of geopolymer binder instead of OPC would save 0.25 million tons of coal, 80 million power units and prevent 1.5 million tons of CO_2 from entering the atmosphere (Fernandez-Jimenez and Puertas, 2003).

ii. Disadvantages

a. Analysis of pozzolan composition

Some of the potential difficulties encountered when considering geopolymers as an alternative to OPC is that the particle size distribution and chemical composition of the source material must be established before use (Skvara *et al*., 2006). For example, the geopolymer production uses different raw materials which can differ depending on their source. Duxson *et al*., (2007) explain that this difference results in the need to develop a separate process for each source, which can be time consuming and expensive. The mechanism of hardened geopolymers is directly related to the mineralogical composition of the pozzolan selected. Slight variances in these materials have significant effects upon the resultant binder properties. According to Rangan (2010), the amount and form of calcium in the source material play significant roles in determining the reaction pathway and the physical properties of the final product. It is expected that before activation, a micro-analysis of the pozzolanic materials need to be performed in order to identify minerals present and their quantity relative to the overall mass because this will help to dictate the proper activating agent to be used and the required concentration to achieve optimum reaction (Khale and Chaudhary, 2007). Rangan (2005), opines that the fineness of the source material is also critical in mechanical strength development, for example, where pozzolanic ash with particle less than 45μm was used to form geopolymer paste; good compressive strength value was derived from the paste formed. Generally, these factors are highly important to the development of geopolymer cements and must be examined in detail prior to a finalization of mix design. Proper understanding of the structure and dissolution properties of the source material is essential to the commercial application of geopolymer binders (Rangan, 2010).

b. Decreased workability

The workability properties of geopolymer concrete are different from those found in Portland cement concretes. According to Jeffery *et al.,* (2012) the Pozzolanic based geopolymer concrete have higher static and dynamic viscosities than Portland cement products and might require vibration efforts to minimize entrained air pockets in the fresh paste. However, another practical solution for a stiff mix is the utilization of superplasticizers admixtures but provisions to the mix design must be made accordingly in-order to avoid ratio upsets (Skvara *et al.*, 2006). Furthermore, the addition of naphthalene sulphonate-based superplasticizers, up to four percent of the pozzolana by mass, improves the workability of the fresh geopolymer; however, dosages greater than 2 percent can cause slight degradation of compressive strength in the hardened product. Additional research and testing of these materials is still paramount, because there is no code applying to them. (Erin, 2009).

2.4.7 Applications of geopolymer mortars and concretes

Bondar (2009), found out that they are used for pre-cast and mass concretes as in dam construction, where roller compacted geopolymer concrete may be a viable construction method. With respect to the description of the specifications of this type of concrete, it can also be used as railway traverse, waste water pipe line, hydraulic structures and pre-tension concrete structures and in countries with greater resources of natural pozzolan, which is rich in silica and alumina, this type of concrete, can help decrease energy consumption and environmental impacts. They can also be used in heat resistant pavement because they do not readily decompose when exposed to high temperatures and are more stable structurally under such conditions compared to OPC concrete (Fernandez-Jimenez and Puertas, 2002).

In the case of toxic metals, geopolymer binder possesses a high potential for their immobilization. This is due to their inherently dense micro-structural development; their low permeability is also one of the properties that favor their use as materials for immobilization systems of metals (Jeffery *et al.*, 2012).

2.5 Sustainability of Concrete Construction

The World Commission on Environment and Development (WCED) of the United Nations (UN) defined sustainability as meeting the needs of the present without compromising the ability of the future generations to meet their own needs (Tarun, 2008). Nurdeen and Shahid (2010), explained that sustainability seek to balance the economic, social and environmental impact, while having it in mind that the population growth will continue. The quest to promote sustainable development put pressure on the adoption of proper methodology needed to protect the environment across all industries including the construction industry (Mukherjee and Vesmawala, 2013). According to Malhotra (2004), the production of Portland cement lead to the emission of large amount of CO_2 and other greenhouse gases (GHG) and as explained by Tarun (2008), in this era, environmental issues associated with CO_2 play a leading role in the sustainable development of cement and concrete. The dwindling amount of lime stone forms another threat to the sustainability in the cement industry. The utilization of a sustainable concrete or green concrete is the solution to this problem, because it eliminates the negative impact of the cement industry while minimizing environmental impact (Mukherjee and Vesmawala, 2013). According to Tarun (2008), a sustainable concrete is one that is constructed so that the total environmental impact during its entire life cycle is minimal. Building in a sustainable manner means, to focus attention on the effects on human health, energy conservation, and physical environment. With a sustainable concrete and infrastructure, a sustainable future for generation to come can be developed by the construction industry,

The advantage of sustainable concrete is that buildings constructed with such concrete have reduced maintenance and energy costs. According to Tarun (2008), a number of characteristics apply to sustainable concrete products which include:

i. They are produced with precast or cast-in-place reinforced concrete elements that are made with Portland cement and pozzolanic materials that include renewable components, recycled components, or both.

ii. The products are constructed to improve the performance of concrete elements, which may also contain recycled concrete as aggregates. High performance materials are intended to reduce cross sections and the volume of concrete produced.

iii. They are made with the intention to increase the durability of concrete structures, reduce maintenance needs and limit the amount of non-renewable special repair materials that need to be used in maintaining the concrete (Coppola, Cerulli and Salvioni, 2004).

CHAPTER THREE

3.0 EXPERIMENTAL PROGRAMME

This chapter gives a detailed description of all the materials used in the experimental programme and the method used for conducting the various tests

3.1 Research Materials

Materials used in this research include the following: Cement, metakaolin as the source material, coarse aggregates (recycled concrete aggregate, natural coarse aggregate), fine aggregate, alkaline solution, which is Sodium Hydroxide (NaOH) and Sodium Silicate and (Na_2SiO_3); water.

3.1.1 Cement

Ordinary Portland Cement (OPC) was used for this research as the binder for the control specimen and it satisfies the minimum requirement as provided by BS 12 (1996). The OPC is the Dangote brand of cement

3.1.2 Metakaolin

Metakaolin used for this research was obtained from kaolin sourced from Kankara Local Government of Kastina State, Nigeria. The sample was pound using mortar and then sieved in the Department of Building Laboratory, Ahmadu Bello University, Zaria. It was sieved through 150microns sieve after which, it was calcined in the Chemical Engineering Department of the University at a temperature of $650^{O}C$ for about 90mins as shown in Plate I.

Plate I: Calcination of kaolin to metakaolin

3.1.3 Natural coarse aggregate (NCA)

The natural coarse aggregate was obtained within Zaria, Kaduna State. Sieve analysis was carried out in accordance with BS 933 part 1(1997) to distribute the aggregate into various sieve sizes. The aggregate required comprised of 20mm as its maximum and 4.75mm as its minimum size and they were used in the Saturated Surface Dry (SSD) condition.

3.1.4 Fine aggregate

River sand was obtained within Zaria and used. It was kept in the SSD condition prior to use in the laboratory of the Department of Building, ABU, Zaria. Sieve analysis in accordance with BS 112 (1971) was carried out to distribute the particles in their required sieve sizes and also remove impurities and bigger size aggregates.

3.1.5 Recycled concrete aggregate (RCA)

RCA was obtained manually from a demolition site within Zaria; by crushing the rubbles with sledge hammer. Because it was crushed into various sizes, sieve analysis was carried out in line with BS 933 part 1(1997) in order to determine its particle size distribution.

Aggregate that fall between 20mm up to 4.75mm were used in their saturated surface dry condition (SSD).

3.1.6 Alkaline solution

A combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) was used as the alkaline activator. The process is described as follows:

i. Sodium hydroxide(NaOH)

NaOH which is in pallet or flake form with 97%- 98% purity was obtained from a supplier and dissolved in tap water to make a solution. For this work, 16Molar concentration was used which means that the molarity multiplied by the molecular weight of NaOH (40). This means (16 x 40 = 640) gives the quantity in grams of NaOH solids per liter of water.

ii. Sodium silicate (Na_2SiO_3)

The sodium silicate solution (Na_2O = 13.7%, SiO_3 = 29.4%, and H_2O = 55.9% by mass) was purchased from a supplier within Zaria and used in this work.

3.1.7 Water

Portable water fit for drinking was used for this research. It was used for mixing and dissolving the alkaline activator and also used for the production of the concrete specimens.

3.2 Research Methodology

The research was carried out through the following processes;

3.2.1 Experimental program

The experiment was conducted as follows:

A. Preliminary investigation

The tests carried out include the physical, mechanical and chemical properties of the materials used for the research which include:

i. Particle Size Distribution

The particle size distribution for both the NCA, fine aggregate with the RCA was carried out using sieve analysis as described in accordance with BS 812-103 (1990). This was done to determine the grading of the aggregates.

ii. Specific Gravity

The specific gravity (Gs) of the metakaolin, alkaline solution, NCA, fine aggregate and RCA was determined by using pykonometer method in accordance to BS 1377:2(1970). The apparatus used include density bottle and stopper, funnel, spatula and weighing balance. The relationship used to find the specific gravity is given by:

$$\text{Specific Gravity} = \frac{W_2 - W_1}{(W_4 - W_1)(W_3 - W_1)} \text{-----------------} (3.1)$$

Where: W_1 = Weight of density bottle

W_2 = Weight of density bottle + Sample

W_3 = Weight of density bottle + Water (full) + Sample

W_4 = Weight of density bottle + Water (full)

iii. Bulk Density

This was determined in accordance with BS 812: Part 2 (1995) for the RCA, natural and fine aggregates used for this research. The relation below was used to determine the bulk density of the sample:

$$\text{Bulk Density} = \frac{W_1 - W}{V} ------------------(3.2)$$

Where W_1 = Weight of container + sample

W = Weight of empty container

V = Volume of container

iv. Water Absorption Capacity

The Absorption capacity test was carried out on the aggregates (that is the coarse and fine aggregate and RCA). This was done as stipulated by BS 1881-122 (1983).

v. Moisture Content.

This test was determined in accordance with BS 812: 109 (1990). The procedure for the test was carried out as adopted by Gambo (2014).

vi. Aggregate impact value and aggregate crushing value

Aggregate impact value was carried out on the NCA and RCA to determine their toughness under impact. This was done in accordance with BS 812-112 (1990). The crushing value was used to measure the resistance of the NCA and RCA under applied compressive load. The method adopted by Shetty (2005) was used to determine the impact and crushing value.

vii. Chemical properties

Chemical analysis was carried out at the Defence Industries Corporation of Nigeria (DICON), Kakuri Industrial Layout, Kaduna, Kaduna State of Nigeria using XRF test to determine the oxide composition such as Silicon Oxide (SiO_2), Aluminum Oxide (Al_2O_3), Iron Trioxide (Fe_2O_3) and others. In order investigate if they are in line with the ASTM C 618-94: (1994) classes of pozolana. The ASTM standard stipulates that for any material to be used as pozolana, it should fall within the following classes; *Class N*, Class *F* or *Class C.*

B. Tests on hardened concrete specimens

The tests carried out on hardened concrete specimens include the following**:**

(a) Compressive Strength

(b) Resistance to magnesium sulphate ($MgSO_4$) attack test

(c) Split Tensile Strength

(d) Abrasion Resistance

(e) Water Absorption

3.3 Production of Concrete Specimens

3.3.1 Production of geopolymer concrete specimen (GPC)

i. Mix design

Currently, no standard mix design is available for the production of GPC (More, 2013). This means that the mix design for the production of geopolymer concrete is based on trial and error. For this reason, the method adopted by Anuradha, Sreevidya, Venkatasubramani and Rangan (2011), in designing fly ash based geopolymer concrete was used to design grade 25 metakaolin based geopolymer concrete. In designing for the quantity of alkaline, Ramujee and Potharaju (2014b), method was adopted after series of trial and error. Details of the procedure are shown in Appendix A3.

ii. Preparation of alkaline solution

A combination of NaOH and Na_2SiO_3 was used as the alkaline solution in this research. For the purpose of this research, the 16molar concentration of NaOH pallet was dissolved in water to make a solution. The ratio of NaOH to Na_2SiO_3 was (1: 2.5) as shown in Table A3.2 of the Appendix. The alkaline solution were mixed together a day before it was used to produce the geopolymer concrete. This was done because when it was mixed, it started to react thereby emitting a large amount of heat and for this reason; the heated solution was allowed to cool at room temperature before use.

iii. Mixing and casting of geopolymer concrete

The method used for mixing the GPC specimens was similar to that used when producing PCC. All the aggregates used for the casting were kept in the saturated surface dry condition (SSD). Metakaolin and the aggregates (both fine aggregate, NCA and RCA) were mixed together thoroughly, after which the alkaline solution was added and the GPC specimen mixed for about 8mins as shown in Plates II, III and IV respectively. In order to improve the workability of the mixes, extra water was added and mixed thoroughly. After mixing, the fresh GPC was cast into 100mm x 100mm x 100mm moulds in 2 layers while each layer was compacted by rodding with a tapping rod in order to achieve a smooth compaction of the specimen.

Plate II: Mixing of aggregate and Metakaolin

Plate III: Pouring of Alkaline Solution

Plate IV: Mixing of GPC Specimen

3.3.2 Production of Portland cement concrete specimens (PCC)

i. Mix design

Grade 25 concrete was also designed for the PCC. This was done to create a basis for comparison with GPC specimens. In this case, Building Research Establishment (BRE) method of mix design was used for designing the grade of concrete. Details of the procedure are shown in Appendix A2.

ii. Mixing and casting of Portland cement concrete specimens (PCC)

The same method used in mixing the GPC specimens was also used in mixing the PCC. After mixing, the fresh PCC specimen were cast into 100mm x 100mm x 100mm mould in 2 layers; while each layer was compacted by giving it 25 blows with a tapping rod in order to achieve a smooth compaction of the specimens.

3.3.3 Curing of GPC specimens

After casting, the specimens were kept for 24hrs rest period. The metakaolin based GPC specimens were then de-moulded, wrapped in a polythene bag and cured in the oven at 60°C for 24hrs as shown in Plate V because according to Suresh and Manojkumar (2013) heat curing assists the chemical reaction in the geopolymer paste. After heat curing for 24hrs, it was then removed from the oven and unwrapped from the polythene bag and left to cure at the room temperature in the laboratory until the days required for testing which is 7, 14, 28 and 56 days as shown in Plate VI.

Plate V: Heat Curing of GPC Specimens

Plate VI: Stacking of GPC Specimens.

3.3.4 Curing of PCC specimens

Specimens were allowed to set for 24hrs before de-moulding and immersion in a pool of portable water tank for ages 7, 14, 28 and 56 days to allow for effective curing.

3.4 Testing of Fresh Concrete Specimens

3.4.1 Workability test

Before casting the fresh GPC and PCC specimen into moulds, the slump value of each fresh concrete was measured to determine the workability of the mix as presented in Plate VII. This was done as recommended by BS 1881-102 (1983). The apparatus used in carrying out the slump test includes steel tamping rod, base plate, hand scoop, trowel and metal cone.

Plate VII: Slump test for GPC specimen

3.5 Concrete Specimens Produced

Four different specimens were produced for GPC and PCC specimen and tested at various ages of 7, 14, 28 and 56 days. They include specimen **X** which is PCC containing 0% RCA as control, specimens $\mathbf{A_1}$, $\mathbf{A_2}$ and $\mathbf{A_3}$ which is PCC samples containing 20%, 30%, 40% RCA respectively. Specimen **Y** which is GPC containing 0% RCA as control and specimen $\mathbf{B_1}$, $\mathbf{B_2}$ and $\mathbf{B_3}$ made with 20%, 30% and 40% RCA respectively. The variation in the percentages of RCA aggregate was done so that any change in trend due to variation of the RCA percentage replacement could be determined. A total of 336 specimens were cast for this research; the details of specimens cast are shown in Table 3.1 and Table 3.2.

Table 3.1: Breakdown of GPC and PCC Specimens, Tests and Curing Days

TEST	**CURING DAYS**	**SAMPLE**							
		X	**A**			**Y**	**B**		
			A_1	A_2	A_3		B_1	B_2	B_3
		0% RCA	20% RCA	30% RCA	40% RCA	0% RCA	20% RCA	30% RCA	40% RCA
Compressive Strength		3	3	3	3	3	3	3	3
Tensile Strength	7	3	3	3	3	3	3	3	3
Absorption Capacity									
Abrasion Resistance									
Aggressive Environment $MgSO_4$									
Compressive Strength	14	3	3	3	3	3	3	3	3
Tensile Strength		3	3	3	3	3	3	3	3
Absorption Capacity									
Abrasion Resistance									
Aggressive Environment $MgSO_4$									
Compressive Strength	28	3	3	3	3	3	3	3	3
Tensile Strength		3	3	3	3	3	3	3	3
Absorption Capacity		3	3	3	3	3	3	3	3
Abrasion Resistance		3	3	3	3	3	3	3	3
Aggressive Environment $MgSO_4$		3	3	3	3	3	3	3	3
Compressive Strength	56	3	3	3	3	3	3	3	3
Tensile Strength		3	3	3	3	3	3	3	3
Absorption Capacity		3	3	3	3	3	3	3	3
Abrasion Resistance		3	3	3	3	3	3	3	3
Aggressive Environment $MgSO_4$		3	3	3	3	3	3	3	3

Source: Laboratory Research Work (2016)

Table 3.2: Summary of Specimens

Specimen Name	Type Specimen	No of Specimen
X(PCC with 0% RCA)	Cubes	42
A (PCC with 20%, 30% and 40% RCA)	Cubes	126
Y(PCC with 0% RCA)	Cubes	42
B (GPC with 20%, 30% and 40% RCA)	Cubes	126
Total sample		**336**

Source: Laboratory Research Work (2016)

3.6 Testing of Hardened Concrete Specimens

After curing the GPC and PCC specimens, they were subjected to the following test at the end of each curing ages which include:

3.6.1 Compressive strength test

Compressive test was carried out after different curing ages of 7, 14, 28 and 56 days for GPC and PCC specimens containing 0%, 20%, 30% and 40%. A total of 96 specimens were tested for compressive strength and it was done as stipulated by BS 1881, part 116 (1983). Three (3) cubes each were tested to failure for all specimens. The maximum failure load was then recorded and the compressive strength calculated using the relation:

$$\text{Compressive Strength} = \frac{\text{maximum load(KN)X1000}}{\text{Cross} - \text{sectional Area (mm}^2\text{)}} - - - - - - - - - (3.3)$$

3.6.2 Resistance to magnesium sulphate ($MgSO_4$) attack test

After casting, the GPC and PCC specimens were kept for a rest period of 24hrs at room temperature after which they were de-moulded. The GPC specimens were cured in the oven for 24hrs, while the PCC specimens were cured in water for 24hrs.The specimens were then cured in Magnesium Sulphate ($MgSO_4$) for the required hydration period of 28 and 56 days before testing. A total of 48 cubes were immersed in $MgSO_4$ solution with each specimen containing 0%, 20%, 30% and 40% RCA. Three (3) cubes were tested and their compressive strength determined at the end of 28 and 56 days curing age. The concentration of $MgSO_4$ used was 2.5%, which was categorized by Gupta and Gupta (2012) as a severe attack. The relationship adopted by Ibrahim (2015) was used to achieve the quantity of $MgSO_4$ that gives the concentration. The relationship is thus:

If 50 liters of water = 5000g by weight

5000g of water = 100% concentration

Using 2.5% concentration, the quantity of water = Xg

Therefore, mathematically,

$$\text{Xg} = \frac{5000\text{g x } 2.5}{100} \text{ ------------------------ } (3.4)$$

Therefore, for every 5000g of water, 125g of $MgSO_4$ was dissolved in the water.

3.6.3 Split tensile strength test

The split tensile strength test was determined at different curing ages of 3, 7, 28 and 56 days on the GPC and PCC specimens containing 0%, 20%, 30% and 40% RCA respectively. A total of 96 specimens were tested for split tensile strength. The mean value of the failure load for each was taken as the split tensile strength. The split tensile strength of the concrete specimen was determined using the equation adopted by (Gambo, 2014).

$$\text{Split Tensile Strength} = \frac{0.518 \text{ X P}}{\text{S}^2} \text{ ------------------ } (3.5)$$

Where:

P = Load at failure (N)

S= Surface area of the concrete specimen.

3.6.4 Abrasion resistance test

Abrasion resistance is used to measure the resistance of concrete to surface wear by abrasion. It is aimed at determining the abrasion resistance of a material through sliding or scraping, thus causing a wearing down by friction. Gupta and Gupta (2012) explained that abrasion value should not be more than 30% for wearing surface and 50% for other surfaces. A total of 48 specimens were tested after 28 and 56 days of curing. Three (3) cubes each for GPC and PCC specimens containing 0%, 20%, 30% and 40% respectively were tested for abrasion resistance after different curing ages. On the day of testing, the initial weight of each concrete sample was determined before brushing and recorded as W_1, after which a weight of 3.5kg was mounted and tightly fixed to the wire brush. It was then used to brush the surface of concrete specimen 60 times and the specimen was then re-weighed while the value was recorded as W_2. The relation used to determine abrasion resistance of the concrete sample is given as

$$\text{Abrasion Resistance} = \frac{W_1 - W_2}{W_1} \text{X}100 -----------------(3.6)$$

Where

W_1 = Initial weight of a concrete specimen

W_2 = Final weight of a concrete specimen

3.6.5 Water absorption capacity test

This test was conducted at the curing ages of 28 and 56 days on GPC and PCC specimen containing 0%, 20%, 30% and 40% RCA in accordance with BS 1881-122:(1983). A total of 48 specimens were tested for absorption capacity and on each day of testing, three cubes each were placed in the electric oven to dry the specimens at 105^0C for 24 hours. The specimens were removed from the oven and allowed to cool at room temperature before determining the initial weight which was recorded as (W_1). The final weight was determined after the concrete specimen has been immersed in water for 24hrs. It was removed and dried with a piece of cloth; re- weighed and recorded its weight as W_2. The equation was used to compute the absorption capacity for the specimens is given as:

$$\text{Water Absorption Capacity} = \frac{W_2 - W_1}{W_2} \times 100 - - - - - - - - - - - - - - - (3.7)$$

Where:

W_1 = Weight of the concrete sample after oven dry

W_2 = Weight of the saturated surface dry concrete sample

CHAPTER FOUR

4.0 DATA PRESENTATION, ANALYSIS AND DISCUSSION

4.1 Presentation of Test Results

The results presented in this chapter are obtained from the tests carried out on the type of materials and concrete samples used for this research. Physical properties and chemical analysis tests for the materials used in the experiment as well as the test results for both the fresh and hardened concretes are presented and discussed in this chapter.

4.2 Physical, Mechanical and Chemical Properties of Materials

4.2.1 Particle size distribution of aggregates

Table 4.1 present the results for sieve analysis of fine aggregate which shows that the percentage of fines passing through sieve 600micron sieve size is 21.3% which is within the range of 15 – 34 signifying that the aggregate is within the range of Zone 1 as prescribed by BS 882:1965**.** The implication of this is that a harsh concrete mix can be produced. According to Neville (2003), this type of sand is more suitable for rich mix or where low workability is required in concrete.

Table 4.1: Particle Size Distribution of Fine Aggregate.

BS Sieve Size	Weight Retained (g)	Weight Passing (g)	Percentage Retained (%)	Cumulative Percentage Passing (%)	BS 882 (ZONE 1)
10mm	0	1000	0.00	100	100
5mm	52	948	5.2	94.8	90 – 100
2.36mm	79	869	7.9	86.9	60 – 95
1.18mm	233	636	23.3	63.6	30 – 70
600 µm	423	213	42.3	21.3	15 – 34
300 µm	181	32	18.1	3.3	5 – 20
150 µm	19	13	1.9	1.3	0 – 10
Pan	13	0	1.3	0.00	0

Source: Laboratory Reseach Work (2016)

Figure 4.1 present the grading curve for NCA and RCA for aggregates with 20mm nominal size. It can be seen that NCA and RCA fall between zones 1 and 4. This means that the aggregate is suitable for general construction work. Details of the results are presented in Appendix A1.

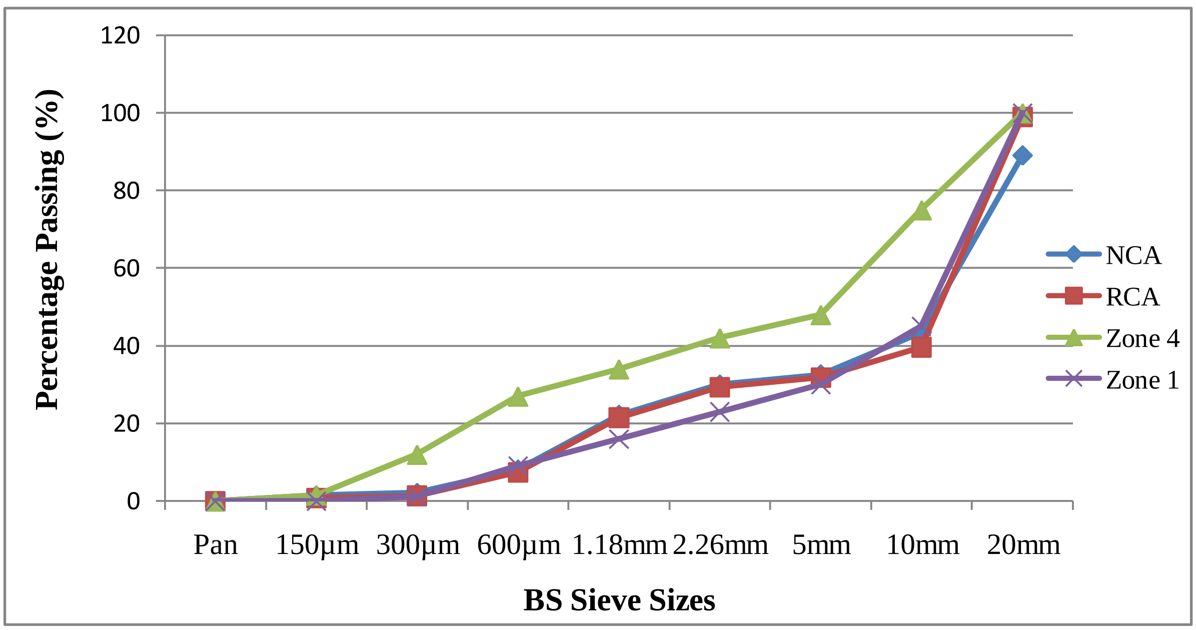

Figure 4.1: Sieve analysis of NCA and RCA

4.2.2 Specific gravity of materials

Table 4.2 gives specific gravity for the aggregates (coarse and fine), metakaolin, sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The specfic gravity for Natural Coarse aggregates was found to be 2.5, that of RCA was 2.4 and fine aggregate was 2.51. This shows that the result of specific gravity of aggregates falls within the range of 2.30 to 2.90 respectively as specified by ACI EI 201 (2001). The specific gravity of metakaolin was 2.51 which fell within the range of 2.4 to 2.6 as given by Sanjay *et al.*, (2013). The result obtained for sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) are 1.47 and 1.6 respectively, which is the same as reported by Anuradha *et al*., (2011)

Table 4.2: Specific gravity of Materials.

Sample	**Specific Gravity Kg/m^3**
Natural Coarse Aggregate	2.5
RCA	2.4
Fine Aggregate	2.5
Metakaolin	2.51
NaOH	1.47
Na_2SiO_3	1.6

Source: Laboratory Reseach Work (2016)

4.2.3 Aggregate moisture content, absorption capacity and bulk density

Table 4.3 presents the results for aggregate moisture content, absorption capacity and bulk density. The moisture content value obtained for NCA and RCA were 0.10% and 1.26% which shows that RCA contain more moisture than RCA. The absorption capacity of 1.4% for NCA and 4.5% for RCA indicates that the absorption capacity for RCA is higher compared to NCA. This could be that the old mortar that inherently clings to the RCA during manufacturing creates a more porous system and as a result increase the absorption capacity as suggested by Verian *et al.,* (2013). Though the values obtained fall within the range of 0.8 – 3.7 for NCA and 3.7 – 8.7 obtained by ACPA (2009).

The bulk density of NCA and RCA was obtained as 1554kg/m^3 and 1475kg/m^3 .This shows that RCA is lighter in weight than NCA, though they satisfy the requirements of BS 812: Part 2 (1995) that states the range for normal weight aggregates to be between 1280 and 1920 kg/m^3.

Table 4.3: Aggregate Moisture Content, Absorption Capacity and Bulk Density.

Sample	**Aggregate** Moisture Content	**Aggregate** Absorption Capacity	**Aggregate** Bulk Density
NCA	0.10	1.5	1554
RCA	1.26	4.5	1475

Source: Laboratory Reseach Work (2016)

4.2.4 Aggregate crushing and impact values

Table 4.4 gives the aggregate crushing value (ACV) and aggregate impact value (AIV) of the NCA and RCA. The aggregate crushing values results are 25.32% and 32.24%. This means that NCA has higher ability to resist crushing than RCA though the values obtain still fell within the 45% reported by Gupta and Gupta (2012).The percentage of aggregates impact of NCA and RCA was found to be 15.40% and 25.52% respectively. This indicates that NCA is more resistant to impact than RCA. The values are in line with the 45% reported by Gupta and Gupta (2012).

Table 4.4: Aggregate Crushing and Impact Value.

Sample	**Aggregate Crushing Value**	**Aggregate Impact Value**
NCA	25.32	15.40
RCA	32.24	25.52

Source: Laboratory Reseach Work (2016)

4.2.5 Chemical properties of metakaolin

Table 4.5 presents the chemical composition of metakaolin used for the research. The major oxides detected were SiO_2, Al_2O_3 and Fe_2O_3 with percentage values of 50.5%, 45.6% and 1.440% respectively. This means that metakaolin satisfies the chemical requirement for N-class pozzolana in ASTM C 618- (2005).

Table 4.5: Chemical composition of Metakaolin

Oxides	**Percentage Composition (%)**	**Summation of Oxide for Metakaolin (%)**	**ASTM C-618 Requirement (%)**
Aluminium oxide (Al_2O_3)	45.6	(SiO_2) = 50.5	(SiO_2)
Silicon oxide (SiO_2)	50.5	+ +	+
Potassium oxide (K_2O)	0.734	(Al_2O_3) = 45.6 } 97.54	(Al_2O_3) } 70
Titanium oxide (TiO_2)	0.0582	+ +	+
Vanadium oxide (V_2O_5)	0.003	(Fe_2O_3) =1.440	(Fe_2O_3)
Manganese oxide (MnO)	0.047		
Iron trioxide (Fe_2O_3)	1.440	Sulfur trioxide (SO_3)	Sulfur trioxide
Copper oxide CuO	0.014	= Nill	(SO_3)= 4.0
Germanium oxide (Ga_2O_3)	0.039		
Selenium dioxide(SeO_2)	0.14		
Silver oxide (Ag_2O)	0.737	Moisture Content	Moisture Content
Antimony trioxide (Sb_2O_3)	0.070	=Nill	= 3.0
Praseodymium (III) Oxide (Pr_2O_3)	0.036		
Neodymium (II) Oxide (Nd_2O_3)	0.060		
Europium(III) oxide (Eu_2O_3)	0.039		
Rhenium(VII) oxide (Re_2O_7)	0.089		
Titanium(III) oxide (Ti_2O_3)	0.31		
LOI	1.22	LOI = 1.22	LOI = 10.0

Source: Laboratory Reseach Work (2016)

4.3 Fresh Properties of Concrete Specimens

4.3.1 Workability test

Table 4.6 presents the slump tests results of the concretes made with GPC and PCC. Workability of GPC specimens containing 0%, 20% and 30% RCA was between low slump (25 – 50mm), while GPC specimens with 40% RCA fall within very low slump (0 –

25mm). For PCC specimens, though the workability is higher than with GPC specimens, the slump values obtained for PCC specimen containing 0%, 20%, 30% and 40% RCA was within medium slump (25 – 100mm). The decrease in workability of GPC specimens can be attributed to the molar concentration of NaOH used because according to Reddy *et al.* (2010), increase in the molar concentration of NaOH solution result to decrease in workability of the concrete.

For GPC and PCC specimens containing 20%, 30% and 40% RCA, the decrease in workability noticed when compared to GPC and PCC with 0% could be due to the introduction of RCA. This therefore satisfies Smith and Tighe (2008) report that concrete produced with RCA may have less slump value when compared with that made with NCA at the same water/cement ratio, Roesler and Hunley (2008) attributed the decrease in workability of the concrete made with RCA to the angularity of RCA, rough surface texture and higher absorption capacity.

Table 4.6: Slump values for GPC and PCC specimens

Specimen	**0% RCA (mm)**	**20% RCA (mm)**	**30% RCA (mm)**	**40% RCA (mm)**
GPC	37	35	27	20
PCC	80	65	50	40

Source: Laboratory Reseach Work (2016)

4.4 Hardened Properties of Concrete Specimens

4.4.1 Compressive strength

Figure 4.2 presents the results for average compressive strength of GPC and PCC specimens containing 0%, 20%, 30% and 40% RCA cured at 7, 14, 28 and 56days, respectively. From the figure, there was general increase in compressive strength from 7 to

56 days curing period for the PCC and GPC specimens; however, 22.29% increase in compressive strength at 56 days curing age was noticed between PCC and GPC specimens containing 0% RCA. The GPC specimen attained a higher compressive strength than the PCC specimens; this could be as a result of the type of binder used in the production of the GPC specimen. Bachhav and Dubey (2016), affirm that compressive strength of PCC is less as compared with GPC because the compressive strength of GPC specimen increases with increase in molarities of NaOH solution.

Percentage decrease in compressive strength at 56 days curing occurred for PCC and GPC specimens containing 20%, 30% and 40% RCA when compared to PCC and GPC specimen with 0% RCA. Percentage decrease of 10.71%, 16.03%, 22.61% were respectively noticed for PCC specimens while the GPC specimens had 1.54%, 12.24%, 15.08% decrease respectively. This may be due to the RCA introduced since James, (2009) had affirmed that the concrete produced with RCA had decrease in compressive strength compared to those of NCA. According to Verien *et al*., (2013), the higher the percentage replacement of RCA, the greater the reduction in strength. Details of the results are presented in Appendix A4.

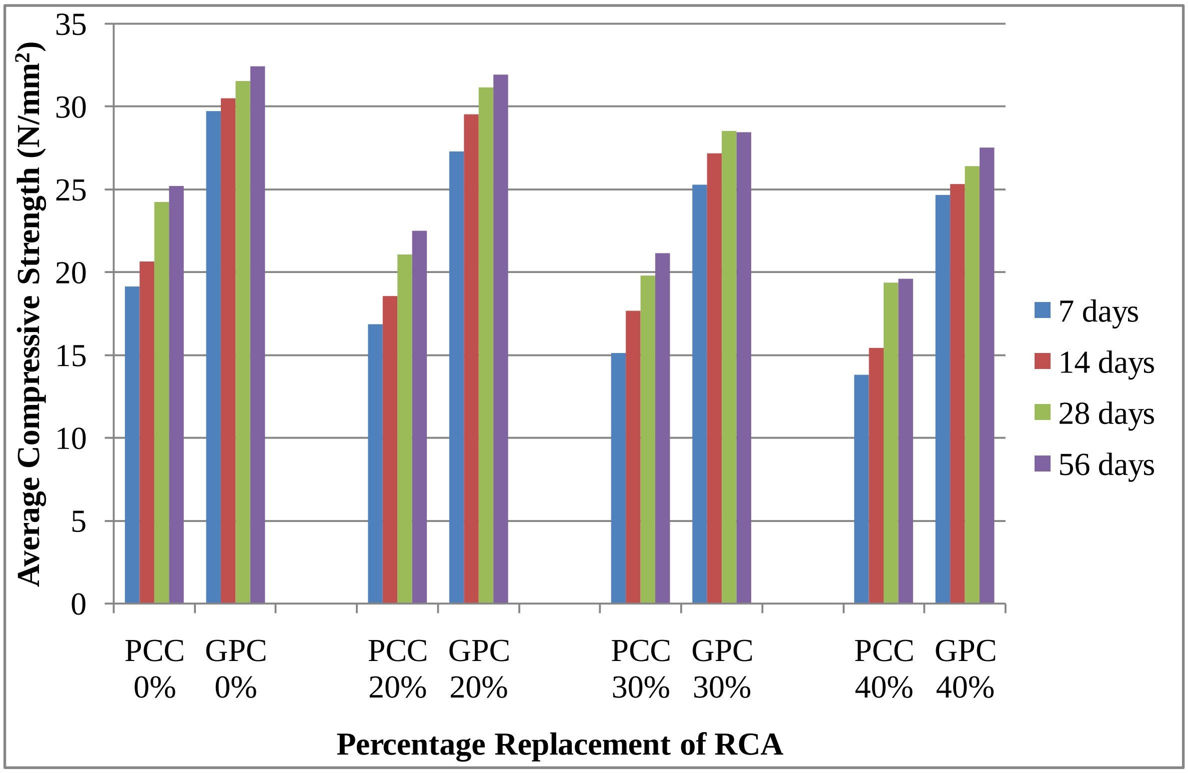

Figure 4.2: Average Compressive Strength of Hardened Concrete Specimen

4.4.2 Resistance to magnesium sulphate ($MgSO_4$) attack.

Figure 4.3 represents the average compressive strength of PCC and GPC specimens containing 0%, 20%, 30% and 40% RCA exposed to 2.5% concentration of $MgSO_4$ and cured at 28 and 56 days, respectively. There was general decrease in compressive strength at 56days curing period for the PCC and GPC specimens. However, 20.03% increase in compressive strength at 56 days curing age was noticed between PCC and GPC containing 0% RCA. GPC specimens had better resistance to $MgSO_4$ attack than the PCC specimens. This may be due to the absence of calcium hydrates or aluminates in the binder used to produce the GPC specimens. This therefore justifies the assertion by Rangan (2014), that the main product of geopolymerization are not vulnerable to sulphte attack due to the fact that there is no gypsum or ettringite in the formation of the product of geopolymerization.

For PCC and GPC specimens containing 20%, 30% and 40% RCA when compared to PCC and GPC with 0% RCA after their exposure to $MgSO_4$, percentage decrease in compressive strength of 16.91%, 21.71% and 25.56% were respectively noticed for the PCC specimens and that of GPC were recorded as 7.82%, 16.12% and 21.62%, respectively. This could be that the magnesium salt reacted with the cement mortar in the PCC specimens and the old cement mortar attached to the RCA contained in the GPC specimens. Gupta and Gupta (2012), affirm that magnesium sulphate ($MgSO_4$) decomposes calcium hydroxide $Ca(OH)_2$ and hydrated tricalcium aluminate (C_3A) present in cement which eventually form hydrated magnesium silicate that has no binding properties. Details of the results are presented in Appendix A5.

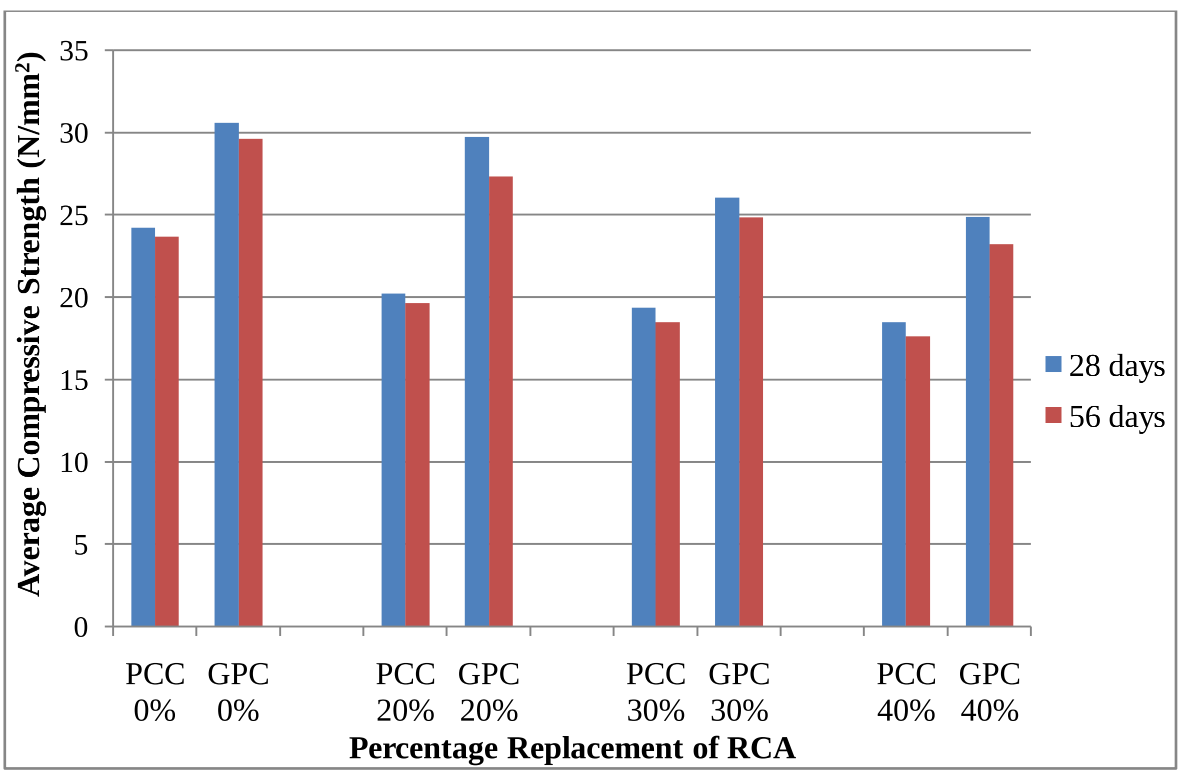

Figure 4.3: Compressive Strength of Hardened Concrete Specimen exposed to $MgSO_4$ Attack

4.4.3 Split tensile strength.

Figure 4.4 present the average split tensile strength of PCC and GPC specimens tested at 7, 14, 28 and 56days. An increase of 15.96% in split tensile strength occurred between PCC and GPC specimen containing 0% RCA at 56 days curing period. This perhaps could be as a result of the type of binder used in the production of the concrete specimen for Preethy *et al.*, (2015) discovered that the split tensile strength increases with increasing the molarity of sodium hydroxide as in the case of compressive strength. Higher concentration of NaOH solution gives higher split tensile strength of GPC specimens because it makes good bonding between the aggregates and paste of the concrete

However, PCC and GPC specimens containing 20%, 30% and 40% RCA when compared to with PCC and GPC specimens containing 0% RCA had 4.66%, 11.11% and 14.69% decreases for the PCC specimens while, GPC specimens had 15.38%, 23.49% and 25.90% decreases respectively. This could possibly be due to the introduction of RCA since Sherif, Kareem, Annam, Amani and Hiba, (2015) had explained that the reduction of up to 10 % in split tensile strength could be when NCA is substituted with RCA. Details of the results are presented in Appendix A6.

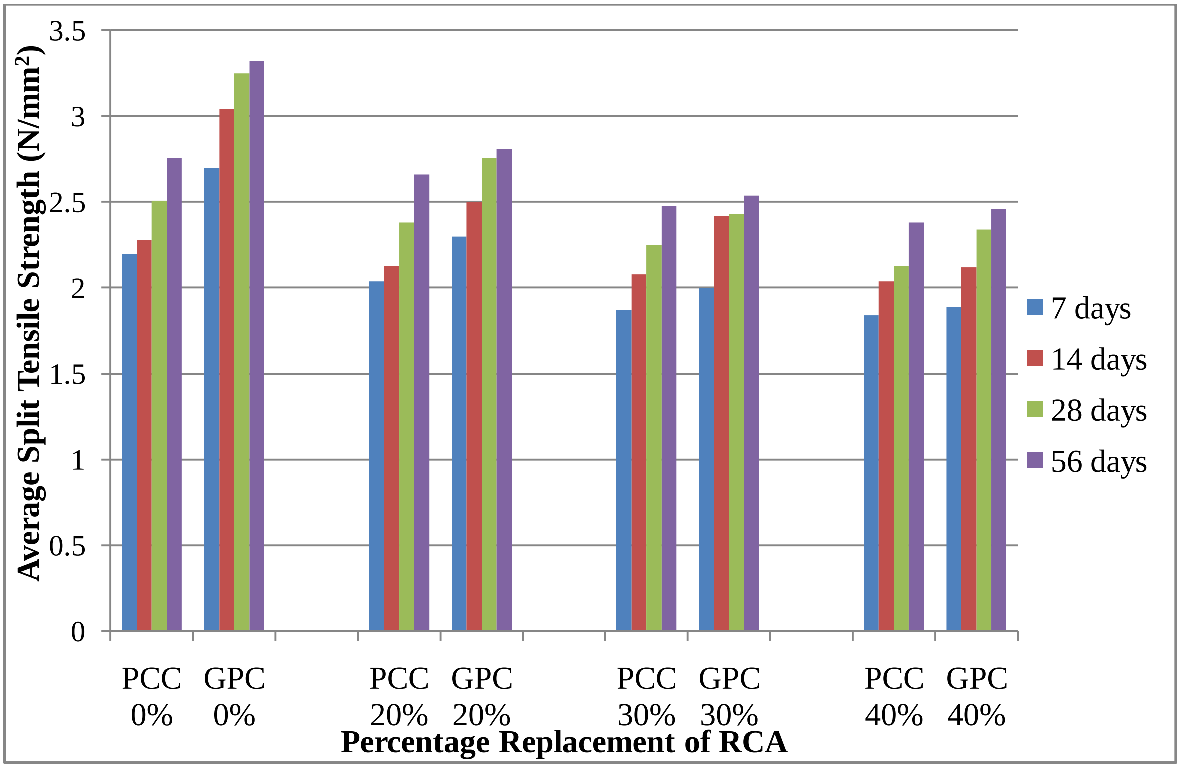

Figure 4.4: Average Split Tensile Strength of Hardened Concrete Specimen

4.4.4 Abrasion resistance

Figure 4.5 represents the average abrasion resistance of PCC and GPC specimens tested at 28 and 56days curing periods. The results shows that GPC specimens containing 0% RCA have less percentage loss in weight of about 0.05% compared to PCC with the same replacement which have 0.06% weight loss. This perhaps could be as a result of the type of binder used because Ramujee and Potharaju (2014a), compared the abrasion resistance of PCC and GPC specimens by placing an abrasive charge on the surface of the specimens for the paddle to rotate at a required speed for 12hrs duration and discovered that GPC specimens had better resistance to abrasion than PCC specimens because the depth of wear in GPC specimens is smaller compared to PCC specimens. Details of the results are presented in Appendix A7.

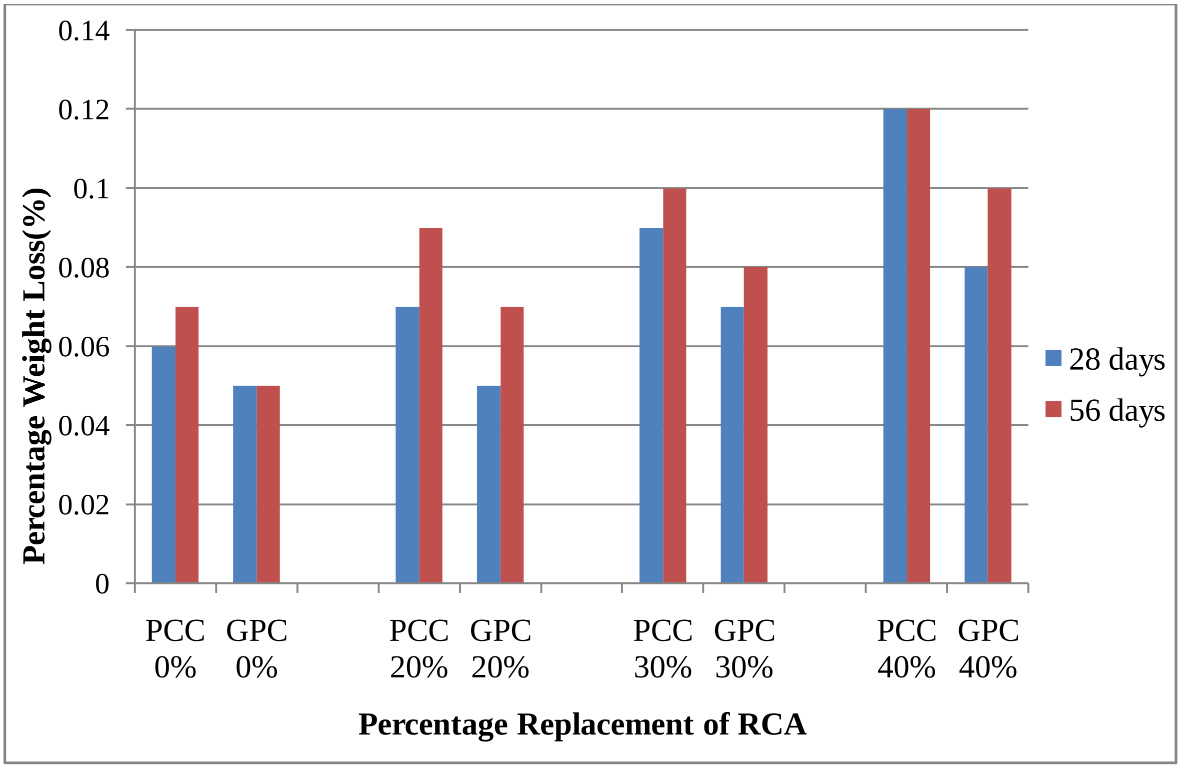

Figure 4.5: Average Abrasion Resistance of Hardened Concrete Specimen

4.4.5 Water Absorption capacity

Figure 4.6 shows the average water absorption capacity of the PCC and GPC specimens cured at 28 and 56 days. The GPC specimens containing 0% RCA had high absorption capacity of 8.44% at 56 day curing period compared to PCC specimens with 0% RCA. This possibly could be due to the release of water contained in the GPC specimens when cured in the oven. It therefore justifies the claims by Rangan (2010), that water is released during the formation of geopolymer (that is, during curing and further drying period of the matrix) leaving behind nano-pores. The implication of this is that it could make GPC specimens susceptible to attack. Details of the results are presented in Appendix A8.

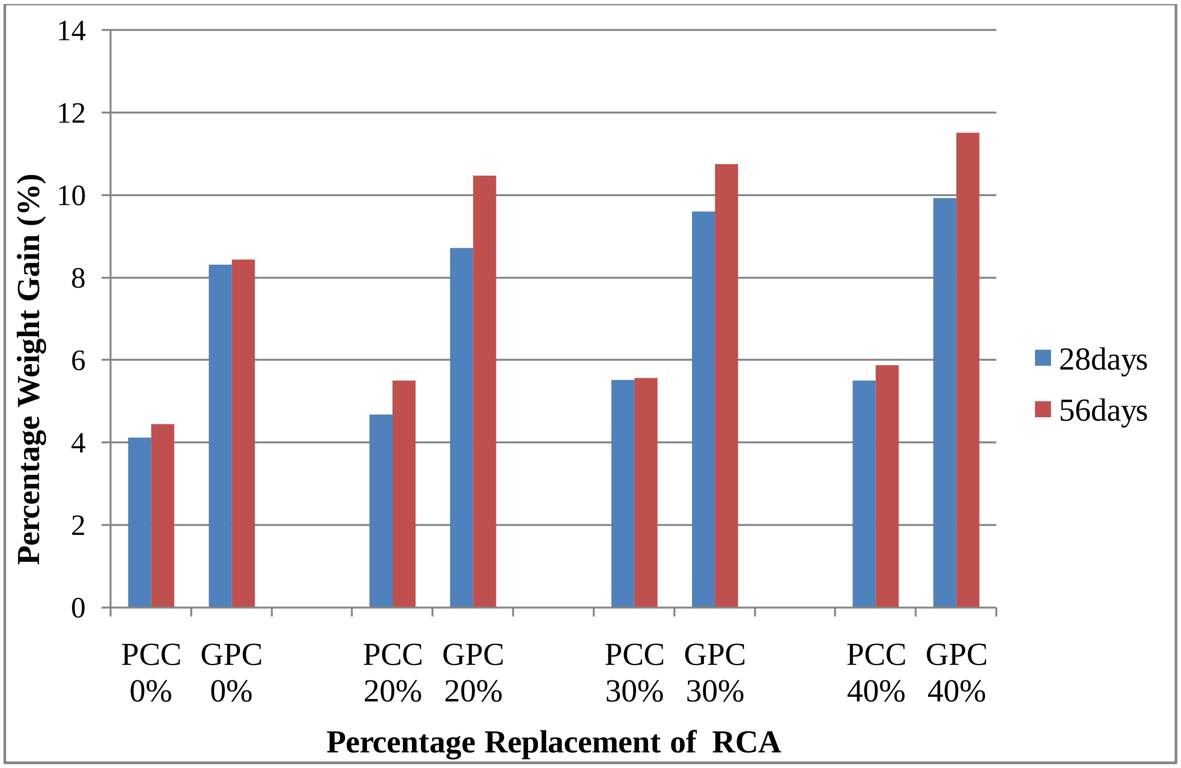

Figure 4.6: Average Water Absorption Capacity of Hardened Concrete Specimen

CHAPTER FIVE

5.0 SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary of the Major Findings

The highlights of the major findings are summarized as follows:

i. The specific gravity, bulk density, moisture content and absorption capacity for NCA and RCA were found to be 2.5 and 2.4 , 1554kg/m^3 and 1475kg/m^3 , 0.10% and 1.26% , 1.4% and 4.5%, respectively. Aggregate impact and crushing values for NCA and RCA were 25.32% and 32.24%, 15.40% and 25.52%, respectively.

ii. The summation of elements found in metakaolin is 99.92%. However it contain 50.5% amount of silica oxide and 45.6% amount of Alumina oxide.

iii. The workability of PCC specimens with 0%, 20%, 30% and 40% RCA specimens were within the limit of medium slump (that is 25 - 100mm). GPC specimens with 0%, 20%, and 30% RCA fall within low slump (that is 25 - 50mm), while that with 40% RCA was within very low slump (0 - 25mm slump).

iv. PCC and GPC specimens with 0% RCA had 22.29% increases in compressive strength. However PCC and GPC specimens containing 20%, 30% and 40% RCA had a decrease in strength of 10.71%, 16.03% and 22.61%, 1.54%, 12.24%, and 15.08%, respectively when compared with PCC and GPC specimens with 0% RCA.

v. PCC and GPC specimens having 0% RCA had percentage increase of 15.96% for split tensile strength and percentage decrease of 4.66%, 11.11% and 14.69%, 15.38%, 23.49% and 25.90%, respectively were noticed in PCC and GPC specimens with 20%, 30% and 40% RCA when compared with PCC and GPC specimen containing 0% RCA.

vi. For PCC and GPC specimens exposed to $MgSO_4$ attack, the percentage increase in compressive strength between PCC and GPC with 0% RCA was 24.66%. PCC and GPC specimens containing 20%, 30% and 40% RCA when compared with PCC and GPC specimens containing 0% RCA had decrease values of 14.68%, 17.59% and 20.23% for PCC specimens and 7.82%, 16.12% and 21.62% respectively for GPC specimens.

vii. The abrasion resistance of GPC specimens with 0% RCA shows less percentage weight loss of 0.05% than that of PCC specimens having 0% RCA. GPC specimens containing 0% RCA show appreciable increase of 8.44% in water absorption capacity when compared to PCC specimens containing 0% RCA.

5.2 Conclusions

After carrying out the experiments, observations, analysis and discussions, on the evaluation of properties of concrete made with RCA using metakaolin based geopolymer, the following conclusions were drawn:

i. The physical and mechanical properties such as specfic gravity, bulk density, moisture content and absortion capacity, aggregate crushing and impact values for NCA were found to be higher than that for RCA.

ii. The workability of GPC specimen is less than that of PCC with the same replacement of RCA.

iii. Mechanical properties of hardened concrete specimens shows that GPC with various replacement of RCA have higher compressive and split tensile strengths than PCC specimes with the same replacement of RCA.

iv. The durabilitiy properties of hardened concrete specimens shows that GPC specimens with various replacement of RCA have high resistance to magnesium sulphate attack and high abrasion resistance than PCC specimes with the same replacement of RCA, but had higer absorption capacity.

5.3 Recommendations

i. It is recommended that Kaolin obtained from Kankara in Kastina State be used to produce GPC.

ii. GPC containing RCA up to 40% RCA should be used for structural concrete

iii. It is recommended GPC specimens containing RCA should be used in areas exposed to magnesium sulphate attack.

iv. It is also recommended that the GPC produced with RCA in this research, can be used as a standard material on Nigerian construction sites; and inclusion in the Nigerian specification of cinstruction materials when developed.

5.4 Recommendations for Futher Studies

i. Research should be carried out on the use of water reducing admixtures to enhance the workability of GPC.

ii. Durability properties such as exposure to aggressive environment and elevated temperature should be carried out on GPC made with percentage replacement of RCA.

iii. Effect of different molarities and curing regime need to be carried out on metakaolin based geopolymer concrete containing RCA.

iv. Due to its high absorption rate, it is recommended that cold compressive strength be carried out on the GPC specimens.

v. Further research should be carried out with increase in RCA replacement in GPC production beyond 40%.

5.5 Contributions to Knowledge

i. The study established that the use of geopolymer based geopolymer concrete containing recycled concrete aggregate using metakaolin leads to increase of 22.76% higher than the conventional concrete.

ii. It was also discover that where high early strength is required, geopolymer based concrete using metakaolin can be used as the increase after 7, 14, 28 and 56days were 35.64%, 32.31%, 22.76% and 22.29% higher than the conventional concrete.

iii. The study established that metakaolin is a viable source material which can be used in production of geopolymer binder thereby reducing the use of the most expensive constituent material in concrete production (cement).

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APPENDICES

Appendix A1

Particle Size Distribution Results: Natural Coarse Aggregate and Recycled Concrete Aggregate

Table A1.1: Natural Coarse Aggregate with Fine Aggregate

BS Sieve Size	Weight Retained (g)	Weight Passing (g)	Percentage Retained (%)	Cumulative Percentage Passing (%)
20mm	330	2670	11	89
10mm	1365	1305	45.5	43.5
5mm	327	978	10.9	32.6
2.36mm	79	899	2.6	29.97
1.18mm	233	666	7.77	22.2
600 µm	423	243	14.1	8.1
300 µm	181	62	6.03	2.07
150 µm	19	43	0.63	1.43
Pan	43	0	1.43	0

Source: Laboratory Research Work (2016)

Table A1.2: Recycled Concrete Aggregate with Fine Aggregate

BS Sieve Size	Weight Retained (g)	Weight Passing (g)	Percentage Retained (%)	Cumulative Percentage Passing (%)
20mm	30	2970	1	99
10mm	1780	1190	59.33	39.67
5mm	232	958	7.73	31.9
2.36mm	79	879	2.6	29.3
1.18mm	233	646	7.77	21.53
600 µm	423	223	14.1	7.43
300 µm	181	42	6.03	1.40
150 µm	19	23	0.6	0.77
Pan	23	0	0.77	0.00

Source: Laboratory Research Work (2016)

Appendix A2

Mix Design for Grade C25 Concrete Using Building British Research Establishment Method (BRE)

Design Stipulations and Test data for Materials

Compressive strength at 28 days = 25N/mm^2

Type of concrete = Plain Concrete

Grade of cement = 42.5

Coarse aggregate type = crushed granite

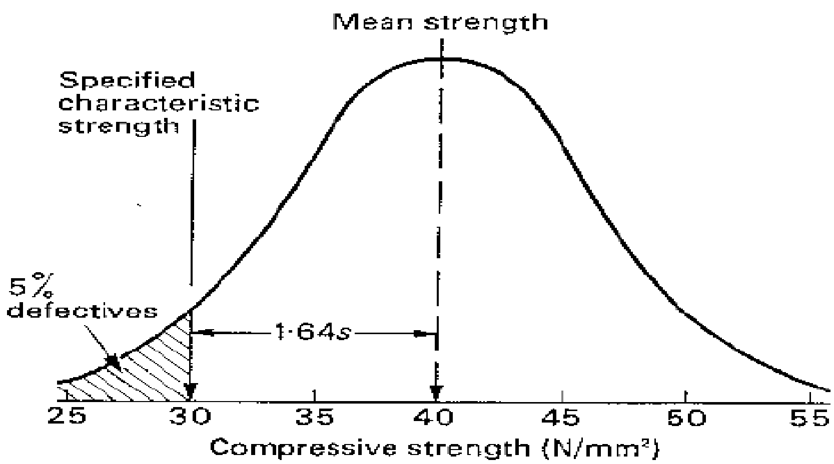

Figure A2.1: Normal Distribution of Concrete Strength

Source: Building Research Establishment (1997)

Table A2.1: K factor used in Statistical Control

Percentage	K
16	1.00
10	1.28
5	1.64
2	2.05
1	2.33

Source: Building Research Establishment (1997)

<u>Step 1</u>: Compute Mean Target Strength

$f_m = f_c + ks$

Where

f_m= the target mean strength

f_c=the specified characteristic strength

ks = the margin, which is the product of:

s = the standard deviation, and

k = a constant

From fig. A2.1 select margin factor = 5

From table A2.1, k = 1.64 and s =4

f_m= 30N/mm^2 +(1.64 x 4)

f_m =25+6.56

f_m= 31.56N/mm^2

<u>Step 2</u>: Information on the Materials to be used

a) Coarse aggregate = 20mm Maximum sieve size

b) Percentage of fine aggregate passing through 600µm sieve = 26%

c) Specific gravity of coarse aggregate based on SSD = 2.50

d) Condition of Exposure = Alternate Wetting and Drying

<u>Step 3</u>: Determine the Required Water Cement Ratio

Using cement grade 42.5 and crushed course aggregate at 28 day as it is seen from table A2.2

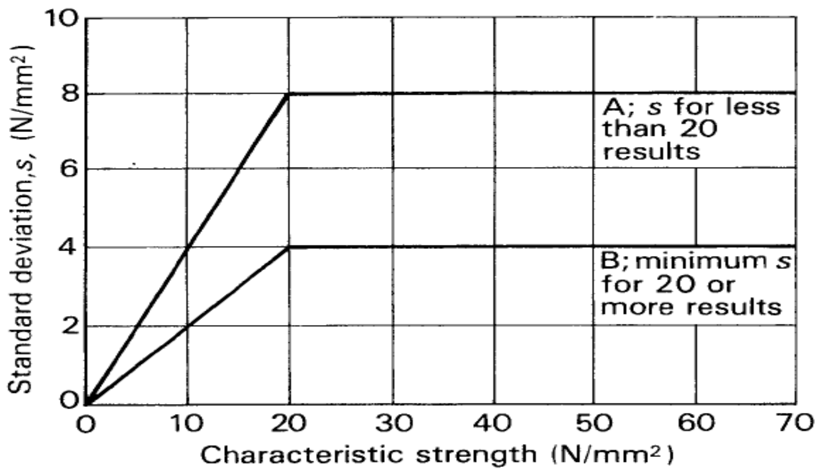

Figure A2.2: Characteristic Strength Versus Standard Deviation Relationship

Source: Building Research Establishment (1997)

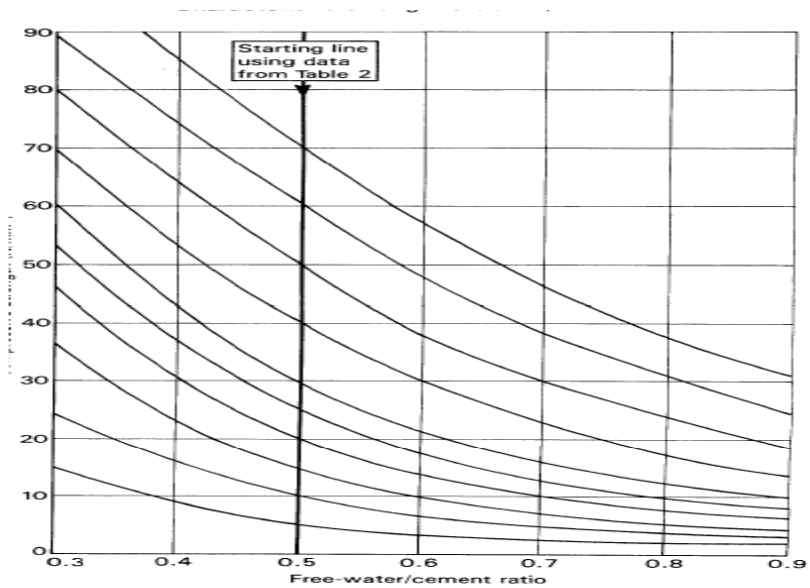

Figure A2.3: Relationship between Compressive Strength and Water/Cement Ratios

Source: Building Research Establishment (1997)

Table A2.2: Approximate Compressive Strength of Concrete Mix with a Free-Water/Cement Ratio of 0.5

Cement strength class	Type of coarse aggregate	Compressive strengths (N/mm²) Age (days)			
		3	7	28	91
42.5	Uncrushed	22	30	42	49
	Crushed	27	36	49	56
52.5	Uncrushed	29	37	48	54
	Crushed	34	43	55	61

Source: Building Research Establishment (1997)

Table A2.3: Maximum water cement ratio for reasonable durability

Condition of Exposure	Maximum Water Cement Ratio	
	Plain Concrete	Reinforced Concrete
Internal, Subject to heavy condensation	-	0.60
Alternate wetting and drying	0.60	0.60
Freezing and Thawing	0.55	0.50
Seawater or salt spray	0.50	0.45
Water retaining structure	-	0.50

Source: Building Research Establishment (1997)

Anticipate strength = 49N/mm^2

Target strength = 31.56N/mm^2

Free water/cement ratio =0.5

To determine the new free water/cement ratio to be used:

From Figure A2.3

Use the curve drawn from 0.5 free water/cement ratio and 49N/mm^{2}anticipated strength to trace the new water/cement ratio with target strength of 31.56N/mm^2

New free water/cement ratio = 0.63 which is not OK according to the standard because from table A2.3, maximum allowable water/cement ratio for alternate wetting and drying condition of exposure, plain concrete = 0.60

Therefore, maximum allowable water/cement ratio = 0.60

Step 4: **Selecting an appropriate degree of Workability (Slump)**

Table A2.3: Workability, Slump and Compacting factor of concrete with 19mmor 38mmsize of aggregate

Degree of workability	Slump mm	Slump in.	Compacting factor	Use for which concrete is suitable
Very low	0–25	0–1	0.78	Roads vibrated by power-operated machines. At the more workable end of this group, concrete may be compacted in certain cases with hand-operated machines.
Low	25–50	1–2	0.85	Roads vibrated by hand-operated machines. At the more workable end of this group, concrete may be manually compacted in roads using aggregate of rounded or irregular shape. Mass concrete foundations without vibration or lightly reinforced sections with vibration.
Medium	25–100	2–4	0.92	At the less workable end of this group, manually compacted flat slabs using crushed aggregates. Normal reinforced concrete manually compacted and heavily reinforced sections with vibration.
High	100–175	4–7	0.95	For sections with congested reinforcement. Not normally suitable for vibration.

(Building Research Establishment, Crown copyright)

From A2.3, Select medium degree of workability with a slump ranging from 25 - 100mm.

<u>Step 5</u>: Determine the Required Free Water Content (kg/m^3)

From Table A2.4, based on the selected workability, maximum size and type of aggregate, the required free water content = 210kg/m^3

Table A2.4: Approximate Free-Water Content (Kgm^3) Required to Give Various Levels of Workability.

Slump (mm)		0-10	10-30	30-60	60-180
Vebe time (s)		>12	6-12	3-6	0-3
Max. size of aggregate (mm)	Type of Aggregate				
10	Uncrushed	150	180	205	225
	Crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	Crushed	170	190	210	225
40	Uncrushed	115	140	160	175
	Crushed	155	175	190	205

Source: Building Research Establishment (1997)

<u>Step 6</u>: Calculate the Cement Content by using the W/C Ratio

Cement content (kg/m^3) = $\frac{Water\ \ Content\ \ (kg/m^3)}{w/c}$

Cement content (kg/m^3) = $\frac{210kg/m^3}{0.60}$

Cement (kg/m^3) = 350kg/m^3

Step 7: Compare the Amount of the Cement Obtained with the minimum Allowable Content for Durability.

Table A2.5: Maximum Cement Content for Concretes with 20mm Maximum Aggregate Size under Different Condition of Exposure

Exposure Conditions	Minimum Cement Content for Concrete (Kg/m^3)		
	Plain	**Reinforced**	**Pre-stressed**
Non-corrosive	220	250	300
buried or sheltered from rain	250	290	300
Exposed to alternate wetting and drying or seawater	310	360	360
subject to de-icing salt	280	390	300

Source: Building Research Establishment (1997)

From Table A2.4, the minimum cement content for plain concrete exposed to alternate wetting and drying = 310kg/m^3 which is less than the 350kg/m^3. Therefore, 350kg/m^3 is adequate.

Step 8: **Determine the Wet Density of the Concrete using Free Water Content**

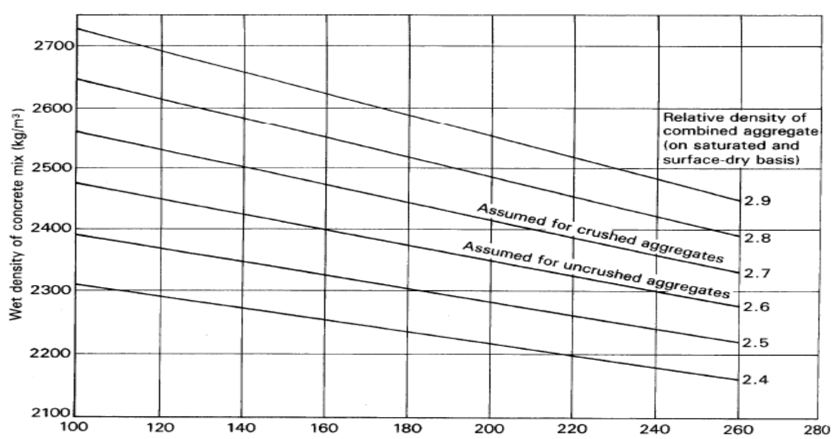

Figure A2.3: Relationship between free-water content and wet density of concrete

Source: Building Research Establishment (1997)

From Figure A2.3

Free water content = 210kg/m^3 (from step 5)

Combined specific gravity of aggregate at SSD = 2.50

Therefore, Wet density (plastic density) = 2280kg/m^3

<u>Step 9</u>: Deducing the Proportion of the Fine Aggregate.

Water/cement ratio= 0.60, Slump = 50mm Maximum aggregate size = 20mm

Percentage of fine aggregate that passed through 600µm BS sieve = 21.3%

From Figure.A2.4,the proportion of fine aggregate = 43%

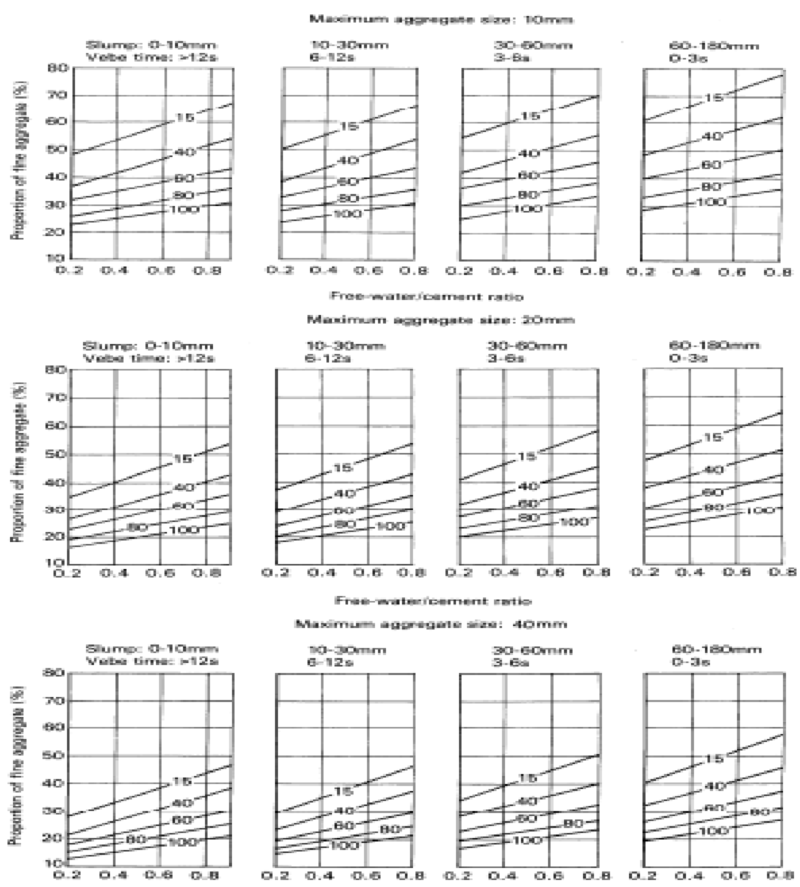

Figure A2.4: Recommended Percentages of fine aggregate in total aggregate as a function of free-water/cement ratio for values of workability and maximum size of aggregate

Source: Building Research Establishment (1997)

<u>Step 10</u>: Compute the Quantity of Aggregate

1. Total Aggregate Content based on Supersaturated surface dry (SSD)

Total Aggregate Content= Plastic Density – Cement content – Water content
(TAC) (PD) (CC) (WC)

TAC $= 2280kg/m^3 – 350kg/m^3 – 210kg/m^3$

TAC $= 1710kg/m^3$

2. Fine Aggregate Content (FAC) = TAC x Proportion of fine aggregate(FA)

$$FAC = 1710\ kg/m^3 x\ \frac{43}{100}$$

$$FAC = 735.30\ kg/m^3$$

3. Course Aggregate Content (CAC) = TAC – FAC

$$CAC = 1710kg/m^3 – 735.30\ kg/m^3$$

$$CAC = 974.70\ kg/m^3$$

<u>Step 11</u>: Deducing the Mix Proportion by Weight Taking Cement as 1

Cement Content = $350kg/m^3$

Fine Aggregate Content = $735.30\ kg/m^3$

Coarse Aggregate Content = $974.70\ kg/m^3$

Water Content = $210kg/m^3$

Mix Proportion $=\frac{350}{350} : \frac{735.30}{350} : \frac{974.70}{350}$ and $\frac{210}{350}$

$= 1: 2\frac{2}{25} : 2\ \frac{17}{20}$ and W/C = 0.60.

<u>Step 12:</u> Adjust the quantity of mix water to take care of moisture condition of the aggregate on site if necessary (the aggregates used were at saturated surface dry condition)

<u>Step 13</u>: Quantity of materials in kg per the required volume of concrete

Computing the total volume of concrete required.

Unit volume of cube = 0.1 x 0.1 x 0.1 = $0.001m^3$.

Add 20% waste of the total volume of concrete = $0.001 + (\frac{20}{100}\ X\ 0.001)$

= $0.0012m^3$

Quantity of Material required by volume for 0.6w/c ratio required per m^3

Quantity of Cement = $0.0012m^3$x 350kg/m^3 = 0.42kg

Quantity of Fine Aggregate = $0.0012m^3$ x 735kg/m^3= 0.88kg

Quantity of Natural Coarse Aggregate = $0.0012m^3$ x 975kg/m^3= 1.174kg

Quantity of water = $0.0012m^3$ x 210kg/m^3= 0.25kg

Total quantity of material required for each sample

<u>Sample 1</u>

Containing 100% NA and 0% RCA

Cement = 0.42 kg x 42 = 17 kg

Fine Aggregate = 0.88kg x 42 = 36.96kg

Natural Aggregate = 1.17kg x 42 = 49.14kg

Water = 0.25 x 42 = 10.5

Table A2.6: Mix Proportion for 0% RCA

Cement	Fine Aggregate	Coarse Aggrgate	Water
$\mathbf{0.42\ kg}$	$0.88\ kg$	$1.17\ kg$	$0.25kg$

Source : Laboratory Research Work (2016)

Sample 2

Containing 80% NA and 20% RCA

Cement = 0.42 kg x 42 = 17 kg

Fine Aggregate = 0.88kg x 42 = 36.96kg

Natural Aggregate = 0.94kg x 42 = 39.48kg

Recycled Concrete Aggregate = 0.23kg x 42 = 9.66kg

Water = 0.25 x 42 = 10.5

Table A2.7: Mix Proportion for 20% RCA

Cement	Fine Aggregate	Coarse Aggrgate	RCA	Water
$\mathbf{0.42\ kg}$	$0.88\ kg$	$0.94\ kg$	$0.23kg$	$0.25kg$

Source : Laboratory Research Work (2016)

Sample 3

Containing 70% NA and 30% RCA

Cement = 0.42 kg x 42 = 17 kg

Fine Aggregate = 0.88kg x 42 = 36.96kg

Natural Aggregate = 0.82kg x 42 = 34.44kg

Recycled Concrete Aggregate = 0.35kg x 42 = 14.7kg

Water = 0.25 x 42 = 10.5

Table A2.8 : Mix Proportion for 30% RCA

Cement	Fine Aggregate	Coarse Aggrgate	RCA	Water
$\mathbf{0.42\ kg}$	$0.88\ kg$	$0.82\ kg$	$0.35kg$	$0.25kg$

Source : Laboratory Research Work (2016)

Sample 4

Containing 60% NA and 40% RCA

Cement = 0.42 kg x 42 = 17 kg

Fine Aggregate = 0.88kg x 42 = 36.96kg

Natural Aggregate = 0.70kg x 42 = 29.40kg

Recycled Concrete Aggregate = 0.47kg x 42 = 19.74kg

Water = 0.25 x 42 = 10.5

Table A2.8 : Mix Proportion for 40% RCA

Cement	Fine Aggregate	Coarse Aggrgate	RCA	Water
$\mathbf{0.42\ kg}$	$0.88\ kg$	$0.70\ kg$	$0.47kg$	$0.25kg$

Source: Laboratory Research Work (2016)

Appendix A3

Materials Calculation for Mix Design of Grade 25 Geopolymer Concrete Using the Method Prescribed By Anuradha *et al.*, (2011) and Ramujee and Potharaju (2014).

Data for Mix Design

The basic data required to be specified for design of geopolymer concrete mix are as follows:

A = Characteristic compressive strength of Geopolymer concrete after curing.

B = the maximum size, type of fine and coarse aggregates to be used (Table A3.2.)

C = Specific gravity of the ingredients of the concrete (table 4.2)

D = Selection of alkaline liquid, ash ratio to compressive ratio (from fig A3.1, and A3.2 respectively)

For desired workability, the quantity of mixing per unit volume of concrete and the ratio of fine aggregate to total aggregates are estimated from tables as applicable, depending upon the nominal maximum size and type of aggregates.

Step 1: Selection of Metakaolin to Compressive Ratio

The quantity of metakaolin for grade 25 geopolymer concrete is 470 kg/m^3 based on figure A3.1 prescribed by Anuradha (*et al.*, 2011)

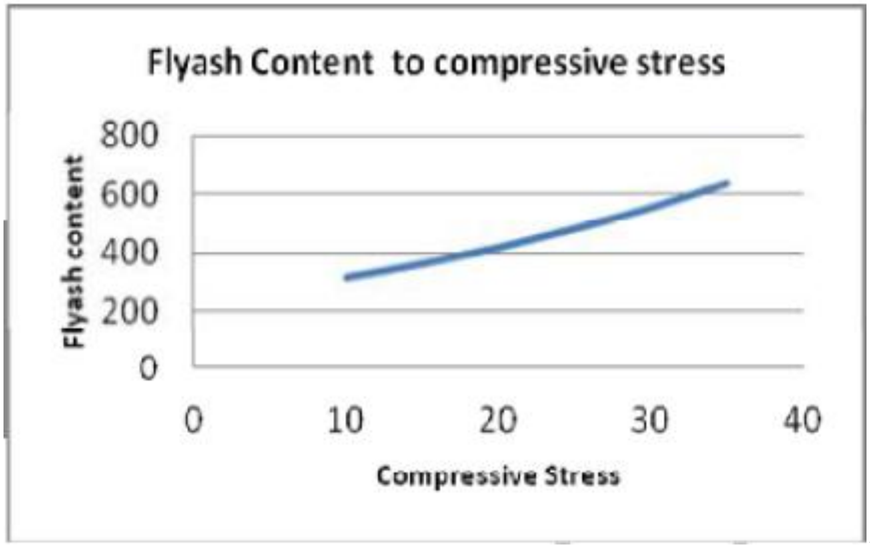

Figure A3.1: Metakaolin to the compressive strength

Source: Anuradha, *et al.*, (2011)

Step 2: Selection of Alkaline Liquid Ratio

The alkaline liquid to metakaolin ratio selected as against compressive strength is 0.62 using the alkaline to flyash ratio and compressive strength figure prescribed by Anuradha (*et al*, 2011)

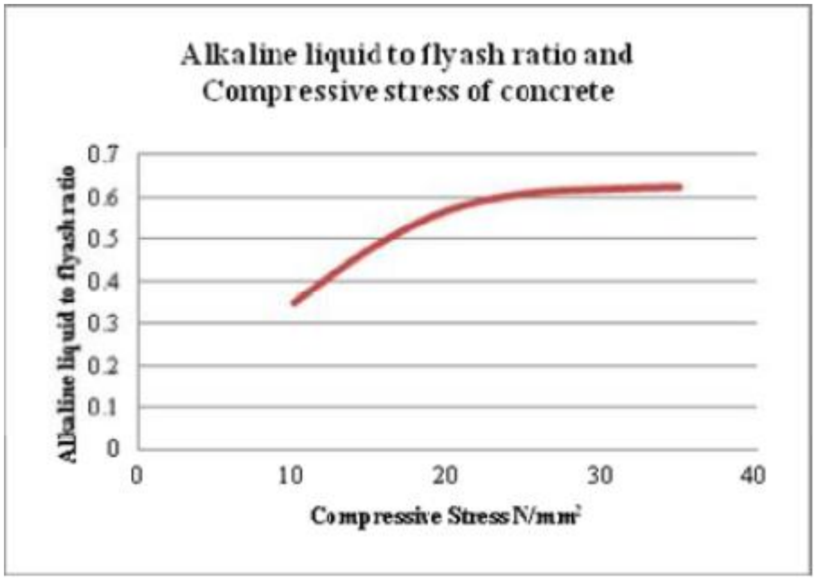

Figure A3.2 relation between free alkaline liquid to flyash ratio and compressive strength of concrete

Source: Anuradha *et al.*, (2011)

The ratio between Sodium Hydroxide (NaOH) to Sodium Silicate (Na_2SiO_3) ratio is 1:2.5 according to Anuradha (*et al.*, 2011). See Table A3.1

Table A3.1: Sodium hydroxide to sodium silicate ratio in accordance to compressive Strength.

Compressive Strength	Sodium Hydroxide	Sodium Silicate
10	1	3
15	1	2.5
20	1	2.5
25	1	2.5
30	1	2.5
35	1	2.5
40	1	2.5
45	1	2.5

Source: Anuradha *et al.*, (2011)

Amount of alkaline liquid= 470 x 0.62 = 291.4kg/m^3

*****Calculation of Amount of Sodium Hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3) according to Ramujee and Potharaju (2014)**

Amount of Sodium Hydroxide (NaOH)= $\frac{291.4}{(1+2.5)}$

$= \frac{291.4}{(3.5)}$

$$= 83.3\ kg/m^3$$

Amount of Sodium Silicate (Na_2SiO_3) = $291.4 - 83.3$

$$= 208.1\ kg/m^3$$

Step 3: Selection of Water Content

According to Anuradha *et al*., (2011), the maximum extra water content added is 0.06 water/flyash ratio while 0.02 is the minimum. In the case of this research, after series of trial, the extra water content added for metakaolin is 0.18 water /metakaolin ratio.

Amount of water add extra is 0.18 to water /metakaolin ratio = $0.18\ x\ 470$

$$= 85\ kg/m^3$$

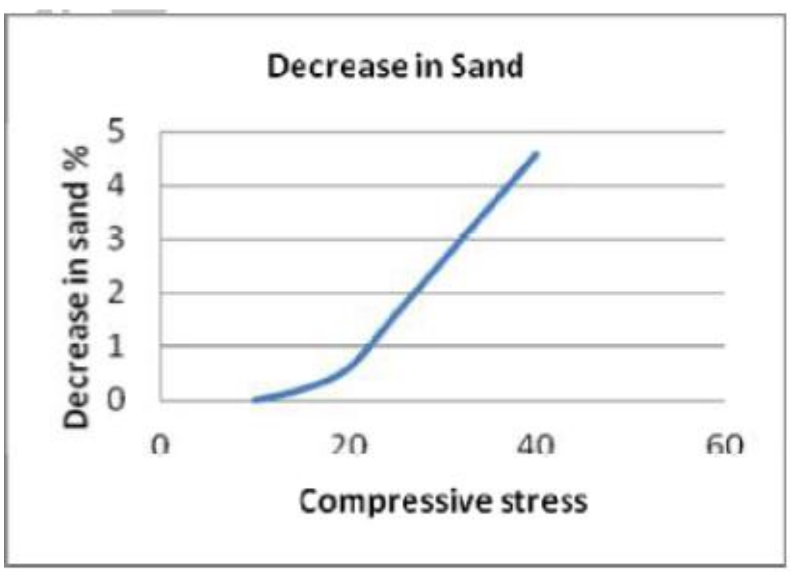

Figure A3.3: Adjustment of values in sand content percentage
Source: Anuradha *et al.*, (2011)

Step 4: Calculation of Aggregate Content in Metakaolin Base Geopolymer Concrete

The following table obtained from Anuradha *et al.*, (2011) was used to calculculate the amount of aggregate.

Table A3.2: Approximate amount of entrapped air to be expected in normal (non-air-entrained) concrete

Nominal Size of Coarse Aggregate	Sand as Percentage of Total Aggregate By Absolute Volume
10mm	**40**
20mm	**35**

Source: Anuradha *et al.*, (2011)

Change in Condition	Sand content in %
For sandconforming to Zone I	**+1.5%**
For decrease in sand content	**+1.56%**
Total	**–3.06%**

Source: laboratory research work (2016)

From fig A3.3, decrease in sand content = 1.56%

For sand conforming to Zone 1 = +1.5%

Total Sand Content in % = (1.56 + 1.5) % = 3.06 %

Therefore total aggregate by absolute volume = (35 + 3.06) % = 38.6% = 0.38

Table A3.3: Approximate sand per cubic meter of concrete

Nominal Maximum size of aggregate (mm)	Entrapped air, as percentage of volume of concrete
10	**3%**
20	**2%**

Source: Anuradha *et al.*, (2011)

Calculating for the total aggregate per unit volume of concrete using the following equations;

$$\mathbf{V}= \left(\frac{SO}{Sso} + \frac{S}{Ss} + \frac{F}{SF} + \frac{1}{p}\frac{Fa}{SFa}\right)\mathbf{x}\frac{1}{100} ---------- (i)$$

$$V = \left(\frac{SO}{Sso} + \frac{S}{Ss} + \frac{F}{SF} + \frac{1}{1-p}\frac{Ca}{SCa}\right)\mathbf{x}\frac{1}{100} ---------- (ii)$$

Where,

V= Absolute volume of fresh concrete, which is equal to gross volume minus the volume of entrapped air. $\frac{100-2}{100}$=0.98

S = Sodium Silicate Solution kg/ m^3 of concrete

S_o= Sodium Hydroxide Solution kg/m^3 of concrete

F= Weight of Metakaolin in kg/m^3 of concrete

S_F= Specific Gravity of Metakaolin

P= Ratio of fine aggregate to total aggregate by absolute volume

$F_{a,}$ Ca= Total mass of fine aggregate and coarse aggregate kg/m^3 of concrete respectively

SF_a SC_a= Specific gravity of saturated surface dry fine and coarse aggregate respectively.

S_s= Specific gravity of sodium silicate solution

S_{so}=Specific gravity of sodium hydroxide solution

Design stipulations

i. Characteristic compressive strength required = 25KN/mm
ii. Maximum size of aggregate = 20mm
iii. Specific gravity of metakaolin = 2.51
iv. Specific gravity of natural coarse aggregate =2.5
v. Specific gravity of Recycled Concrete aggregate = 2.4
vi. Specific gravity of fine aggregate = 2.5

vii. Sand conforming = zone 1 (from table A3.2)

viii. Specific gravity of NaOH = 1.47

ix. Specific gravity of Na_2SiO_3 =1.6

x. V = 0.98

xi. P =0.38

Substituting the values in equation (i) to calculate the quantity of fine aggregate required in metakaolin based geopolymer concrete

I. Calculation for Fine Aggregate

$$0.98 = \left(\frac{83.25}{1.47} + \frac{208.15}{1.6} + \frac{470}{2.51} + (\frac{1}{0.38})(\frac{Fa}{2.5})\right) \text{x} \frac{1}{100}$$

$$0.98 = \left(56.63 + 130.09 + 187.25 + (\frac{Fa}{0.95})\right) \text{x} \frac{1}{100}$$

$$0.98 = (373.97 + 1.05Fa) \text{x} \frac{1}{100}$$

$$0.98\, x\, 1000 = (373.97 + 1.05Fa)$$

$$980 - 373.97 = 1.05Fa$$

$$1.05Fa = 606.03$$

$$Fa = \frac{606.03}{1.05}$$

$$Fa = 577.17 kg/m^3$$

II. Calculation for the Quantity of CoarseAggregate

$$0.98 = \left(\frac{83.25}{1.47} + \frac{208.15}{1.6} + \frac{470}{2.51} + (\frac{1}{1-0.38})(\frac{Ca}{2.5})\right) \text{x} \frac{1}{100}$$

$$0.98 = \left(56.63 + 130.09 + 187.25 + (\frac{Ca}{1.55})\right) \text{x} \frac{1}{100}$$

$$0.98 = (373.97 + 0.65Ca) \text{x} \frac{1}{100}$$

$$0.98\, x\, 1000 = (373.97 + 0.65Ca)$$

$$980 - 373.97 = 0.65Ca$$

$$0.65Ca = 606.03$$

$$Ca = \frac{606.03}{0.65}$$

$$Ca = 932.35 kg/m^3$$

Mix Proportion

Sample 1: Mix proportion for 0% RCA

Sodium Silicate	Sodium Hydroxide	Extra Water	Metakaolin	Fine Aggregate	Coarse Aggrgate
$\mathbf{208.1\ kg/m^3}$	$83.3\ kg/m^3$	$85\ kg/m^3$	$470\ kg/m^3$	$577.17\ kg/m^3$	$932.35 kg/m^3$

Source: Laboratory Research Work (2016)

Sample 2: Mix proportion for 20% RCA

Sodium Silicate	Sodium Hydroxide	Extra Water	Metakaolin	Fine Aggregate	Coarse Aggrgate	RCA
$\mathbf{208.1\ kg/m^3}$	$83.3\ kg/m^3$	$85\ kg/m^3$	$470\ kg/m^3$	$577.17\ kg/m^3$	$745.90 kg/m^3$	$186.5 kg/m^3$

Source: Laboratory Research Work (2016)

Sample 3: Mix proportion for 30% RCA

Sodium Silicate	Sodium Hydroxide	Extra Water	Metakaolin	Fine Aggregate	Coarse Aggrgate	RCA
$\mathbf{208.15\ kg/m^3}$	$83.3\ kg/m^3$	$85\ kg/m^3$	$470\ kg/m^3$	$577.17\ kg/m^3$	$652.68 kg/m^3$	$279.72 kg/m^3$

Source: Laboratory Research Work (2016)

Sample 4: Mix proportion for 40% RCA

Sodium Silicate	Sodium Hydroxide	Extra Water	Metakaolin	Fine Aggregate	Coarse Aggrgate	RCA
$\mathbf{208.15\ kg/m^3}$	$83.3\ kg/m^3$	$85\ kg/m^3$	$470\ kg/m^3$	$577.17\ kg/m^3$	$599.4 kg/m^3$	$372.94 kg/m^3$

Source: Laboratory Research Work (2016)

<u>Appendix A4</u>:

Compressive Strength of Concrete Specimens Produced

Table A4.1: Compressive Strength Result of GPC Specimen at 7days

SAMPLE	**7days**			
	Weight	**Failure Load (KN /mm^2)**	**Compressive Strength (N/mm^2)**	**Average Compressive Strength(N/mm^2)**
0%	W_1= 2.10	306.97	30.69	
RCA	W_3= 2.12	294.38	29.44	29.74
	W_3= 2.14	290.90	29.09	
20%	W_1= 2.04	268.24	26.82	
RCA	W_2= 2.14	277.63	27.77	27.31
	W_3= 2.12	273.41	27.34	
30%	W_1= 2.10	250.56	25.06	
RCA	W_2= 2.06	249.44	24.94	25.28
	W_3= 2.04	258.85	25.85	
40%	W_1= 2.00	243.22	24.32	
RCA	W_2= 2.06	249.22	24.92	24.67
	W_3= 2.04	247.69	24.77	

Source: Laboratory Research Work (2016)

Table A4.2 Compressive Strength Result of GPC Specimen at 14days

SAMPLE	14days			
	Weight	**Failure Load (KN /mm²)**	**Compressive Strength (N/mm^2)**	**Average Compressive Strength(N/mm^2)**
0% RCA	W_1= 2.08	309.14	30.91	
	W_2= 2.10	301.47	30.15	30.51
	W_3= 2.10	304.73	30.47	
20% RCA	W_1= 2.04	298.56	29.86	
	W_2= 2.14	298.26	29.83	29.53
	W_3= 2.12	289.06	28.91	
30% RCA	W_1= 2.04	280.54	28.05	
	W_2= 2.00	264.46	26.45	27.17
	W_3= 2.06	270.16	27.02	
40% RCA	W_1= 2.04	250.28	25.03	
	W_2= 2.04	254.20	25.42	25.32
	W_3= 2.06	255.06	25.51	

Source: Laboratory Research Work (2016)

Table A4.3 : Compressive Strength Result of GPC Specimen at 28days

SAMPLE	28days			
	Weight	**Failure Load (KN/mm^2)**	**Compressive Strength (N/mm^2)**	**Average Compressive Strength(N/mm^2)**
0% RCA	W_1= 2.08	319.79	31.98	
	W_2= 2.08	311.05	31.11	31.54
	W_3= 2.12	315.38	31.54	
20% RCA	W_1= 2.08	312.48	31.25	
	W_2= 2.04	305.69	30.57	31.17
	W_3= 2.04	316.92	31.69	
30% RCA	W_1= 2.00	272.83	27.28	
	W_2= 2.00	296.83	29.68	28.55
	W_3= 2.04	287.00	28.70	
40% RCA	W_2= 2.00	254.71	25.47	
	W_3= 2.02	272.20	27.22	26.40
	W_4= 2.02	265.02	26.50	

Source: Laboratory Research Work (2016)

Table A4.4: Compressive Strength Result of GPC Specimen at 56days

SAMPLE	56days			
	Weight	**Failure Load (KN/mm^2)**	**Compressive Strength (N/mm^2)**	**Average Compressive Strength(N/mm^2)**
0%	W_1= 2.10	352.31	35.23	
RCA	W_2= 2.10	322.90	32.29	32.43
	W_5= 2.06	293.76	29.78	
20%	W_2= 2.00	297.04	29.70	
RCA	W_3= 2.00	319.15	31.92	31.93
	W_4= 2.06	341.80	34.18	
30%				
RCA	W_1= 1.98	299.76	29.98	
	W_2= 2.04	278.59	27.86	28.81
	W_3= 2.00	285.85	28.59	
40%				
RCA	W_1= 2.04	281.92	28.19	
	W_2= 1.96	263.37	26.34	27.54
	W_3= 2.04	280.91	28.09	

Source: Laboratory Research Work (2016)

Table A4.5 Compressive Strength Result of PCC Specimen at 7days

SAMPLE	7days			
	Weight	**Failure Load (KN/mm^2)**	**Compressive Strength (N/mm^2)**	**Average Compressive Strength(N/mm^2)**
0%	W_1= 2.38	192.72	19.72	
RCA	W_2= 2.32	181.21	18.12	19.14
	W_3= 2.34	195.99	19.59	
20%	W_1= 2.32	171.68	17.17	
RCA	W_2= 2.28	168.61	16.86	16.87
	W_3= 2.20	165.98	16.59	
30%	W_1= 2.26	165.22	16.52	
RCA	W_2= 2.28	143.01	14.30	15.13
	W_3= 2.22	145.01	14.53	
40%	W_1= 2.22	131.78	13.18	
RCA	W_3= 2.24	134.84	13.48	13.81
	W_5= 2.26	147.65	14.77	

Source: Laboratory Research Work (2016)

Table A4.6: Compressive Strength Result of PCC Specimen at 14days

SAMPLE	14days			
	Weight	**Failure Load (KN /mm^2)**	**Compressive Strength (N/mm^2)**	**Average Compressive Strength(N/mm^2)**
0%	W_1= 2.34	195.00	19.50	
RCA	W_2= 2.40	203.41	20.34	20.65
	W_3= 2.40	221.00	22.10	
20%	W_1= 2.26	183.70	18.37	
RCA	W_2= 2.28	186.31	18.63	18.57
	W_3= 2.30	187.03	18.70	
30%	W_1= 2.22	184.00	18.40	
RCA	W_2= 2.38	168.65	16.86	17.69
	W_3= 2.12	178.00	17.80	
40%	W_1= 2.16	159.23	15.92	
RCA	W_2= 2.22	156.52	15.65	15.42
	W_3= 2.24	147.40	14.70	

Source: Laboratory Research Work (2016)

Table A4.7: Compressive Strength Result of PCC Specimen at 28days

SAMPLE	28days			
	Weight	**Failure Load (KN /mm^2)**	**Compressive Strength (N/mm^2)**	**Average Compressive Strength(N/mm^2)**
0%	W_1= 2.38	247.80	24.78	
RCA	W_2= 2.38	242.00	24.20	24.36
	W_3= 2.34	240.85	24.09	
20%	W_1= 2.26	209.40	20.94	
RCA	W_2= 2.30	217.30	21.73	21.09
	W_3= 2.30	205.87	20.59	
30%	W_1= 2.26	194.11	19.41	
RCA	W_2= 2.22	204.03	20.40	19.81
	W_3= 2.30	196.25	19.63	
40%	W_1= 2.26	193.04	19.30	
RCA	W_2= 2.22	185.00	18.50	19.37
	W_3= 2.22	200.30	20.30	

Source : Laboratory Research Work (2016)

Table A4.8: Compressive Strength Result of PCC Specimen at 56days

SAMPLE	56days			
	Weight	**Failure Load (KN/mm^2)**	**Compressive Strength (N/mm^2)**	**Average Compressive Strength(N/mm^2)**
0% RCA	W_1= 2.42	242.65	24.25	
	W_2= 2.40	249.32	24.93	25.20
	W_3= 2.40	258.83	25.88	
20% RCA	W_1= 2.26	235.88	23.59	
	W_2= 2.30	222.36	22.24	22.50
	W_3= 2.40	216.81	21.68	
30% RCA	W_1= 2.30	220.54	22.05	
	W_2= 2.28	204.03	20.40	21.16
	W_3= 2.30	210.24	21.02	
40% RCA	W_1= 2.26	192.73	19.27	
	W_2= 2.24	201.69	20.17	19.59
	W_3= 2.22	193.29	19.33	

Source : Laboratory Research Work (2016)

Appendix A5:

Compressive Strength of Concrete Specimen exposed to ($MgSO_4$) Attack

Table A5.1: Compressive Strength of GPC exposed to $MgSO_4$ at 28days

SAMPLE	**28days ($MgSO_4$)**			
	Weight	**Failure Load (KN /mm^2)**	**Compressive Strength (N/mm^2)**	**Average Compressive Strength(N/mm^2)**
0%	W_1= 2.22	318.45	31.85	
RCA	W_2= 2.22	301.17	30.12	
	W_3= 2.28	298.74	29.87	30.61
20%	W_1= 2.16	291.05	29.11	
RCA	W_2= 2.18	339.04	30.36	29.77
	W_3= 2.18	298.39	29.84	
30%	W_1= 2.14	258.16	25.82	
RCA	W_2= 2.16	268.75	26..88	26.05
	W_3= 2.18	254.57	25.46	
40%	W_1= 2.14	250.06	25.01	
RCA	W_2= 2.14	238.50	23.85	24.89
	W_3= 2.16	258.13	25.81	

Source : Laboratory Research Work (2016)

Table A5.2: Compressive Strength of GPC exposed to $MgSO_4$ at 56days

SAMPLE	56days ($MgSO_4$)			
	Weight	**Failure Load (KN /mm^2)**	**Compressive Strength (N/mm^2)**	**Average Compressive Strength(N/mm^2)**
0%	W_1= 2.20	279.66	27.97	
RCA	W_2= 2.24	320.61	32.06	28.44
	W_3= 2.22	252.97	25.29	
20%	W_1= 2.22	261.61	26.16	
RCA	W_2= 2.24	273.26	27.33	26.74
	W_3= 2.22	267.25	26.73	
30%	W_1= 2.14	224.75	22.48	
RCA	W_2= 2.16	236.50	23.65	23.07
	W_3= 2.18	230.79	23.08	
40%	W_1= 2.16	232.35	23.24	21.86
RCA	W_2= 2.16	213.80	21.38	
	W_3= 2.18	209.64	20.96	

Source: Laboratory Research Work (2016)

Table A5.3: Compressive strength of PCC exposed to $MgSO_4$ at 28days

SAMPLE	28days ($MgSO_4$)			
	Weight	**Failure Load (KN /mm^2)**	**Compressive Strength (N/mm^2)**	**Average Compressive Strength(N/mm^2)**
0%	W_1= 2.40	232.52	23.25	
RCA	W_2= 2.44	248.12	24.81	24.23
	W_3= 2.42	246.34	24.63	
20%	W_1= 2.36	202.98	20.29	
RCA	W_2= 2.38	208.01	20.80	20.23
	W_3= 2.38	195.90	19.59	
30%	W_1= 2.30	191.36	19.14	
RCA	W_2= 2.28	205.17	20.52	19.38
	W_3= 2.34	184.79	18.48	
40%	W_1= 2.26	172.81	17.28	
RCA	W_2= 2.24	181.11	18.11	18.48
	W_3= 2.28	193.29	19.33	

Source : Laboratory Research Work (2016)

Table A5.4: Compressive strength of PCC exposed to $MgSO_4$ at 56days

SAMPLE		56days	($MgSO_4$)	
	Weight	**Failure Load (KN/mm^2)**	**Compressive Strength (N/mm^2)**	**Average Compressive Strength(N/mm^2)**
0% RCA	W_1= 2.40	231.97	23.20	
	W_2= 2.36	246.34	24.63	23.71
	W_3= 2.38	232.96	23.30	
20% RCA	W_1= 2.36	191.40	19.14	
	W_2= 2.32	190.87	19.09	19.67
	W_3= 2.34	207.89	20.79	
30% RCA	W_1= 2.30	186.28	18.63	
	W_2= 2.28	184.61	18.46	18.50
	W_3= 2.34	183.95	18.39	
40% RCA	W_1= 2.26	177.89	17.79	
	W_2= 2.24	172.82	17.28	17.65
	W_3= 2.28	178.38	17.84	

Source: Laboratory Research Work (2016)

Appendix A6:

Split Tensile Strength of Concrete Specimen Produced

Table A6.1: Split Tensile Strength of Result GPC Specimen at 7days

SAMPLE	7days			
	Weight	**Failure Load (KN/mm^2)**	**Split Tensile Strength (KN/mm^2)**	**Average Split Tensile Strength(KN/mm^2)**
0% RCA	W_1 =2.08	50.00	2.59	
	W_2=2.10	55.02	2.85	2.70
	W_3=2.08	51.26	2.66	
20% RCA	W_1 =2.08	48.50	2.51	
	W_2=2.02	43.06	2.23	2.30
	W_3=2.04	41.22	2.14	
30% RCA	W_1 =2.04	40.40	2.09	
	W_2=2.02	36.20	1.88	2.00
	W_3=2.10	38.40	1.99	
40% RCA	W_1 =2.04	36.50	1.90	
	W_2=2.02	34.40	1.80	1.89
	W_3=2.06	38.00	1.97	

Source: Laboratory Research Work (2016)

Table A6.2: Split Tensile Strength of Result GPC Specimen at 14days

SAMPLE	14days			
	Weight	**Failure Load (KN/mm^2)**	**Split Tensile Strength (KN/mm^2)**	**Average Split Tensile Strength (KN/mm^2)**
0% RCA	W_1 =2.02	55.16	2.86	
	W_2=2.08	58.03	3.00	3.04
	W_3=2.04	63.20	3.27	
20% RCA	W_1 =2.18	46.01	2.31	
	W_2=2.10	48.12	2.49	2.50
	W_3=2.12	52.03	2.70	
30% RCA	W_1 =2.04	45.00	2.33	
	W_2=2.02	52.13	2.70	2.42
	W_3=2.10	43.06	2.23	
40% RCA	W_1 =2.04	44.08	2.28	
	W_2=2.02	38.40	1.99	2.12
	W_3=2.10	40.22	2.08	

Source : Laboratory Research Work (2016)

Table A6.3: Split Tensile Strength of Result GPC Specimen at 28days

SAMPLE	28 days			
	Weight	**Failure Load (KN/mm^2)**	**Split Tensile Strength (KN/mm^2)**	**Average Split Tensile Strength (KN/mm^2)**
0% RCA	W_1 =2.12	63.05	3.27	
	W_2=2.16	62.07	3.22	3.25
	W_3=2.14	63.13	3.27	
20% RCA	W_1 =2.08	49.24	2.55	
	W_2=2.10	55.00	2.85	2.76
	W_3=2.10	53.11	2.75	
30% RCA	W_1 =2.04	47.00	2.43	
	W_2=2.06	43.13	2.23	2.43
	W_3=2.06	52.00	2.70	
40% RCA	W_1 =1.98	52.00	2.70	
	W_2=2.02	40.06	2.07	2.34
	W_3=2.04	43.38	2.25	

Source : Laboratory Research Work (2016)

Table A6.4: Split Tensile Strength of Result GPC Specimen at 56days

SAMPLE	56 days			
	Weight	**Failure Load (KN/mm^2)**	**Split Tensile Strength (KN/mm^2)**	**Average Split Tensile Strength (KN/mm^2)**
0% RCA	W_1 =2.10	58.15	3.01	
	W_2=2.06	65.03	3.37	3.32
	W_3=2.12	69.43	3.59	
20% RCA	W_1 =2.08	49.11	2.54	
	W_2=2.10	58.06	3.01	2.81
	W_3=2.10	55.44	2.87	
30% RCA	W_1 =2.04	47. 43	2.46	
	W_2=2.06	48.86	2.53	2.54
	W_3=2.06	51.00	2.64	
40% RCA	W_1 =2.02	49.40	2.56	
	W_2=2.04	47.36	2.45	2.46
	W_3=2.04	45.80	2.37	

Source : Laboratory Research Work (2016)

Table A6.5: Split Tensile Strength Result of PCC Specimen at 7days

SAMPLE	7days			
	Weight	**Failure Load (KN/mm^2)**	**Split Tensile Strength (KN/mm^2)**	**Average Split Tensile Strength (KN/mm^2)**
0% RCA	W_1 =2.38	42.85	2.22	
	W_2=2.32	46.03	2.38	2.20
	W_3=2.36	38.33	1.98	
20% RCA	W_1 =2.30	43.63	2.26	
	W_2=2.34	38.61	2.00	2.04
	W_3=2.28	36.03	1.87	
30% RCA	W_1 =2.30	32.32	1.67	
	W_2=2.30	36.24	1.88	1.87
	W_3=2.28	40.00	2.07	
40% RCA	W_1 =2.20	34.40	1.78	
	W_2=2.44	36.54	1.90	1.84
	W_3=2.22	35.47	1.84	

Source : Laboratory Research Work (2016)

Table A6.6: Split Tensile Strength Result of PCC Specimen at 14days

SAMPLE	14days			
	Weight (mm^2)	**Failure Load (KN/mm^2)**	**Split Tensile Strength (KN/mm^2)**	**Average Split Tensile Strength (KN/mm^2)**
0%	W_1 =2.34	44.63	2.22	
RCA	W_2=2.36	44.59	2.38	2.28
	W_3=2.32	43.22	1.98	
20%	W_1 =2.28	40.23	2.08	
RCA	W_2=2.30	42.29	2.19	2.13
	W_3=2.32	41.12	2.13	
30%	W_1 =2.28	39.05	2.02	
RCA	W_2=2.26	38.33	1.99	2.08
	W_3=2.24	43.10	2.23	
40%	W_1 =2.24	41.31	2.14	
RCA	W_2=2.22	40.81	2.11	2.04
	W_3=2.26	36.01	1.87	

Source: Laboratory Research Work (2016)

Table A6.7: Split Tensile Strength Result of PCC Specimen at 28days

SAMPLE	28days			
	Weight	**Failure Load (KN/mm^2)**	**Split Tensile Strength (KN/mm^2)**	**Average Split Tensile Strength (KN/mm^2)**
0%	W_1 =2.40	45.03	2.33	
RCA	W_2=2.38	53.06	2.75	2.51
	W_3=2.38	47.10	2.44	
20%	W_1 =2.32	41.28	2.03	
RCA	W_2=2.36	46.82	2.43	2.38
	W_3=2.36	49.34	2.56	
30%	W_1 =2.26	43.78	2.26	2.25
RCA	W_2=2.28	47.96	2.48	
	W_3=2.30	38.13	2.00	
40%	W_1 =2.22	43.03	2.23	2.13
RCA	W_2=2.24	39.06	2.02	
	W_3=2.26	41.23	2.14	

Source: Laboratory Research Work (2016)

Table A6.8: Split Tensile Strength Result of PCC Specimen at 56days

SAMPLE	56 days			
	Weight	**Failure Load (KN/mm^2)**	**Split Tensile Strength (KN/mm^2)**	**Average Split Tensile Strength (KN/mm^2)**
0% RCA	W_1 =2.36	51.05	2.64	
	W_2=2.34	56.27	2.91	2.79
	W_3=2.38	54.43	2.82	
20% RCA	W_1 =2.36	48.24	2.50	
	W_2=2.30	52.00	2.70	2.66
	W_3=2.34	54.11	2.80	
30% RCA	W_1 =2.22	52.00	2.69	
	W_2=2.28	44.13	2.29	2.48
	W_3=2.26	47.28	2.45	
40% RCA	W_1 =2.22	42. 52	2.20	
	W_2=2.22	46.06	2.39	2.38
	W_3=2.24	49. 43	2.56	

Source : Laboratory Research Work (2016)

<u>Appendix A7</u>:

Abrassion resistant of concrete specimen produced

Table A7.1: Abrasion resistance Result of GPC Specimen at 28days

SAMPLE	**28days**				
	Weight Before Brushing	**Weight After Brushing**	**Difference**	**%**	**Average %**
0% RCA	2144	2143	1.00	0.05	
	2123	2122	1.00	0.05	0.05
	2138	2137	1.00	0.05	
20% RCA	2181	2180	1.00	0.05	
	2134	2133	1.00	0.05	0.05
	2089	2086	1.00	0.05	
30% RCA	1996	1995	1.00	0.05	
	2082	2081	2.00	0.10	0.07
	2058	2057	1.00	0.05	
40% RCA	1953	1952	1.00	0.05	
	1982	1981	2.00	0.10	0.08
	2055	2053	2.00	0.10	

Source: Laboratory Research Work (2016)

Table A7.2: Abrasion resistance Result of GPC Specimen at 56days

SAMPLE	56days				
	Weight Before Brushing	**Weight After Brushing**	**Difference**	**%**	**Average %**
0%	2128	2127	1.00	0.05	
RCA	2110	2109	1.00	0.05	0.05
	2157	2156	1.00	0.05	
20%	1800	1798	2.00	0.11	
RCA	2049	2049	1.00	0.05	0.07
	2032	2031	1.00	0.05	
30%	2053	2051	2.00	0.10	
RCA	2010	2008	2.00	0.10	0.83
	1923	1922	1.00	0.05	
40%	1863	1952	2.00	0.11	
RCA	1979	1981	2.00	0.10	0.10
	2014	2053	2.00	0.10	

Source : Laboratory Research Work (2016)

Table A7.3: Abrasion resistance Result of PCC Specimen at 28days

SAMPLE	28days				
	Weight Before Brushing	**Weight After Brushing**	**Difference**	**%**	**Average %**
0%	2356	2354	2.00	0.08	
RCA	2445	2444	1.00	0.04	0.06
	2396	2394	2.00	0.08	
20%	2315	2313	2.00	0.09	
RCA	2311	2310	1.00	0.04	0.07
	2370	2368	2.00	0.08	
30%	2336	2334	2.00	0.09	
RCA	2241	2239	2.00	0.09	0.09
	2237	2235	2.00	0.09	
40%	2236	2233	3.00	0.13	
RCA	2272	2270	2.00	0.09	0.12
	2191	2187	3.00	0.14	

Source : Laboratory Research Work (2016)

Table A7.4: Abrasion resistance Result of PCC Specimen at 56days

SAMPLE		56days			
	Weight Before Brushing	**Weight After Brushing**	**Difference**	**%**	**Average %**
0% RCA	2373	2371	2.00	0.08	
	2375	2374	1.00	0.04	0.07
	2383	2381	2.00	0.08	
20% RCA	2317	2315	2.00	0.09	
	2321	2319	2.00	0.09	0.09
	2299	2297	2.00	0.09	
30% RCA	2256	2254	2.00	0.09	
	2229	2226	3.00	0.13	0.10
	2238	2236	2.00	0.09	
40% RCA	2217	2215	2.00	0.14	
	2196	2193	2.00	0.09	0.12
	2105	2103	3.00	0.14	

Source: Laboratory Research Work (2016)

Appendix A8:

Water Absorption capacity of concrete specimen produced

Table A8.3: Water Absorption Capacity Result of GPC Specimen at 28days

SAMPLE	**28days (GPC)**				
	Weight After Oven	**Weight At SSD**	**Difference**	**%**	**Average %**
0% RCA	1916	2166	250	11.55	
	2089	2190	101	4.61	8.31
	1975	2165	190	8.78	
20% RCA	2016	2210	194	9.63	
	1864	2029	165	8.13	8.71
	1852	2021	169	8.36	
30% RCA	2100	2328	218	9.36	
	2137	2366	229	9.68	9.60
	1885	2089	204	9.77	
40% RCA	1822	2053	231	11.25	
	1847	2048	201	9.81	9.93
	2085	2286	201	8.79	

Source : Laboratory Research Work (2016)

Table A8.4: Water Absorption Capacity Result of GPC Specimen at 56days

SAMPLE	56 days (GPC)				
	Weight After Oven	**Weight At SSD**	**Difference**	**%**	**Average %**
0% RCA	2100	2294	194	8.45	
	2080	2276	196	8.52	8.44
	2063	2251	188	8.35	
20% RCA	1912	2140	228	10.65	
	1873	2103	230	10.94	10.48
	1931	2142	211	9.85	
30% RCA	1984	2185	214	10.54	
	1815	2022	200	9.25	10.76
	1873	2147	259	12.60	
40% RCA	1984	2185	201	9.20	
	1815	2022	207	10.24	11.51
	1873	2147	260	12.10	

Source : Laboratory Research Work (2016)

Table A8.1: Water Absorption Capacity Result of PCC Specimen at 28days

SAMPLE	28days (PCC)				
	Weight After Oven	**Weight At SSD**	**Difference**	**%**	**Average %**
0% RCA	2371	2470	99	4.01	
	2459	2572	133	4.40	4.12
	2479	2581	102	3.95	
20% RCA	2234	2341	107	4.60	
	2238	2344	106	4.52	4.67
	2134	2244	110	4.90	
30% RCA	2115	2235	120	6.11	
	1995	2130	135	4.94	5.22
	2065	2187	122	4.60	
40% RCA	2204	2554	150	5.87	
	2168	2291	123	5.37	5.50
	2290	2415	125	5.18	

Source: Laboratory Research Work (2016)

Table A8.2: Water Absorption Capacity Result of PCC Specimen at 56days

SAMPLE	56 days (PCC)				
	Weight After Oven	**Weight At SSD**	**Difference**	**%**	**Average %**
0% RCA	2348	2459	111	4.45	
	2344	2450	106	4.33	4.54
	2286	2402	116	4.83	
20% RCA	2289	2411	122	5.06	
	2387	2515	128	5.09	5.50
	2299	2420	121	5.00	
30% RCA	2215	2335	120	5.14	
	2295	2430	135	5.56	5.56
	2265	2387	122	5.11	
40% RCA	2204	2354	130	5.40	
	2168	2191	141	6.34	5.88
	2090	2115	125	5.90	

Source: Laboratory Research Work (2016)

Appendix A9

Effects of $MgSO_4$ on GPC and PCC Specimens with Different Replacement

PCC specimens

(a) 0% RCA

(b) 20% RCA

(c) 30% RCA

(d) 40% RCA

GPC specimens

(a) 0% RCA

(b) 20% RCA

(c) 30% RCA

(d) 40% RCA