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Evaluation of the Properties of Geopolymer Concrete with the Addition of Bamboo Leaf Ash as a Natural Pozzolanic Material

MSc Thesis

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A thesis submitted in partial fulfilment of the requirements for the award of the Degree of Master of Science in Civil Engineering (Structural Engineering) at the Department of Civil & Construction Engineering, University of Nairobi

JUNE 2023

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ABBREVIATIONS

ACRONYM	MEANING
ACI	American Concrete Institute
Al_2O_3	Alumina oxide
ASTM	American society for Testing and Material
BLA	Bamboo leave ash
BS	British Standard
BS EN	British Standards European Norm
Cag	Coarse aggregate
C-A-S-H	Calcium alumina silicate hydrate
CO_2	Carbon Dioxide
C-S-H	Calcium silicate hydrate
FA	Fly ash
Fag	Fine aggregate
GPC	Geopolymer Concrete
H_2SO_4	Sulfuric acid
KOH	Potassium Oxide
KOH	Potassium Hydroxide
LCFA	Low calcium fly ash
$MgSO_4$	Magnesium sulphate
MPa	Mega Pascal
Na_2SiO_2	Sodium Silicate
NaCl	Sodium chloride
NaOH	Sodium Hydroxide
SCMs	Supplementary Cementous material
SiO_2	Silica Dioxide
XRF	X-ray Fluorescence

ABSTRACT

As a result of growing environmental concerns in the cement industry and rising costs of building materials, there has been an increased interest in alternative cement technologies. New binders are now necessary for better environmental and durability performance. For this study, geopolymer concrete containing industrial products (fly ash Class F) and agricultural wastes (calcined bamboo leaf ash) was chosen as a cement substitute in the making of concrete. This research was an experimental study evaluating the impact of bamboo leaf ash on geopolymer concrete by addition as a partial substitute of fly ash. The test samples were 100x100x100 mm cubes and 300x150mm cylinders at the environmental curing temperature. The target mix proportion of class 25 was used for this study. This research aimed to explore the suitability of the use of calcined bamboo leaf ash (BLA) as a mixing material in geopolymer concrete in more environmentally friendly industries. The properties that were investigated in this study are the basic aggregate tests, XRF analyses of BLA and fly ash class F; and workability tests by evaluating slump and compaction factor tests. Compressive strength and splitting tensile strength were also tested after curing at ambient temperature for 28, 56 and 90 days. Moreover, water absorption, sulphate resistance, acid resistance, and chloride attack were evaluated as part of the durability parameters. Therefore, in this study, various levels of bamboo leaf ash were utilized, including 0% (100% fly ash class F), 5%, 10%, 15%, and 20% BLA. The ratio of alkaline liquid to the binder for all mixes was fixed at 0.6, whereas the Na_2SiO_3 to NaOH proportion was 2.5 with a molarity (M) of 16. The findings of the workability test indicate that adding more bamboo leaf ash gradually decreases the liquid and leads the concrete to harden when compared to control samples without bamboo ash. Mechanical properties, such as compressive and splitting tensile strengths, indicated that the fly ash replacements containing 5% and 10% of the bamboo leaf had greater strengths than the other mixtures, measuring around 38.7 MPa, 40.8 MPa, 4 MPa, and 4.22 MPa, respectively. Results for the durability performance indicate that the water absorption of geopolymer concrete values increases with the increasing percentage of bamboo leaf ash by 2.46% up to 5.06%. While all samples exposed to 5% of $MgSO_4$, H_2SO_4, and NaCl as an exposure solution indicate excellent resistance in terms of change in mass, variation of compressive strength, and change in appearance. Therefore, bamboo leaf ash (BLA) can be one of the constituent materials in geopolymer concrete when the concern is the aggressive environmental conditions and mechanical properties.

CHAPTER ONE

1. INTRODUCTION

1.1 Background of the Study

Cement production has increased worldwide, producing 3.6 billion tons of cement in 2011 (Armstrong, 2012). In 2020, carbon dioxide (CO_2) emissions increased by 50% due to Portland cement production (Andrew, 2018). One tonne of cement produces approximately one tonne of carbon dioxide in the environment (Shaikh, 2016). Concerns about environmental conservation are frequently raised with regard to cement being used in concrete as a binder. Moreover, the cost of cementitious materials for the construction sector is continually rising. According to Andrew (2018), the global concrete industry is in dire need of binding materials, which is likely to lead to less cement usage. In light of these facts, the development of new sustainable materials is a very effective line of work for the modernization of the construction industry. One of the most acceptable possibilities in this regard is the processing of geopolymer concrete (GPC). Thus, geopolymer materials represent a potential solution to minimize both the environmental effects and the cost of binding materials in the construction industry.

Geopolymers are inorganic polymeric materials that have a chemical composition similar to zeolites but containing an amorphous structure and possessing ceramic-like structure and properties. In a simple definition, geopolymer is a new material that does not require the presence of ordinary Portland cement as a binder. Alternatively, pozzolanic materials with high silicon and aluminium content, such as industrial products (fly-ash, slags, silica-fume, etc.) or agricultural wastes (rice-husk, bamboo leaf ash, etc.), are activated by alkaline liquids to generate the binder. Thus, geopolymers can provide the possibility of preparing inorganic bonds. Additionally, silica (Si) and alumina (Al) dissolve in an alkaline solution where they polymerize into molecular chains and function as binders (Aleem et al., 2012). Additionally, the final composition of geopolymer concrete significantly impacts the silicon to aluminium content (Si: Al) ratio, with the silicone to aluminium content of the materials most often used in transportation infrastructure typically ranging between 2 and 3.5 (Lloyd et al., 2009). Accordingly, this study provided knowledge on fly-ash based geopolymer concrete with bamboo leaf ash. Instead of Portland cement, fly ash (ASTM Class F) was utilised as the main source material when manufacturing the concrete. In terms of civil engineering applications, geopolymer concrete has shown a higher performance of mechanical properties, resisting weathering action, chemical attack, and lower creep effects than ordinary Portland cement (OPC), according to Bagheri et al. (2014) and Wallah (2010).

The most common materials in geopolymer concrete are pozzolanic resources, whether natural pozzolanic or industrial by product. Pozzolans comprise silica and alumina that could interact with lime at room temperature to form cementitious compounds like calcium silicate, calcium aluminate, and calcium sulphoaluminate hydrates in the presence of moisture (ASTM C 618). Moreover, the pozzolanic reaction is a simple acid base reaction between calcium hydroxide Ca $(OH)_2$ and silicon oxide (SiO_2) to generate calcium silicate hydrate (C-S-H), as illustrated in Equations (1) and (2).

$$3\mathrm{Ca}\ (\mathrm{OH})2\ +\ 2\mathrm{SiO2}\ \rightarrow\ 3\mathrm{CaO}.2\mathrm{SiO2}.3\mathrm{H2O} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ \ Eq.1$$

$$Abbreviated\ form\ 3CH\ +\ 2S\ \rightarrow\ C3S2H \ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots.\ldots\ldots\ldots\ \ Eq.2$$

Pozzolanic materials containing less calcium oxide, such as calcined agricultural wastes and fly ash, and do not react with normal water; they need an activator. The most often used activators are alkaline liquid solutions comprising sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), and potassium hydroxide (KOH). When comparing sodium hydroxide and potassium hydroxide, sodium hydroxide (NaOH) is preferred because it has a better capability to liberate silicate and aluminate monomers (Duxson et al., 2007). This study also utilizes one of the agricultural waste materials known as bamboo leaves. Bamboo leaf ash (BLA) is one of the new pozzolanic materials in geopolymer concrete, which has a high silicone content. Producing bamboo leaf ash requires drying, burning, and heating in the furnace before using it. The development and use of agricultural waste materials in construction procedures have increased worldwide due to the increasing rate of carbon emissions, global warming, and ozone layer depletion. Using additive materials such as bamboo leave ash (BLA) is one of the solutions that minimize environmental hazards and the total cost of concrete materials. Bamboo in east Africa is grown in tropical countries such as Kenya, Uganda, Malawi, Tanzania, etc., according to Poulsen et al. (2020). A total of 133,273 hectares of bamboo are grown in Kenya, mostly in mountain ranges and national government managed forests (Ministry of Environment and Forestry, 2019).

From the literature review, after investigating the empirical studies (Umoh et al., 2014; Prabu et al., 2014; Oyebisi et al., 2017; Saloma et al., 2017; Ishak et al., 2019; Oyebisi et al. 2020; Bajpai et al., 2020), found that geopolymer concrete incorporating bamboo leaf ash as a partial substitute of fly ash was not adequately studied. In addition, the information on the durability of bamboo leaf ash added to geopolymer concrete was not found in the past studies.

Consequently, this study is unique since it focuses on the impact of calcined bamboo leaf ash on geopolymer concrete with regard to the fresh properties of GPC and mechanical properties, including compressive strength and splitting tensile strength. Moreover, the durability performance through parameters including water absorption, sulphate attack, acid attack, and chloride attack resistances.

1.2 Problem Statement

Continuous cement manufacturing has increased the amount of carbon dioxide (CO_2) emitted into the atmosphere, aggravating the problem of rising temperatures with a detrimental effect on the environment. Hence, it is extremely essential to adopt a more sustainable strategy and to carefully evaluate the current admixture used to replace traditional concrete. Furthermore, the increasing cost of the binding materials of concrete structures around the world has attracted researchers toward geopolymer-based cementitious materials. Several researchers believe geopolymer will replace cement as the preferred form of construction in the future.

In this regard, numerous studies (Ishak et al., 2019; Oyebisi et al., 2020; Bajpai et al., 2020) have been conducted on geopolymer concrete, and there has been limited research work performed on bamboo leaf ash with geopolymer concrete. Moreover, there is a lack of studies associated with the durability of geopolymer concrete with bamboo leaf ash. Previous studies (Van Jaarsveld et al. 2002; Al-Hubboubi et al. 2022) showed that the curing temperature influences the material characteristics as well the strength declines with an increase in temperature. Furthermore, the higher temperature causes the shrinkage of the material which results in the crack of the concrete. In this regard, this study focused on curing at ambient temperature due to the gradual increase in strength over time. Hence, this achievement brings to the use of geopolymer concrete.

The chemical attack is one of the major durability challenges for concrete structures, particularly those exposed to environments with sulphate and acid solutions. Chemical attacks could cause spalling, cracking, and decreased strength of concrete structures (Mehta & Siddique, 2017). A chloride-rich environment is generally found in the sea or brackish waters. The existence of chloride ions has a damaging effect on the embedded steel rather than the concrete itself. In summary, there is a need to utilize ecological concrete by substituting conventional concrete with modern results. In this regard, the innovation of geopolymer concrete is a promising method, that can be formed by utilizing industrial and agricultural wastes.

Therefore, this study investigated the effects of bamboo leaf ash on the engineering characteristics of geopolymer concrete under ambient temperature curing. The aspects that were examined are workability, mechanical properties, and durability performance.

1.3 Research Objective

1.3.1 Overall Objective

The overall objective of this study is to evaluate the properties of geopolymer concrete with the addition of bamboo leaf ash as a partial replacement for fly ash class F.

1.3.2 Specific Objectives

1. To investigate the suitability of bamboo leaf ash as an addition to fly ash in geopolymer concrete and to characterize the constituent materials for concrete employed in this study.
2. To establish the effect of the use of bamboo ash on the workability of fresh geopolymer concrete.
3. To evaluate the mechanical properties of geopolymer concrete.
4. To establish the durability of geopolymer concrete with the addition of several percentages of calcined bamboo leaf ash.

1.4 Research Questions

1. How does the addition of calcined bamboo leaf ash to fly ash affect the properties of geopolymer concrete?
2. To what extent does the addition of calcined bamboo leaf ash influence the workability of fresh geopolymer concrete?
3. How does the addition of calcined bamboo leaf ash affect the mechanical characteristics of geopolymer concrete?
4. How does the inclusion of several percentages of calcined bamboo leaf ash affect the durability of geopolymer concrete?

1.5 Justification of the Study

The main reason for conducting this study was to develop alternative materials to Portland cement concrete to minimize both the environmental hazards and the cost of the building structure. Thereby, the outputs of this study can be utilized as guidelines for the aplication of geopolymer concrete incorporating bamboo leaf ash (BLA) in local and international construction activities.

1.6 Research Significance

This research was crucial because it provides structural engineers with the information they need when utilising bamboo leaf ash (BLA) to enhance the performance of geopolymer concrete (GPC). Furthermore, geopolymer binder has an effect since it emits up to nine times less carbon dioxide (CO_2) than Portland Cement, (Neupane, 2022). Therefore, this study is very important for implementing the concept of sustainability in the building industry.

1.7 Scope and Limitation of the Study

The primary source material as binding ingredients for making geopolymer concrete in this research was low-calcium fly ash (ASTM Class F) and bamboo leaf ash (ASTM class N). The fly ash was found from only one source. Additionally, the equipment and techniques employed in the production of OPC concrete were utilised wherever possible to produce geopolymer concrete. The target mix proportion for class 25 was used for all mixtures in the experimental investigations. The utilized percentages of bamboo leaf ash content to replace fly ash were 0% (100% fly ash), 5%, 10%, 15%, and 20% to observe the effect on each proportion in the geopolymer concrete. The limited percentages of BLA up to 20% are related to the specific gravity of bamboo leaf ash being lower than the specific gravity of bamboo leaf ash. The experimental work commenced with the preparation of the constituent materials of the geopolymer concrete. The fly ash utilized in this research was imported to the Rangeela export market in Mumbai, India, while the bamboo leaf ash collected Kenya's rainforests, specifically the Mt. Kenya Forests. The coarse and fine aggregates, as well as the alkaline activators (Na_2SO_4 and NaOH), were acquired from local suppliers in Nairobi. After that, a basic test of raw materials was done containing the grading of aggregates, the chemical composition of binding materials, and hydrometer analysis of bamboo leaf ash and fly ash for particle size distribution. The tests related to the objective of the study were examined, including workability (slump and compaction factor), compressive strength, and splitting tensile strength in addition to the durability through parameters sulphate resistance, acid resistance, and chloride attack. The curing days were 28, 56, and 90 days of ambient temperature and exposure conditions.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Introduction

The chapter presents the previous studies on geopolymer concrete and pozzolanic materials. Furthermore, there was a critical review of the literature, an overview of geopolymer concrete, constituent materials, mechanical properties, and durability performance of GPC related to this study. Additionally, a literature review of factors influencing the characteristics of geopolymer concrete and method of curing was also reviewed. After that, the theoretical framework and the summary of the research gap were presented in the last sections.

2.2 Overview of Geopolymer Concrete (GPC)

2.2.1 History of Geopolymer Concrete

According to (Rajamane et al. 2011), "geopolymers" are a class of mineral binders having a polymeric aluminium silicon oxygen framework structure. The first introduced and developed geopolymer concrete was (Davidovits, 1978), using a group of mineral fillers analogous to zeolite in chemical composition with an indistinct microstructure (Boopalan et al., 2018). It differs from other types of cement where the matrix formation of microstructure and strength does not rely on “calcium silicate hydrates” formation but uses the polymerization of silica and alumina forerunners to accomplish essential quality. The polymerisation mechanism may include dissolution, transportation or orientation, and polycondensation (Abdullah et al., 2011) and occurs through an exothermic process (Davidovits, 1999). Maddalena et al. (2018) In the fallout of different disastrous flames in France from 1970 to 1973, it appeared to be helpful to complete the investigation into new fire-resistance materials such as non-combustible and non-burnable "plastic materials" (Geng et al., 2017). The consequence of this exploration since 1972 was the geopolymers.

2.2.2 Chemical Structure and Geopolymerization of Geopolymer Concrete

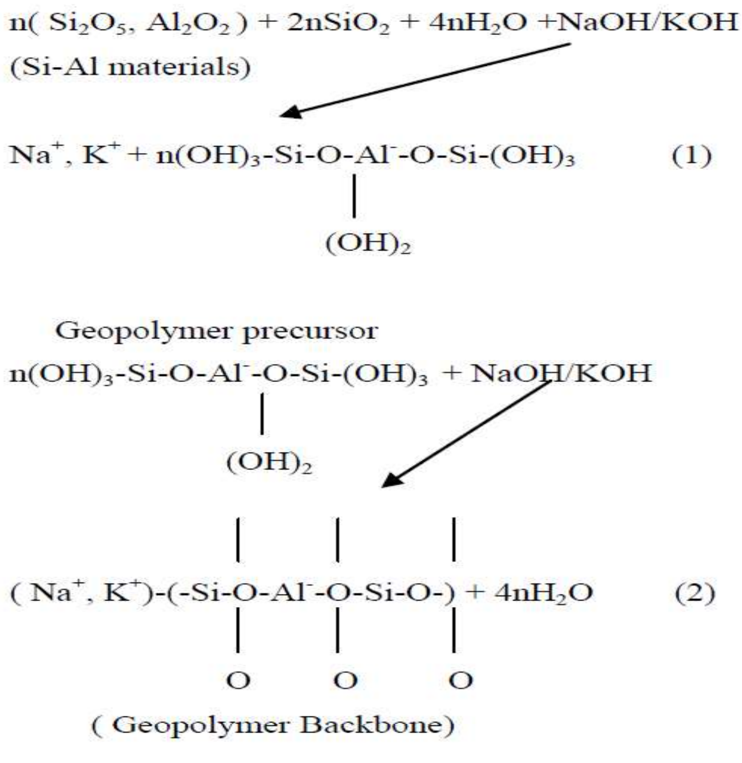
(Yunsheng et al., 2008) presented that the geopolymerization process takes place in several steps. The first phase includes: “the release of silicate and aluminate as beginning materials” which is then activated by alkali to produce geopolymer paste as the ultimate product. According to (Hajimohammadi et al. 2010), hydrolysis occurs in the second phase, and the presence of water molecules helps to more break the bonds, allowing the tetrahedral units of SiO_4 & AlO_4

to combine to form a macromolecular precursor. In the final step, polycondensation took place to harden the geopolymer gel and to form a three-dimensional aluminosilicate network. Liew et al. (2012) concluded that the synthesis of geopolymers is influenced by various factors, including: “Type of Pozzolanic Materials, Alkaline Activator Amount, Concentration, Temperature, Curing Time and Other Parameters". These aspects will influence how the aluminosilicate geopolymer network forms, which will then affect the properties of the final product.

Therefore, geopolymerization methods needs quick chemical reactions in alkaline circumstances on Si & Al materials, which produces three dimensional polymers composed of “Si-O-Al-O” bonds.

Mn[-(SiO2)z-AlO2]k.wH2O Where:

M = alkaline elements or cations such as potassium, sodium, calcium, etc. n = polycondensation or degree of polymerization z = 1, 2, 3 or more (Chanh et al., 2008).



Equations (1) and (2) depict the conceptual development of geopolymer products, according to Chanh et al. (2008). So, the exact setting and hardening mechanism of geopolymer materials is unclear. Nevertheless, the following points are the most often reported chemical reactions:

1. Due to the action of hydrogen ions, the silicon dioxide (Si) and aluminum oxide (Al) ions in the raw material are dissolved.

2. Monomers are formed by directing, transporting, or condensing precursor ions.

3. Set monomer polycondensation/polymerization into polymeric structures (Chanh et al., 2008).

When sialic refers to silico-oxo-aluminate structural units, these backbones are called polysilanes. The sialic acid network comprises SiO4 and AlO4 tetrahedra connected by exchanging all oxygen atoms. A positive ion (Na+, K+, Ca2+) must be present to balance the negative charge of the tetracoordinate Al. Rings and chains are typically made with sialic acid Si-O-Al bridges and may be crosslinked togetherPolysialic acids are amorphous to semi-crystalline chains and cyclic polymers having four Si4+ and Al3+ coordinated with oxygen. Three dimensional silicoaluminate structures ranging from amorphous to semi-crystalline are classified as 'geopolymers' under grade (Van Deventer et al. 2007).

2.2.3 Microstructure of Geopolymer Concrete

Geopolymers do not develop "calcium-silicate-hydrates" (CSH) for the formation of matrix or final product, in contrast to regular Portland cement. Instead, silica and alumina precursor polycondensation and elevated alkali content are used to achieve structurally strong materials. The microstructure of geopolymer compositions is amorphous as opposed to crystalline, although they are analogous to "natural zeolitic materials". The surface of fly ash and particles was examined by utilizing an electron microscope for scanning (SEM) after and before reacting with sodium hydroxide. Figures 2.1 and 2.2 show the roughness of the surface due to the NaOH interaction with fly ash particles (Chanh et al. 2008). While Figure 2.3 show further magnification after the reaction of sodium hydroxide and fly ash particles.

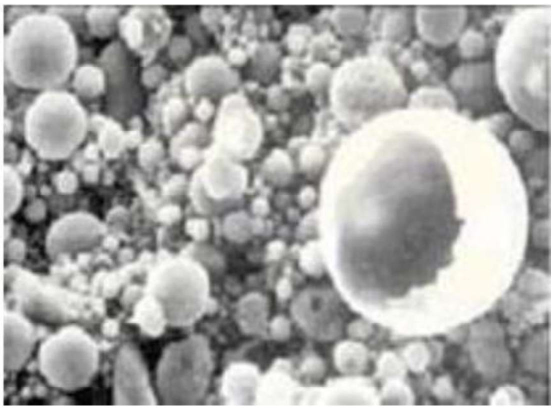


Figure 2.1: Before NaOH interacts with fly ash (Chanh et al. 2008)

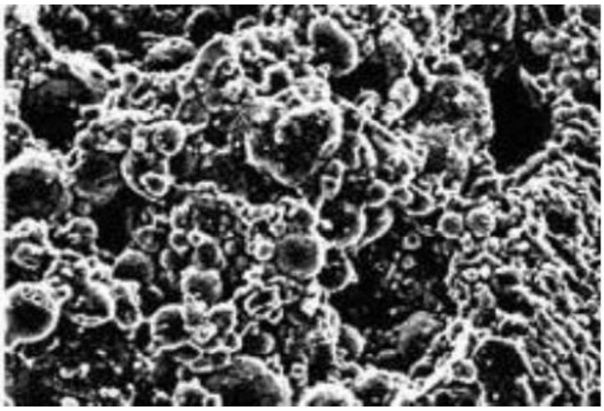


Figure 2.2: After NaOH interacts with fly ash (Chanh et al. 2008)

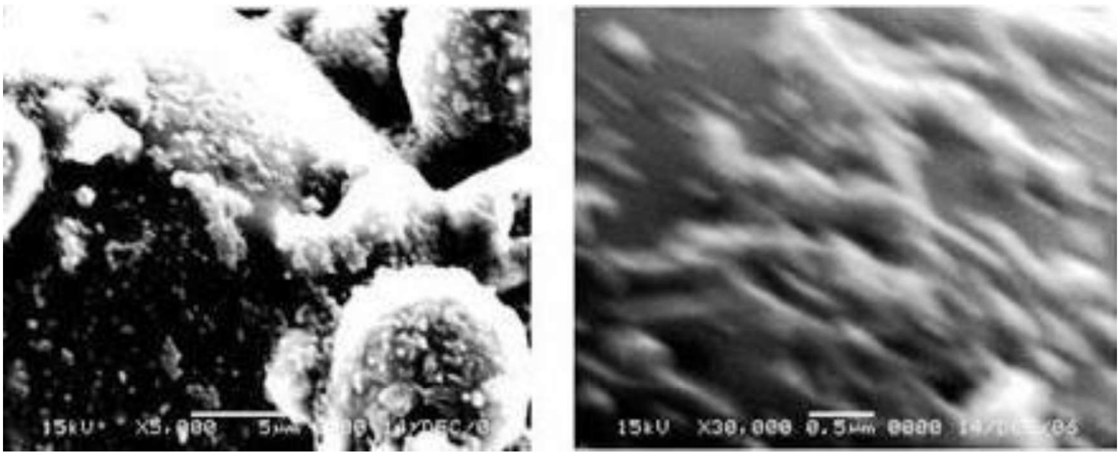


Figure 2.3: Further exaggeration after reaction between NaOH and fly ash (Chanh et al. 2008)

2.2.4 Geopolymer Frameworks

The polymerization process of geopolymer results in the development of alumina silicate structures as illustrated in Figure 2.4. Sialate is an acronym for alkali silicon oxo aluminate, where alkali is (Na, K, Li, Ca) and poly(sialate) refers to any geopolymers comprising at least one "(K, Na, Ca, Li) (Si-O-Al) (K, Na, Ca, Li)". The structural compounds found in the frameworks of sodalite and kalsilite include "Na-(O, Si, Al-O-) & K-(-Si-O-Al-O-)" which are chain and ring polymers formed by the polycondensation of the monomer, ortho sialate (OH)3-Si-O-Al (OH)3. The sanidine frame, "K-(-Si-O-Al-O-Si-O-Si-O-Si-O-)" which might be formed by the condensation of an orthosialate with two orthosilicates Si(OH)4 (Davidovits, 1988).

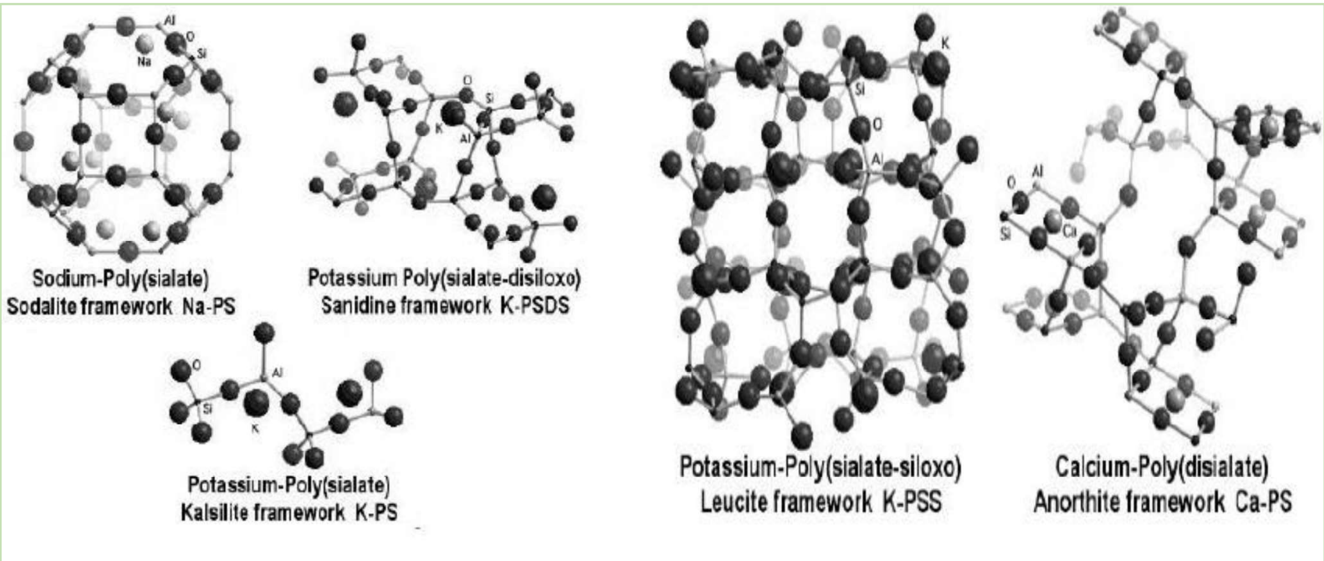


Figure 2.4: Polymer structure formed by monomer polymerization (Davidovits, 2008)

2.2.5 Application of Geopolymer Concrete

Davidovits (1999), reported that geopolymeric materials have a broad spectrum of uses in industries such as civil engineering, plastic industries, non-ferrous, aerospace, foundries, and metallurgy. The chemical structure, especially the Si/Al molecular ratio in polysialate, governs the use of geopolymeric materials. The Si/Al proportion, as indicated in Table 2.1, can be used to describe the kind of usage. Low silica-to-alumina ratios of 1.2–3 exhibit very stiff 3D networks, whereas Si: An Al ratio greater than 15 imparts polymeric properties to the geopolymer material. Therefore, low silica and alumina ratio are appropriate for a variety of civil engineering applications.

Table 2.1 Geopolymeric usage based on the ratio of silica (Si) to alumina (Al) atoms (Davidovits, 1999)

Silica to Alumina ratios	*Usage*
1	Bricks Ceramic Fire protections
2	Concrete and cement with low CO2 emissions.
3	fibre glass composite and fire protection Foundry equipment Composites with high heat resistance, 200 to 1000 °C Aeronautical titanium process tooling
>3	200° to 600°C sealants for industrial use Aeronautical titanium process tooling
20 – 35	Fiber composites that withstand fire and heat

In summary, several studies have been carried out on geopolymer concrete, but there is currently no agreement on the influence of various factors on the qualities of geopolymers materials. Furthermore, aluminosilicates source, curing type, alkali activator, type of concentration, and alkali activator to raw material ratios are the primary parameters that influence the characteristics of geopolymer concrete (Mustafa et al., 2012; Faris et al. 2017).

2.3 Previous Studies of the Constituent Materials

2.3.1 Fly-ash Class F

Fly ash class F, is a dry fine powder made from the gases produced when coal is burned to generate electricity. It is also a slow-reacting material with a very strong silica-alumina glassy chain. The performance of the burning process could be affected by the quality of the fly ash. Furthermore, in the presence of moisture at room temperature fly ash reacts with calcium hydroxide and forms a product that helps it to be harder (Temuujin et al., 2009). According to published estimates, one billion tons of fly ash are generated every year and cause anthropogenic pollution (Jindal et al., 2019). Fly ash comprised of alumina and silica, reacted with alkalinity solutions creating a solution referred to as aluminosilicate which works in geopolymer concrete as a binding material. Additionally, the amorphous silica in fly ash reacts chemically with calcium hydroxide to produce calcium silicate hydrates. This pozzolanic interaction of fly ash boosts its significance in many construction applications including concrete. (Siddique et al. 2004; Nonavinakere et al., 1995). Fly ash with a tiny particle size had greater strength than normal fly ash (Chindaprasirt et al. 2005).

The mineral structure of the coal gangue, particularly the inorganic portion of the coal, affects the chemical makeup of fly ash. Typically, alumina ranges from 20 to 30% and silica from 40 to 60% Choi et al. (2019). There are considerable levels of alkalis, with potassium being more abundant than sodium (Khale et al. 2007). The primary reason for employing fly ash in concrete is to improve the durability and longevity associated with its use. Fly ash chemically interacts with calcium hydroxide at the time of the hydration process to form calcium silicate hydrates & calcium aluminates, which decreases the possibility of calcium hydroxide leaching and the permeability of the concrete. Fly ash further reduces the permeability of concrete by decreasing the water-to-cement proportion and, as a consequence, decreases the capillary pore size in the material. The spherical form of fly ash helps the concrete to become more solid and less porous (Pacheco-Torgal et al., 2008).

Using geopolymer concrete based on fly ash is linked for two reasons. The enormous amount of (CO_2) emitted into the atmosphere during the manufacture of OPC and the increased construction cost of materials. Class F fly ash is often activated using sodium hydroxide and sodium silicate geopolymers concrete (Atabey et al. 2020).

Hence, this research used (class f fly ash) instead of high calcium fly ash. Low-calcium fly ash has good strength, very low dry shrinkage, low creep, and better chemical resistance than high-calcium fly ash, (Nuaklong et al, 2019). The chemical makeup of fly ash class F demonstrates in Table 2.2. Variations in the proportions of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), ferric oxide (Fe_2O_3), calcium oxides (CaO), and magnesium oxide (MgO) were persented. These are the chemical components that distinguish between pozzolanic, non-pozzolanic, and cementitious materials.

Table 2.2 Chemical Composition of Fly Ash (Choi, Y. C. et al (2019)

S. No	Fly ash compounds	Abbreviations	Percentage (%)
1	Silicon dioxide	SiO_2	48.2
2	Aluminium dioxide	Al_2O_3	29
3	Ferric oxide	Fe_2O	12.7
4	Magnesium oxides	MgO	0.89
5	Calcium oxides	CaO	1.76
6	Sodium oxides	Na_2O	0.39
7	Potassium oxides	K_2O	0.55
8	Sulphur trioxide	SO_3	0.5
9	Loss on ignition		1.61

2.3.2 Bamboo Leaf Ash (BLA)

A previous experimental study using bamboo leaf ash (Asha et al. 2014) stated that bamboo ash is a pozzolanic agricultural waste because of its large silica concentration and amorphous form. A further empirical investigation on the impact of bamboo leaf ash on concrete was also carried out (Umoh et al., 2014). Concrete samples of (100 mm x 100 mm) were constructed using a 1:2:4 by-weight mix ratio. Bamboo leaf ash in amounts ranging from 2 to 20% by weight was used to replace the cementing ingredient. All mixtures produced a slump of 10-30 mm based on the water to cement ratio. Parameters considered include compressive strength, splitting tensile strength, and water absorption for up to 90 days of curing. The findings showed the bamboo ash content of 10% reached a maximum of 75% in 28 days. Furthermore, the strength varies between 11.75 N/mm2 after 7 days at 20% BLA to 30.12 N/mm^2 after 90 days.

However, samples manufactured of cement with bamboo ash, on the other hand, generally had lower water absorption than the control. For all blended specimens at all curing ages, the tensile strength for splitting performance was above 75%, and it significantly correlated with compressive strength, with a correlation value of 0.790.

2.3.2.1 Pozzolanic Behaviour of Bamboo leaf ash

Studies have demonstrated that pozzolanic additives decrease porosity and enhance density, thus increasing the chemical endurance of the solution containing concrete to sulphate ion. Dimas et al. (2009) hypothesized that silica and alumina-rich materials could interact with extremely alkaline solutions to create an inorganic Al-Si polymer product Si-O–Al–O binds to a substance known as geopolymers. Hardjito et al., (2004) revealed that fly ash (FA) is a geopolymer aluminium material that may be used in geopolymer concrete manufacturing. Ernesto et al. (2007) addressed characterisation of calcium hydroxide (CaOH) to bamboo leaf ash (BLA) pozzolanic behaviour derived from calcining leaf of bamboo. In accordance with the chemical composition, shape and XRD configuration of ash from leaf of bamboo, found that silica is produced from this type of ash with a totally amorphous and high pozzolanic nature.

2.3.2.2 Characterization of Bamboo Leaf Ash

According to Silva et al. (2021), the chemical makeup of bamboo leaf ash was determined using X-ray fluorescence, which is illustrated in Table 2.1. The most abundant element represented by oxides in bamboo leaf ash was silicon dioxide (SiO_2), second by CaO, Fe_2O3, Al_2O_3, K_2O, and P_2O_5. The oxide level was less than 1% for SO_3, TiO_2, Cl, and MnO. Based on the reports of bamboo leaf ash (BLA) by other authors, silicon dioxide (SiO_2) was present in amounts that ranged from 55.5 to 84.4%, which was quite similar. It is feasible that various silicone content is due to the burning procedures, methods, and climates (Umoh et al. 2015; Farias et al. 2012; Villar-Conica et al. 2019).

Little research has been performed on the pozzolanic properties of bamboo ash (Dwivedi et al. 2006) and (Singh et al. 2007). Dwivedi et al. (2006) used various scanning calorimetry (DSC) to study the interaction of (calcium hydroxide & bamboo ash) for 4 hours, whereas Singh et al. (2007) evaluated the hydration of BLA in a blended Portland cement. These researchers came to the conclusion that bamboo ash is a valuable pozzolanic substance.

Table 2.3 Chemical composition of Bamboo Leave Ash (Silva et al 2021)

No.	Constituents	Abbreviations	Composition (%)
1.	Silicon dioxide	SiO_2	83.56
2.	Aluminium oxide	Al_2O_3	2.56
3.	Ferric oxide	Fe_2O_3	2.63
4.	Calcium oxides	CaO	3.71
5.	Magnesium oxides	MgO	1.64
6.	Potassium oxides	K_2O	2.38
7.	Sulphur	SO_3	0.95
8.	Phosphorus pentoxide	P_2O_5	1.15
9.	Chloride	Cl	0.44
10.	Titanium dioxide	TiO_2	0.52
11.	Manganese (II) oxide	MnO	0.17

2.3.3 Alkaline Activators

Pacheco-Torgal et al., (2008) when the fly ash is exposed to alkaline activators, the silica and alumina dissolving process takes place as depicted in Figure 2.5. The macromolecules condense into the gel, and then alkali attacks to the particle's surface of the fly ash. Subsequently, it enlarges to bigger holes, exposing lower-sized particles. When the ash particle is entirely or nearly completely absorbed, the reaction consequence develops both within and outside the sphere's shell. Therefore, the role of the alkaline activator solution in geopolymer concrete is to dissolve the silica and alumina reactive components of the binder contained in the fly ash and produce an alkaline solution for condensation polymerization interactions (Sanni et al. et al., 2013).

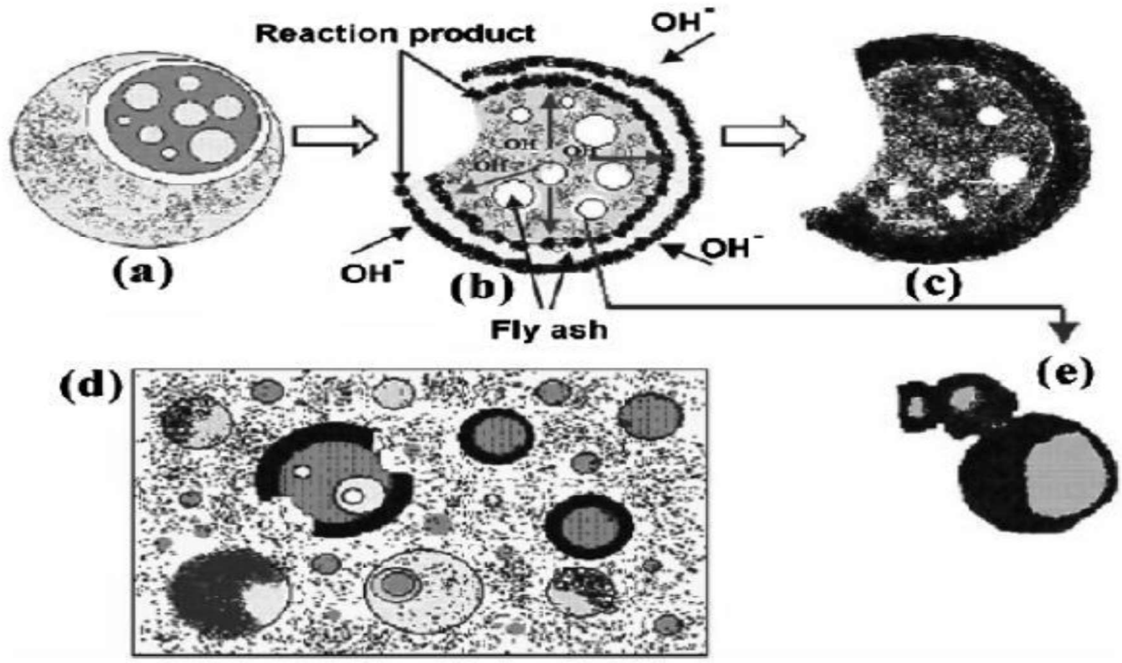


Figure 2.5*: Model that describes the alkali activation of fly ash (Pacheco-Torgal et al., 2008)*

Skvara (2007) reported that the aluminosilicate materials alkaline activation reflects an intricate process that has not yet been fully explained. Si-O-Si bonds are first broken when aluminosilicate minerals react in a very alkaline environment. Later, new phases develop, and the mechanism for their production appears to involve a solution "synthesis by solution". The entering of (Al atoms) into the initial (Si-O-Si) structure is a crucial element of this process. They have the chemical composition Mn [-(Si-O)z - Al-O]n. wH_2O. The formation of the C-S-H and C-A-H phases is also feasible, depending on the initial components and reaction conditions. Secondary H_2O may form as a result of these poly-condensation processes. Amorphous gel-like, partly amorphous, or crystalline substances may be generated depending on the nature of the original raw components and the parameters of the reaction. The concentration of solid matter present has a significant impact on the alkali activation process.

For Figure 2.5, (a) represents the source material which is Fly ash while (b) depicts the combination of fly ash and alkaline liquid. Part (d) illustrates the reaction between the alkaline solution and fly ash. Figure 2.5 (e) shows the mechanics product after the reaction between fly ash and alkaline liquid. Thus, the different stages of a,b,c,d, and e were involved in the development of the formation three-dimensional polymeric chain structure of geopolymer concrete. An alkaline activator must first break, then come together again with the (Si-O & Al-

O) bonds in geopolymer materials to harden them. The form of source material and alkaline liquid affects the reaction behaviour of the Si and Al.

2.3.3.1 Sodium Hydroxide (NaOH)

In geopolymer concrete, the most common alkaline stimulant is sodium hydroxide since it's affordable compared to potassium. The dissolution of solid sodium hydroxide in water is a significantly exothermic reaction, similar to the hydration of sulphuric acid. It is considered that the sodium hydroxide (NaOH) concentration be between 8 and 16 mol/l (Patankar et al. 2014). It also provides an uncomfortable feeling while breathing and handling.

Hardjito (2005) stated that sodium hydroxide blended with sodium silicates or potassium hydroxide combined with a potassium silicate is the most popular alkaline activator employed for the geopolymerization process of geopolymer concrete. The type and amount of alkali activator significantly affect the solubility of binding material. In comparison to potassium hydroxide solution, sodium hydroxide (NaOH) solution typically has higher levels of Al^{3+} and Si^{4+} ion leaching. Therefore, alkali concentration is crucial for regulating the subsequent geopolymerization, mechanical characteristics of hardened geopolymer, and leaching of alumina and silica from fly ash particles (Rattanasak & Chindaprasirt, 2009). On the other hand, Duchesne et al. (2010), reported that the inclusion of NaOH in the activation solution caused the reaction to proceed faster and the gel to be less homogenous. The chemical composition containing the main molecules of sodium hydroxide is shown in Table 2.4.

Table 2.4 Chemical makeup of NaOH (Sauffi, 2022).

No.	***Chemical composition***	***Weight percent (%)***
1.	Na	57.48
2.	O	40
3.	H	2.52

2.3.3.2 Sodium Silicate (Na_2SiO_3)

Sodium silicate soluble is also referred as liquid glass or water glass due to its clear liquid form. It is one of the typical alkalis employed to make geopolymer concretes. The reaction of sodium hydroxide and sodium silicate with depends on the ratio of silicon dioxide (SiO_2) and sodium oxide (Na_2O) as shown in Equation 4.1, preserved as 1.5. Soluble silicate mass and sodium oxides are 28.9 % and 19.6 %, respectively, (Saloma et al. 2019).

SiO_2 (28.9%) + Na_2O (19.6%) → Na_2SiO_3 …………………………………. Eq. 4.1

The sodium silicate solution dissolve quickly and starts to bind fly ash fine particles, according to Tempest et al. (2009). As quickly as possible the liquid can get to the ash particles, open porosity is visible and fills up quickly with gel. The liquid phase is essential because it serves as a fluid transport medium that enables the activator to interact with the fly ash particles. The kind of activator used has a significant impact on the polymerization process, (Palomo et al.1999). When sodium or potassium silicate, a soluble silicate, is used as the alkaline activator instead of just alkaline hydroxides, reactions occur at a much faster rate. Xu and Van Deventer's (2000) study, adding Na_2SiO_3 solution as the alkaline activator to the NaOH increased the interaction between the binding materials and the solution. In another hand, the main compounds of sodium silicate are sodium oxide (Na_2O) and silicon dioxide (SiO_2), as shown in Table 2.5 (Kamseu et al. (2017).

Table 2.5 Chemical Composition of Sodium Silicate Solution Kamseu et al. (2017).

No.	***Chemical composition***	***Weight percent (%)***
1.	Na_2O	19.6
2.	SiO_2	28.9
3.	H_20	51.5
4.	Molar ratio (SiO2/ Na2O)	1.5
Physical Properties of Sodium silicate		
5.	Specific gravity	1.54
6.	Appearance	Light yellow liquid

2.3.4 Aggregates

Aggregates are crucial parts of making concrete that gives it body and minimizes shrinkage. In geopolymer concrete manufacturing, aggregates are occupied 70 to 80% of the total volume of concrete similar to conventional concrete. Additionally, the type and size of aggregates influence various aspects of the concrete, especially workability, strength, durability, and the amount of alkaline liquid required. The grading, angularity, shape, and texture of aggregates play a significant influence on the strength of geopolymer concrete, as in the case of Portland Cement Concrete (Lloyd & Rangan, 2009).

A study on the impact of aggregate content on the engineering characteristics of geopolymer concrete was undertaken by (Benny Joseph et al. 2012). The impact of additional parameters, including curing temperature, curing time, (Na_2SiO_3/NaOH) ratio, (fly ash/alkaline) ratio, and sodium hydroxide molarities, was also examined. According to the findings of the experiments, it was revealed that geopolymer concrete with correct proportioning of total aggregate material and ratio of fine aggregate to total aggregate has better engineering performance than ordinary cement concrete with the same properties. The elasticity modulus of geopolymer concrete was 14.4% more than that of normal concrete.

2.4 Workability of Geopolymer Concrete

According to Hardjito et al. (2003), fresh geopolymer concrete can be handled for up to 120 minutes without showing any signs of setting and without affecting its compressive strength. The flow of geopolymer concrete was observed both without applying any jolts and with 15 jolts after the moulds were taken out. The output of the experiment is summarised in Table 2.6. It was observed that the processed fly Ash Type I (PF-I) was almost identical without and with jolting. However, the mixes containing unprocessed fly ash, specifically UPF-I and UPF-II, were significantly stiffer and exhibited little flow when jolting was not used. Figure 2.6 depicts the flow of geopolymer concrete when jolted in relation to the fineness of fly ash. The Figure also indicates that as the fineness of the fly ash increases, the flow increases. It denotes the impact of fineness of fly ash on workability. (Patankar et al. 2013).

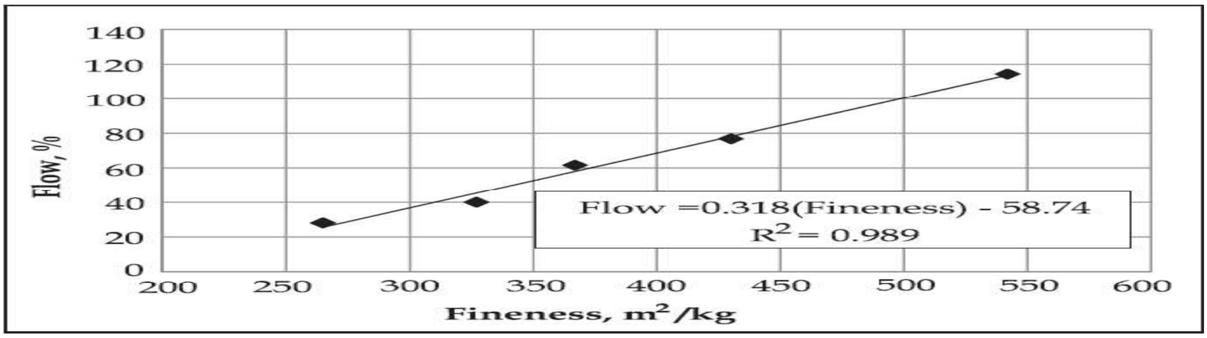


Figure 2.6 Effect of fly ash fineness on flow of Geopolymer Concrete Patankar et al (2013)

Table 2.6 Effect of fines of fly ash on workability on GPC Patankar et al. (2013).

No	Specimen identification mark	Finesses of fly ash, M^3/kg	Workability in terms of flow	
			Without Jolting, %	with jolting, %
1	GPC-PF-I	542	109.30	114.40
2	GPC-PF-II	440	31	76.8
3	GPC-PF-III	367	17	61.6
4	GPC-UPF-I	327	0.00	40
5	GPC-UPF-II	265	0.00	28

2.5 Strength Studies on Geopolymer Concrete

Jamdade et al., (2014) studied the strength of oven-cured geopolymer concrete. Geopolymer concrete is made in this study by combining sodium silicate, sodium hydroxide, and refined fly ash. Curing at different temperatures and conditions increases the strength of concrete e.g., 600°C, 900°C, and 1200°C. Improving the curing temperature above 600 °C did not significantly enhance the strength, but it has been observed that higher curing temperatures improve the compressive strength of geopolymer concrete. On the other hand, longer curing times accelerate the polymerization process and gradually increase the compressive strength of geopolymer concrete.

Yasir et al., (2015) investigate the characteristics of geopolymer concrete made using fly ash. The alkaline liquid to fly ash ratio was 0.3 to 0.45 for M20 grade geopolymer concrete was achived . Mechanical properties such as flexural, compressive and splitting tensile strength were tested on geopolymer concrete samples. Experimental confirmation for these conclusions is given after a review of the variables influencing these properties. Acid attack and permeability, two durability factors, are also studied. Based on the outputs of the tests, it was indicated that geopolymer concrete has excellent compressive strength and durability performance. Strength decreases as the alkaline liquid to fly ash ratio rises, and a ratio of fewer than 0.3 results in a highly stiff material.

Thakur et al. (2009) conducted experimental work on the enhancement of compressive strength and microstructure of geopolymer mortar. The alkaline liquid employed was sodium silicate and sodium hydroxide solution after 24 hours of keeping room temperature. The main parameters studied were the effects of alkali content, silica content, water to geopolymer solids ratio, and sand-to-fly ash ratio on the compressive strength of geopolymer concrete. Results indicate that after curing for 48 hours at 85 °C with an alkali content (Na_2O/Al_2O_3) of 0.62 and a silica content (SiO_2/Al_2O_3) of 4.0, the geopolymer mixtures have a compressive strength of 48.20 MPa.

2.6 Factors affecting the Properties of Geopolymers

Many factors have been recognised as crucial aspects influencing the characteristics of geopolymers. According to Palomo et al. (1999), the curing temperature, curing time, and type of alkaline activator all had a considerable impact on the mechanical strength of fly ash based geopolymers. So, it was identified that a longer curing duration increased compressive strengths. An alkaline activator composed of soluble silicates was found to accelerate the reaction rate when compared to alkaline solutions containing only hydroxides.

(Van Jaarsveld et al. 2002), reported that the content of water, cure technique, and calcining condition of kaolin clay influenced the characteristics of geopolymer concrete. Moreover, the curing at an elevated temperature resulted in cracking and adversely impacted the material properties. Therefore, they recommended, mild curing to further enhance the material's physical characteristics. (Van Jaarsveld et al 2003), noted that the source materials affect the performance of geopolymer, particularly the calcium oxide (CaO) content of the raw material and the liquid to fly ash ratios. (Barbosa et al. 2000) & (Xu and van Deventer, 2000), presented statistical research on the influence of several conditions on the polymerization of metakaolin-based geopolymers. The parameters in concern were the oxides` molar composition. They identified characteristics that influence the compressive strength and polymerisation of natural Si and Al minerals, as well as the performance of geopolymers. The amount of Si dissolution, the type of alkali activator, the source material's molar Si-to-Al ratio, calcium oxide (CaO), potassium oxide, and the molar ratio of (Si/Al) in the solution are all factors.

2.7 Method of Curing Geopolymer Concrete

Adam & Horianto, (2014) conducted a study on the duration and temperature of curing effect on the strength of fly ash geopolymer harden. They observed that the curing period has significantly influenced the final product of geopolymer strength of fly ash and microstructural system. The optimal temperature for heat curing was 120°C for 20 hours. However, they simply took into account mortar paste, and they didn't mention how it behaved in concrete.

Yewale et al. (2016) investigated the effectiveness of a particular geopolymer concrete curing method. In their research, class F fly ash was utilized to create geopolymer concrete. The combination included a BB2 superplasticizer to improve the workability of the geopolymer mixtures. The experimental results indicates that the strength of geopolymer concrete samples increased at higher temperatures and the optimum strength was obtained at 60°C oven dry curing.

In summary, the hardening and rapid setting time of geopolymer concrete depends commonly on three factors weather, duration time, and calcium oxide (CaO) content composed of the binding materials. For example, geopolymer concrete incorporated with grand granulated blast furnace slag (GGBS) has hardened and set early like conventional concrete due to the high content of calcium oxide (CaO). While the geopolymer concrete with low calcium oxide content pozzolanic materials need more sufficient time or curing at elevated temperature due to the lower CaO. So, curing at ambient temperature is very important for practical applications. Therefore, this research is exploring the ambient curing temperature to evaluate the behavior of low calcium content pozzolanic materials in terms of strengths and durability performance.

2.8 Previous Studies on the Durability of Geopolymer Concrete

2.8.1 Water Absorption of Geopolymer Concrete

Olivia & Nikraz, (2008) performed experimental research on fly ash (low calcium) geopolymer concrete's water permeability properties, covering water absorption, the volume of permeable voids, permeability, and sorptivity. This study uses fly ash as a source material to manufacture geopolymer concrete with NaOH and Na_2SiO_3 as an alkaline solution. Seven samples were cast using (100 x 200 mm) cylinders, and the specimens were then cured for 24 hours in the steam curing chamber at 60 C. After 28 days, the cylinders were cut into slices and examined for sorptivity, permeability, and the amount of permeable voids. Scanning electron microscopy (SEM) was also employed to analyse the microstructural properties of the geopolymer concrete. According to the findings, geopolymer concrete has low sorptivity, permeable void volume, and water absorption. It has been observed that geopolymer concrete can be categorised as concrete of average quality based on its water permeability value. Furthermore, it was noted that well-graded aggregates as well as low water to binder ratio, are essential elements in achieving low water penetrability of geopolymer concrete.

Olivia & Nikraz (2011) conducted a study on the strength development of low-calcium fly ash based on geopolymer concrete. The properties tested were aggregate classification, aggregate-to-binder ratios, various water to binder ratios, and alkaline solution-to-fly ash ratios. The findings showed that lowering the ratios of water to binder and aggregate to binder increased the strength of fly ash geopolymer concrete while minimizing the ratio of water to the binder, raising the fly ash content, and using well graded aggregates optimized the water absorption of low calcium fly ash. Additionally, it was noted that the water permeability coefficient for the geopolymer with various parameters did not change significantly.

Sathia et al. (2008), investigated the durability of fly ash-based geopolymer concrete made with sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) as an activator. The observed compressive strength was in the 10-60 MPa range. Water absorption and acid resistance experiments were utilised to assess the performance of all of these concretes in aggressive environments. The results showed that when concrete strength and fly ash content increased, water absorption decreased. In comparison to conventional concrete, all geopolymer concretes demonstrated outstanding resistance to acid attack (3% H_2SO_4).

2.8.2 Sulphate Resistance Test

Sulphates are widespread in the environment, such as underground water, soil, seawater, or industrial wastewater Siad et al. (2015). In addition, magnesium sulphate ($MgSO_4$) has the fastest, most severe effects on concrete, Yildirim & Sumer (2013). Hekal et al. (2002) have shown that magnesium sulphate has a more severe effect on the characteristics of concrete than sodium sulphate. The utilisation of sufficient quantities of supplemental cementitious materials (SCMs), such as slag, is common practice to reduce the effects of a sulphate assault on the concrete (Juenger & Siddique, 2015). According to Neville (2019), using supplementary cementitious materials (SCMs) as cement replacement material may enhance sulphate attack mitigation by lowering the amount of calcium aluminate (C3A) and calcium Hydroxide (CH), which blocks the formation of deleterious compounds like ettringite and gypsum.

Thokchom et al., (2010), an experimental study was carried out to determine how well fly ash-based geopolymer mortar specimens behaved in a magnesium sulphate solution. By activating low calcium fly ash with a sodium hydroxide and sodium silicate solution mixture and thermally curing the material, specimens were manufactured. The samples were soaked in a 10% by weight solution of magnesium sulphate for up to 24 weeks. Performance of the specimens was assessed based on versions strength and mass, pH of solution, and visual appearance during the exposure period. The specimen formed white deposits on its surface, changing from soft to hard crystals over time. The pH of the solution notably raised within the first few weeks, indicating alkali migration from mortar specimens. Samples gained relatively little weight and had a reduction in compressive strength of up to 56% after 24 weeks.

2.8.3 Acid Attack

Acid resistance is among the most crucial qualities of structural building materials. (Abraham, R., Ganesan, N., 2015). Concrete structural members are frequently exposed to acidic conditions such as groundwater, acid rain, and industrial effluents (Ranjbar et al. 2016). Consequently, concrete's ability to withstand acid attack is crucial, especially in constructions located in aggressive environments.

A study of geopolymer incorporating fly ash was performed by (Wang et al. 2005). The samples were cured in in oven dried for 24 hours at 70 degrees Celsius. Concrete samples were exposed in 10% H_2SO_4 solution for 56 days. At a 28-day age, 50 mm cubes had compressive strengths ranging from 53 MPa to 62 MPa. After being soaked in 10% sulfuric acid with a constant ratio of acid volume to specimen surface area of 8 ml/cm2, samples were tested after 7, 28, and 56 days. The properties that were examined are mass loss and residual compressive by using the ASTM C627. The results show that the geopolymer concrete has a mass loss of less than 3 per cent and is particularly resistant to the effects of sulfuric acid. Additionally, the samples for strength showed a substantial load capacity even after the entire specimens had been soaked in the solution.

2.8.4 Chloride Attack

A study on the assessment of the efficiency of geopolymer concretes was made by utilizing fly ash class F and granulated lead smelter Slag (GLSS) (Albitar et al. 2017). In addition, the effectiveness of geopolymer concrete's durability was evaluated using OPC cement concrete as a reference. Concrete samples were soaked for up to nine months in various chemical concentrations, including 3% sulfuric acid, 5% sodium chloride, 5% sodium sulphate, and 5% sodium sulphate, and 5% magnesium sulphate. The change in weight, compressive strength, splitting tensile strength, flexural strength, water absorption, sorptivity, and porosity were evaluated throughout the exposure period. The effects of heating-cooling and wetting-drying cycles on compressive strength and mass loss were also examined. The findings showed that OPC concrete has lesser sorptivity and water absorption than geopolymer concrete. Additionally, it is demonstrated that ordinary Portland cement concrete is more vulnerable to sulfuric acid attack whereas sodium sulphate has the largest effect on geopolymer concretes. The outcomes demonstrated that, overall, Geopolymer Concrete surpasses OPC Concrete in terms of durability performance over the range of the examined exposure.

In summary, the chemical attack on the concrete can result in cracking, mass change, structure deterioration, strength change etc. Further, the life span of the structure is getting shorter and it can cause the failure of structures. To mitigate these problems with the concrete structure, geopolymer concrete is the best solution due to the three-dimensional polymeric chain structure that can resist chemical attack.

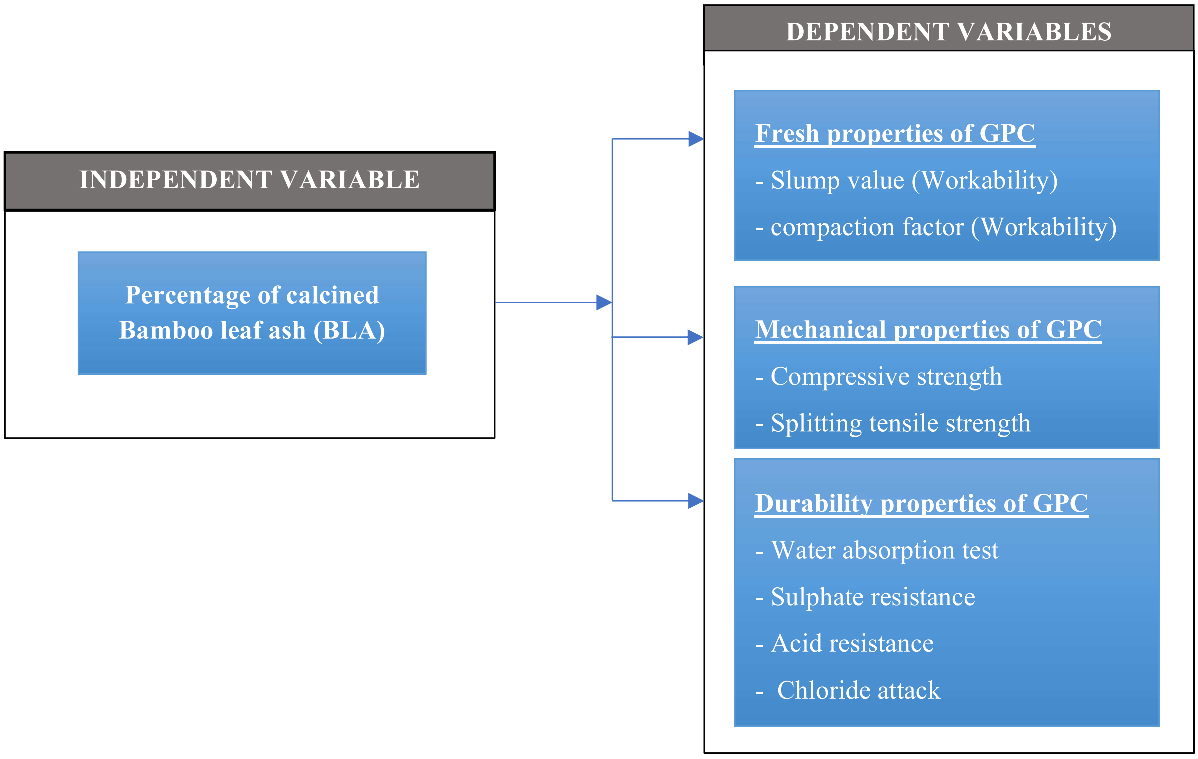
2.9 Knowledge Gaps

There has been a little investigation into geopolymer concrete with natural pozzolanic material. So, after investigating the empirical studies (Umoh et al. 2014; Prabu et al. 2014; Olutoge et al 2017; Saloma et al. 2017; Ishak et al. 2019; Oyebisi et al. 2020; Singh et al. 2020) it is noted that the geopolymer with bamboo leaf ash was not adequately studied especially for mechanical and durability performance.

Therefore, this study investigated the effect of calcined bamboo leaf ash on geopolymer concrete by evaluating the mechanical properties, such as compressive strength and splitting tensile strength. Also, the durability of the geopolymer concrete with bamboo leaf ash was assessed, e.g., water absorption, sulphate resistance, acid resistance test, and chloride attack test.

Secondly, the properties of bamboo leaf ash in different regions and how they relate to geopolymer concrete have not been studied. This research focused mainly on bamboo leaf ash drawn from Kenya's forests, especially the Mt. Kenya Forest. In addition, its chemical composition was also studied. Research into the properties of bamboo leaf ash from other countries and how they compare is an area for further investigation. The study also sought to clarify the scientific basis of how bamboo leaf ash affects the engineering properties of geopolymer concrete. That is, chemical reactions, if any, or changes in physical properties due to exposure conditions.

2.10 Conceptual Framework



CHAPTER THREE

3. METHODOLOGY

3.1 Overview

This chapter is about the experimental work and the procedure of this study to accomplish the planned objectives. Firstly, the constituent materials and experimental program were reviewed. The experimental work began with the fundamental raw material testing that includes aggregate tests, XRF, and particle size distibution of the binder materials. The next step was the assessment of workability by using the slump test and the compaction factor tests. After that, the mechanical properties and durability were tested at various ages, comprising 28, 56, and 90 days. The mechanical parameters that were tested are compressive and splitting tensile strength. Additionally, tests for water absorption, sulphate resistance, acid resistance, and chloride attack were also used to measure the durability performance. It is worth noting that geopolymer concrete, being an emerging material, does not have prescribed or standard procedures for the preparation and testing. Nevertheless, the standard for testing conventional concrete was referred to wherever applicable. The schematic phases of the experiment are illustrated in Figure 3.1 below.

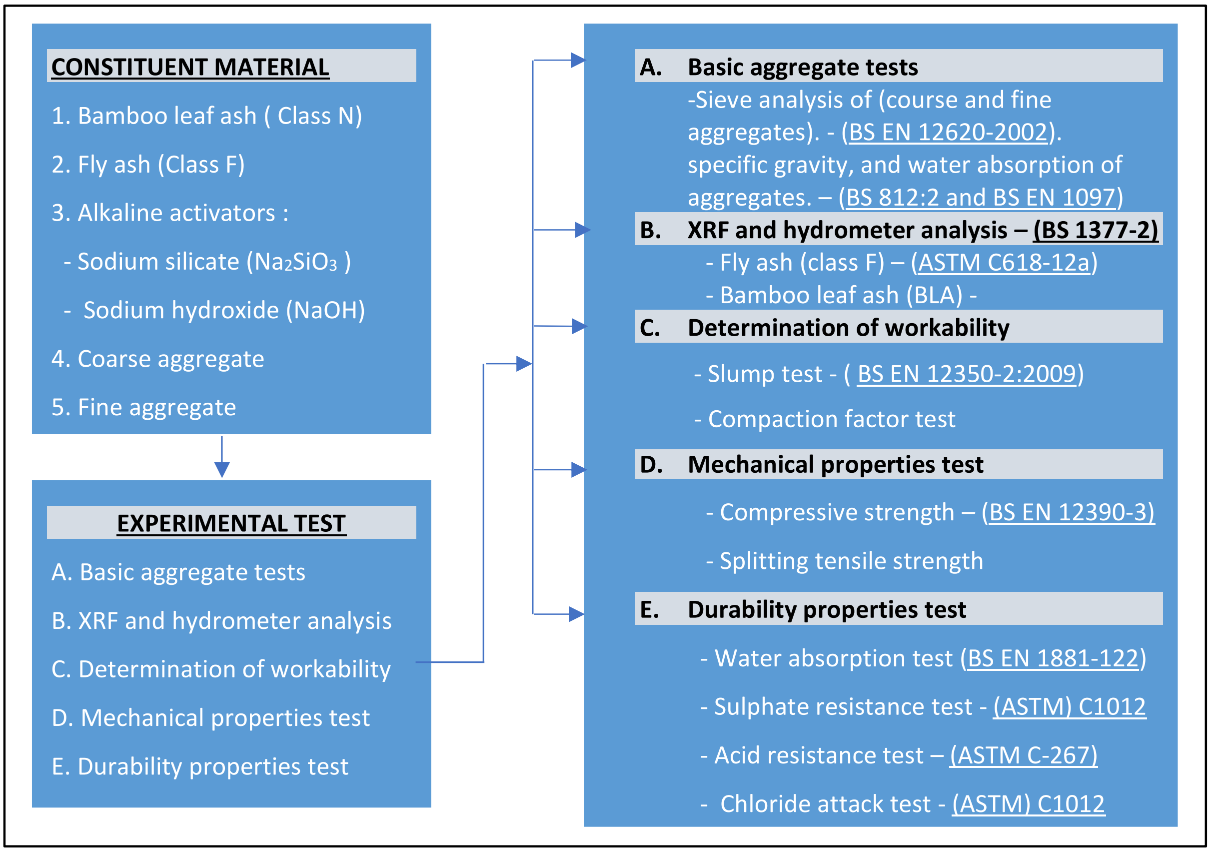


Figure 3.1: Stages of the experimental study

3.2 Basic Raw Material Tests

3.2.1 Grading of Aggregates

The sieve analysis of coarse aggregate (14mm maximum size) and river sand was carried out in compliance with BS EN 12620-2002 to ensure the design, production control, and compliance guidelines. After that, test sieves with varied opening sizes were selected from highest to lowest to obtain the necessary information by the specification for the materials being tested. Moreover, by shaking the sieves for enough time using a manual, the weights of the retained masses were measured and recorded. The test results are presented in Appendix A, Table A1, and Table A2.

3.2.2 Specific Gravity and Water Absorption of Coarse Aggregate

These tests were conducted under BS 812:2 and EN 12390-7 to ensure the quality, strength, and water-holding capacity of the coarse aggregates. The required tools were a balance capacity not less than 3kg, well-ventilated oven capable of maintaining a temperature of 105+5C, air tight container, and glass vessel. A sample of 2Kg coarse aggregate were washed thoroughly to remove fines and then immersed in a container filled with water. The next day, the samples were taken to the oven for drying. After that, the masses of the following samples were measured and recorded on the observation sheet: the mass of the saturated surface dry sample in the air (A), the mass of the container containing the sample and full with water (B), the mass of the container occupied with water alone (C), and the mass of the oven dried sample in the air (D). In order to determine water absorption, the mean values of relative densities were obtained. Therefore, a summary of the test findings was presented in Appendix A, section A3.

3.2.3 Specific Gravity of River Sand

The specific gravity of river sand was performed according to BS EN 1097-6: 200 to verify the type of sand. The mass of the empty container (W1), the mass of the container plus Sand (W2), the mass of the bottle plus sand plus water (W3), and the mass of the container full of water (W4), were measured, and noted. Additionally, the average of three samples was used to compute the specific gravity of river sand. Thus, the results are reported in Appendix A, section A4.

3.2.4 Water Absorption of River Sand

This test was conducted under BS EN 1097-6: 200. The river sand sample was properly washed and cleaned to remove finer particles and dust. Then, the Saturated surface dried weight (A) and oven-dried weight (B) were determined and recorded. The percentage of water absorption was computed by the weight of water dividing the dry weight of river sand and multiplied by 100. The test results were shown in Appendix A, section A5.

3.2.5 Hydrometer Analysis of Bamboo Leaf Ash, OPC, and Fly Ash

These tests were carried out following the BS 1377-2 standard to determine the particles size distribution of bamboo leaf ash, ordinary portland cement and fly ash particles passing the N.200 (75 microns) sieve size. The apparatus included a 1000ml glass cylinder, beaker, time measure, mechanical stirrer, sedimentation cylinder, weight balance, and hydrometer as shown in Figure 3.2. A hydrometer is an instrument tool that is designed to assess the relative density of a liquid which refers to the ratio of the actual density of the substance to the density of the water. First, a 50g dry sample of bamboo leaf ash, OPC, and fly ash were sieved at 0.075mm and tested on three different days. The ash was poured into the mechanical stirrer with a small amount of water and mixed for 5 minutes. Then, the dispersion agents were added into the measuring cylinder in order to avoid the fine particles sticking together and allow every particle size to fall free. The dispersion agents used were a combination of 7 grams of sodium carbonate (Na_2CO_3), 33 grams of sodium hexametaphosphate ($NaPO_3$)6 and 100ml of H_2O. Later, the water was poured into the measuring cylinder up to 1000ml, and then hydrometer was inserted inside gradually until it is stabilized. The scale of the hydrometer then was read and noted based on its submersion at an interval of 0.5 minutes up to 120 minutes. The test findings were demonstrated in Appendix C, Table C1, and Table C2.

Figure 3.2: Hydrometer analysis test

3.2.6 Chemical Composition of Fly ash, BLA, and OPC Cement

These tests were carried out following the requirements of the ASTM C618-12a standard. The chemical composition of fly ash (ASTM class F) and bamboo leaf ash (ASTM class N) and ordinary Portland cement (OPC) was analysed to get detailed information on the materials' characteristics and to ensure the resulting products are to the required standards. And also, the chemical makeup of OPC cement was tested and obtained in order to see and compare the difference between the pozzolanic materials of GPC and the OPC cement. Additionally, this test was conducted to establish the suitability of bamboo leaf ash for use in producing geopolymer concrete. Two grams of fly ash, bamboo leaf ash, and OPC cement were tested using XRF analyse. The test findings were presented in Appendix B Table B1, Table B2, and Table B3, respectively.

3.3 Constituent Materials

The constituent materials employed in this study as binding materials were pozzolanic ingredients, such as industrial products (fly ash class F) and agricultural wastes (calcined bamboo leaf ash). For aggregates, natural coarse aggregate and fine aggregate were used, while alkaline activators such as sodium silicate and sodium hydroxide play a role in water. Additionally, extra tap water (0.1% by weight of fly ash) was utilised if it is essential to maintain the workability of geopolymer concrete.

3.3.1 Bamboo Leave Ash

Bamboo leaf ash, as shown in Figures 3.3 and 3.4 was used in this study. Twenty-seven kilograms of bamboo leaves were collected from Kenya's rainforests at the Mt. Kenya Forest with permission from Kenya Forest Services, Karura Forest headquarter. The leaves were dried until they became folded and husky as illustrated in Figure 3.3, and then the burned in a kiln to produce ash and remove the organic substances. The ash was then taken to the University of Nairobi's Mechanical Department lab, where it was heated at 650–750 °C for two hours in order to eliminate extra carbon in the ash. After cooling the ash, it was sieved using a 75-micron sieve to obtain fine particles similar to the cement, as demonstrated in Figure 3.3(b). Furthermore, the particle size distribution of bamboo leaf ash was conducted using a hygrometer test according to ASTM D7928 (2017). Additionally, the XRF analysis was used to examine the chemical makeup of the bamboo ash. The test results are presented in Appendix B, Table B2.

Figure 3.3: Drying process of bamboo leaves before burning

Figure 3.4: Bamboo leaf ash after drying, burning, and sieving for (75 microns)

3.3.2 Fly Ash class F

The fly ash utilized in this research was low- calcium (ASTM Class F) as the main binding material for the manufacturing of geopolymer concrete, as shown in Figure 3.5. Furthermore, fly ash class F has an aluminosilicate material that contains more than 70% of Al_2O_3, SiO_3, and Fe_2O_3, as shown in Appendix B Table B1. ASTM C-618 was used as the specification for fly ash with a specific gravity of 2.2. So, in this experimental study, the fly ash used was imported from the Rangeela export market in Mumbai, India. The fly ash contained below 10% calcium oxide content. Thereafter, the fly ash was taken into the Geotechnical Survey (Bruker) Laboratory in Nairobi to analyze chemical composition as well as to ensure compliance with standards. A hydrometer test was also conducted to the standard of BS 1377 – 2. In order to ascertain the particle size distribution of fine-grained ash passing through a 75 μ sieve and to measure the specific gravity of the fly ash.

Figure 3.5: Fly ash class F

3.3.3 Alkaline Liquids

The primary binding agents for geopolymer concrete are alkaline liquids. The alkaline liquids used for polymerization were the analytical-grade of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solution, as detailed below in the sub-sections. The ratio of activators for NaOH to Na_2SiO_3 was 2.5. The alkaline liquid to fly ash ratio was chosen to 0.6 after trial mixing.

3.3.3.1 Sodium Hydroxide (NaOH)

Sodium hydroxide, demonstrated in Figure 3.6 with a purity of 98%, was used in this research in order to take part in the geopolymer process. So, the sodium hydroxide (NaOH) flakes were dispersed in water before they were mixed with the other alkaline solutions. To minimize the impact of unidentified impurities, distilled water was utilized to dissolve sodium hydroxide pellets. Additionally, the range of sodium hydroxide (NaOH) concentration used in this study was constant at 16 molars.

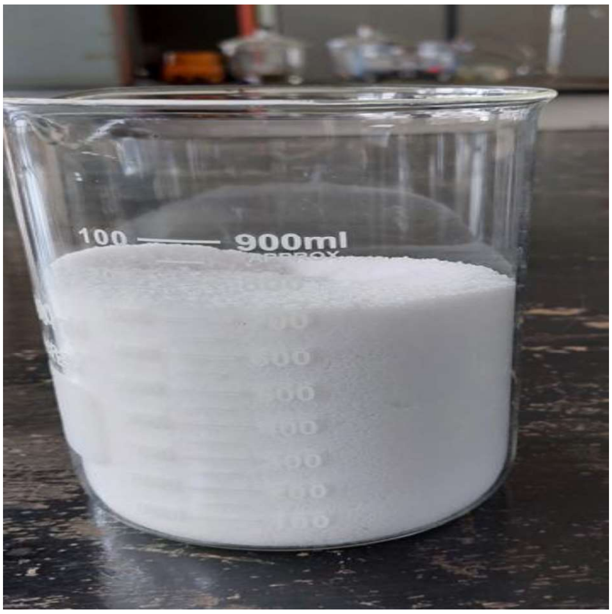


Figure 3.6: Sodium Hydroxide (NaOH)

3.3.3.2 Sodium Silicate (Na_2SiO_2)

The sodium silicate utilized in this study was a liquid form as shown in Figure 3.7.

Figure 3.7: Sodium Silicate (Na_2SiO_3)

3.3.4 Aggregates

Sieve analysis of both fine and coarse aggregates was carried out following BS EN 12620 - (2022) to determine the different fractions of the size of taken aggregate samples and also to ensure standard specification requirements and the compliance of the mix design.

3.3.4.1 Fine Aggregate

Available river sand was used in this study by following the requirements of BS EN 12620 – (2022). Moreover, the sand was properly graded to give a minimum void ratio and free from deleterious materials such as silt content and chloride contamination.

3.3.4.2 Coarse Aggregate

Crushed aggregates with a maximum particle size of 14 mm were used and delivered from local suppliers in Nairobi, Kenya.

3.4 Experimental Methods and Test Procedures

Most of the experimental tests for this study were carried out in the different laboratories at the University of Nairobi, Department of Civil and Constriction Engineering. For all different tests, 375 specimens were cast to determine the effect of bamboo leaf ash in geopolymer concrete. Furthermore, the standard test methods employed in the experimental tests conducted for this study are listed in Table 3.1.

Table 3.1: Standard Test Methods of the Experimental Tests

S/N.	*Experimental tests*	*Standard specification*
1.	Grading of aggregate (Fine and coarse aggregate)	BS EN 12620-2002
2.	Specific gravity test of coarse aggregate	BS 812:2
3.	water absorption test of coarse aggregate	EN 12390-7
4.	Specific gravity test of river sand	BS EN 1097-6: 200
5.	Water absorption test of river sand	BS EN 1097-6: 200
6.	Hydrometer analyse tests of fly ash and bamboo leaf ash	BS 1377-2
7.	Chemical compositions of fly ash and bamboo leaf ash	ASTM C618-12a
8.	Properties of fresh geopolymer concrete tests	BS EN 12350-2:2009
9.	Mechanical properties of geopolymer concrete	BS EN 12390-3: 2002
10.	Water absorption test of geopolymer concrete	BS EN 1881-122(1) 1983
11.	Sulphate resistance test of GPC	(ASTM) C1012
12.	Acid resistance test of GPC	ASTM C-267
13.	Chloride attack test of GPC	(ASTM) C1012

3.4.1 Preparation of Alkaline Activators

The alkaline liquids utilised in this experimental test were a mixture of sodium silicate (Na_2SO_3) and sodium hydroxide (NaOH), as shown in Figure 3.9 solution to activate the fly ash and bamboo leaf ash. The sodium hydroxide pellets were dissolved in distilled water to produce a sodium hydroxide solution with a 16 molar(M) concentration, as shown in Figure 3.8. While sodium silicate solution was kept in a covered bucket as a form of sticky liquid during the preparation of NaOH. The dissolution of sodium hydroxide pellets into water is an exothermal reaction that occurs with massive quantities of heat, which leads to the cycle of geological polymerisation. Previous studies suggested that one day before using alkaline solutions Kaur, Singh, & Kaur, (2018). Yet a day before combining the products leads to consistency and conformity to the solution. Thus, the sodium hydroxide solution was then left at a room temperature for 24 hours to be cool and then mixed with a sodium silicate solution to prepare the final alkaline solution to achieve for successful bonding of the solution. Additionally, the ratio of sodium hydroxide to sodium silicate was 2.5 for all mixtures. Therefore, in this research work, alkaline activators were prepared one day before casting the concrete.

Figure 3.8: Preparation of sodium hydroxide

Figure 3.9: After mixing together (NaOH and Na_2SiO_3)

3.4.2 Mix Proportion of Geopolymer Concrete

Based on the limited previous GPC research Lahoti et al. (2017) the proportion of the mixture components was then chosen. The proportioning of concrete mixes takes into account a number of factors. The ultimate goal of mixture design is to produce a product that is as durable as possible, although other factors like economics and sustainability might influence the material selection. Contrary to OPC concrete, geopolymer concrete has no established mix design guideline. This is mostly due to the lack of adequate data to produce a reliable trend chart for the variation of different influencing parameters. Thus, trial mixes were conducted based on the design mix parameter of conventional concrete. Thus, 75% of the total mass of the geopolymer concrete mix was made up of course and fine particles. This amount is comparable to that used in conventional concrete, which normally varies between 70% and 80% of the entire mass of the mixture. According to (Hardjito & Rangan, 2005), it is demonstrated in earlier research that the average density of geopolymer concrete is comparable to that of OPC concrete (2400 kg/m3). Fly ash, bamboo leaf ash, coarse aggregate, fine aggregate, and alkaline liquids were used to generate the targeted mix percentage for the class 25 mix ratio, as illustrated in Figure 3.10. Additionally, after conducting various trial mixing the final mix ratio attained was 1:1.5:3. Hence, the mass of alkaline liquid and solid materials can be derived from knowing the density of concrete. By assuming the ratio of alkaline liquid to binders (Fly ash and bamboo leaf ash) as a 0.6 fixed. So that, the mass of fly ash, bamboo leaf ash, and mass of alkaline liquid were obtained as shown in Table 3.2 a summarized detail of mix proportioning. Further details of mix proportions calculations including the mix design and alkaline liquid computing, were provided in Appendix H.

Table 3.2 Mix Proportion of Geopolymer Concrete with Bamboo Leaf Ash for Class 25 Target Mix Proportion

Ingredients of GPC	*Bamboo leave ash*	*Fly ash class F*	*Fine Aggregate*	*Coarse Aggregate*	*Na_2SiO_3 (SS)*	*NaOH (SH)*	*SS/SH (117/46.8)*
Quantity (kg)	*27.3*	*245.5*	*409.1*	*818.2*	*117*	*46.8*	*2.5*

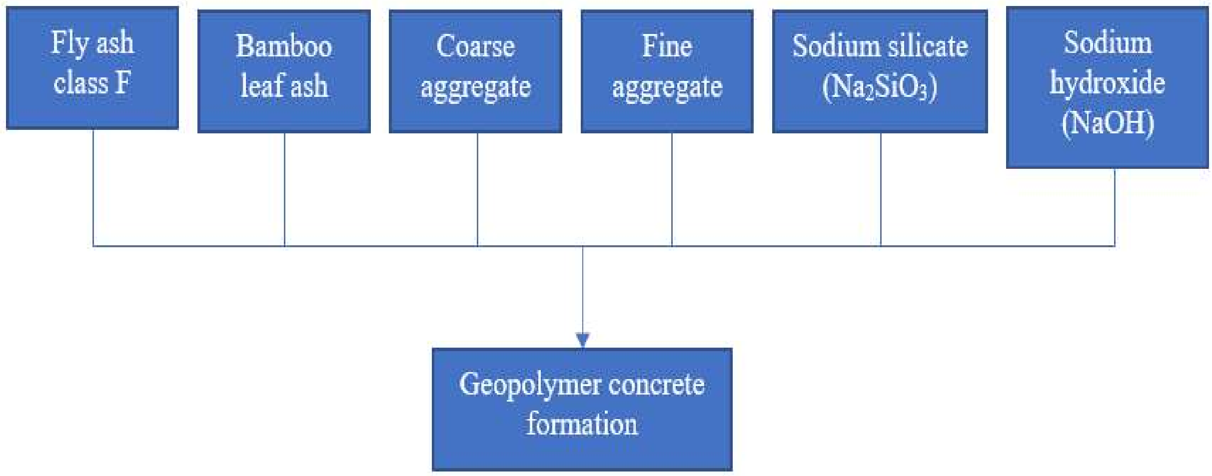


Figure 3.10 : Synthesis of geopolymer concrete

3.4.3 Mixing Method for the Manufacturing of Geopolymer Concrete

The mixing process for geopolymer concrete is the same form as traditional concrete. A pan mixer with a capacity of 70 litres was the tool employed to mix the geopolymer concrete. The mixing pan was thoroughly washed to eliminate residues from previous batches. The inside of the pan was also carefully moistened to minimize water attraction from the mixture. In the mixing pan, coarse aggregates were initially loaded, followed by sand, which was prepared in a saturated surface dry condition. The next two to three minutes were spent thoroughly mixing the aggregates. Then, before applying the activator solution, fly ash, and various amounts of calcined bamboo leaf ash were put into the mixing pan combined, and properly blended for another 2 or 3 minutes. While the mixing was going on, a premixed alkaline activator solution, of sodium silicate and sodium hydroxide, was added gradually. Figure 3.8 below illustrates the formation of geopolymer concrete after combining the raw materials in this study.

3.5 Workability Tests of Geopolymer Concrete

The workability of freshly prepared geopolymer concrete mixtures was assessed by using slump and compaction factor apparatus to evaluate the consistency of fresh concrete before it sets.

3.5.1 Slump Test

The slump test of geopolymer with bamboo leaf ash concrete was evaluated by following BS EN 12350-2:2009 guidelines. The tools used in this test were a slump cone, steel tamping rod, flat steel plate, tape measure, and damp cloth. The slump cone metallic mould dimensions were 200 mm for the bottom open base, 300 mm for the height, and 100 mm for the top diameter. After cleaning and oiling the slump cone, the concrete was poured into about three equal portions and compressed with 25 blows of the steel tamping rod. The tamping rod was a straight steel 600 mm long and 16mm thick. Furthermore, after compacting the last layer the top of the cone was levelled and smoothed with a metal float. The mould was then gently lifted vertically, without lateral or torsional motion, and removed from the concrete straight away. Finally, the difference in dimension between the upper part of the mould and the specimen height was measured and recorded for each batch of the mixing as illustrated in Figure 3.11.

Figure 3.11: Slump test of geopolymer concrete

3.5.2 Compaction Factor Test

This test was performed according to BS 1881-103: 1983 to determine the degree of workability of fresh concrete in terms of the internal energy required for thoroughly compacting concrete. The apparatus tools utilized were a finishing trowel, rounded steel rod, and weight balance. First, a sample of concrete was filled gently into the top hopper using a trowel. After that, the top hopper's trap door was then opened, letting the concrete drop into the bottom hopper. Additionally, the concrete was pushed occasionally as shown in Figure 3.12 when the concrete stuck on the hopper in order to fall down the middle hopper to the cylinder. The centre hopper's trap door was then unlocked, allowing the concrete to drop into the bottom cylinder. In addition, levelling the upper surface of the cylinder was done with a hand trowel as well the exterior of the cylinder was wiped using a towel. After that, the weight of the cylinder, the weight filled with partially compacted concrete, and the weight of fully compacted concrete were measured and recorded to obtain the value of the compaction factor, as illustrated in Equation 3.1 below.

$$\text{Compaction factor} = \frac{\text{Weight of partially compacted concrete}}{\text{Weight of fully compacted conretet}} \ldots\ldots\ldots\ldots.. \text{ Eq. 3.1}$$

Figure 3.12: Compaction factor test of GPC

3.6 Ambient Curing of Geopolymer Concrete

After the casting process, the cubes and cylinders were taken to a mechanical vibrator to remove air bubbles by shaking vigorously. The fact is that low calcium-content pozzolanic materials do not interact with normal water for hydration products. For this regard, the samples were stored at room temperature as shown in Figure 3.13 to allow the geopolymer paste's chemical reaction to occur. During the curing stages, the average temperature recorded was 21 °C. Moreover, geopolymer concrete with a low CaO content did not harden early at ambient curing temperature, unlike OPC concrete. It required enough time to set before demoulding.

Figure 3.13: Specimens under ambient curing temperature

3.7 Mechanical Properties of Geopolymer Concrete

The mechanical properties tests of GPC such as compressive strength and splitting tensile strength were carried out by following the methods, procedures, and techniques of normal concrete testing. The importance of this test is to measure the behaviour and response of geopolymer concrete comprising low calcium fly ash and bamboo leaf ash under a gradually applied load. In addition, the effect of different percentages of bamboo leaf ash contents in geopolymer concrete.

3.7.1 Compressive Strength

The compressive strength test of geopolymer concrete for this study was carried out to BS EN 12390-3 (2002). In this experiment, a cube size of 100x100x100mm was used. The inner surface of the mould was cleaned and oiled to avoid sticking of the concrete. Then the moulds were filled with the prepared geopolymer concrete mix. Once the mould was filled, the top surface of the mould was levelled using a trowel. Additionally, after the concrete hardened the cubes were demoulded and then taken into the curing at room temperature. On the 28th, 56th and 90th days, the specimens were tested at a load rate of 6.8 kN/s using the compression tester shown in Figure 3.14. According to Equation 3.2, the compressive strength of the geopolymer concrete was determined by dividing the breaking load by the specimen`s cross-sectional area. Further details of the compressive strength test of geopolymer concrete are provided in Table 3.3 below.

$$Compression\ strength\ \left(\mathrm{Fc}, \frac{\mathrm{N}}{\mathrm{mm2}}\right) = \frac{Maxmium\ load}{Cross - sectional\ area} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ Eq\ 3.2$$

.

Figure 3.14: Compressive strength test

Table 3.3 Compressive Strength of Geopolymer Concrete Blended with BLA

S.no	***Percentage (%) of bamboo leaf ash (BLA) and fly ash (FA)***	***Curing days at ambient temperature***			***Dimensions of the cube (mm)***	***Grade of geopolymer concrete***
		28	***56***	***90***		
1.	0 % BLA, 100% FA	3	3	3	100x100x100	C 25
2.	5 % BLA, 95% FA	3	3	3	100x100x100	C 25
3.	10 % BLA, 90% FA	3	3	3	100x100x100	C 25
4.	15 % BLA, 85% FA	3	3	3	100x100x100	C 25
5.	20 % BLA, 80% FA	3	3	3	100x100x100	C 25
Total specimens of compressive strength test = 9 x 5 = 45 Cylinders						

3.7.2 Splitting Tensile Strength

The splitting tensile strength test was performed in accordance with BS EN 12390-6:2009. A cylindrical specimen size of 300mm in length and 150mm diameter was preprepared and casted. After curing for 5 days at room temperature, the specimens were removed from the moulds. To ensure that the specimen's two ends are on the same axial position a diametrical line was drawn on them by using a marker. The geopolymer concrete cylinders were subsequently crushed by applying a compressive load without shock at a rate of around 14–21 kg/cm2/minute throughout their entire length, as shown in Figure 3.15. The maximum breaking load (P) was then recorded. The tensile splitting strength was obtained using Equation 3.3 below, and further details on the splitting tensile strength test are given in Table 3.4.

$$Splitting\ tensile\ strength\ (N/mm2) = \frac{2P}{\pi DL} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ Eq\ 3.3$$

Figure 3.15: Splitting tensile strength

Table 3.4 Splitting Tensile Strength of Geopolymer Concrete Blended with BLA

S.no	***Percentage (%) of bamboo leaf ash (BLA) and fly ash (FA)***	***Curing days at ambient temperature***			***Dimensions of the cylinder (mm)***	***Grade of geopolymer concrete***
		28	***56***	***90***		
1.	0 % BLA, 100% FA	3	3	3	300x150	C 25
2.	5 % BLA, 95% FA	3	3	3	300x150	C 25
3.	10 % BLA, 90% FA	3	3	3	300x150	C 25
4.	15 % BLA, 85% FA	3	3	3	300x150	C 25
5.	20 % BLA, 80% FA	3	3	3	300x150	C 25
Total specimens of splitting tensile strength test = 9 x 5 = 45 Cylinders						

3.8 Durability Tests of Geopolymer Concrete

The durability experiments of geopolymer concrete with various percentages of bamboo leaf ash content were conducted in accordance with ASTM C1012, BS EN 1881-122, and previous guidelines of the literature review. Moreover, the summarised detail of the specimens under chemical exposure solutions for durability were presented in Table 3.6. Figures 3.16, 3.17, 3.18 and 3.19 demonstrate before and after the specimens were submerged in the chemical solution.

3.8.1 Water Absorption Test

This test was conducted in conformity with BS EN 1881-122(1) 1983. This test was done to determine the water absorption behaviour of geopolymer blended bamboo ash. After 28 days, three samples of 100x100x100 mm cubes with various bamboo ash were prepared. The cubes were then taken to the oven to dry for 24 hours at a temperature of 110± 5 degrees Celsius. After that, the oven-dried specimens were taken out of the oven to cool in an airtight desiccator at a temperature of 24 ± 2 degrees Celsius. When the drying and cooling processes were completed, the specimens were weighed as dry weight (Wd) and then drawn in a curing tank water at an approximate temperature of 21 degrees Celsius for 72 hours. After being removed from the water, the samples were wiped with a dried towel to remove any remaining surface water and then weighed as saturated weight (Ws). Therefore, water absorption was computed as the variation in mass between oven dried and saturated specimens, and it was presented as a fraction percentage of oven dry mass. Likewise, additional information the water absorption of GPC was provided in the following Table 3.5.

Table 3.5: Water Absorption Test of Geopolymer Concrete

No.	***Percentage of bamboo leaf ash and fly ash***	***Curing days at ambient temperature***	***Specimens size (mm) and mix ratio***
		28 days	
1.	0 % BLA, 100% FA	3	*Cube size of 100x100x100 with C25 mix ratios*
2.	5 % BLA, 95% FA	3	
3.	10 % BLA, 90% FA	3	
4.	15 % BLA, 85% FA	3	
5.	20 % BLA, 80% FA	3	
Total samples of water absorption= 3 x 5 = 15 cubes			

3.8.2 Sulphate Resistance Test

This test was carried out by the guidelines in (ASTM) C1012. Sample cubes of geopolymer concrete with a size of (100 x 100 x 100 mm) were made and cured at room temperature for 28 days before immersing in the magnesium salt solution. Magnesium sulphate ($MgSO_4$) at a concentration of 5% was the standard exposure solution. According to Cang et al. (2017), each 100-gram solution is made up of 5 grammes of magnesium sulphate ($MgSO_4$) powder and 95 grammes of distilled water to make a 5% solution. Additionally, the GPC samples were positioned 50 mm away from the plastic container's walls. The plastic containers were wrapped with aluminium foil to minimize evaporation and dust accumulation. Furthermore, the solution was stirred once a week to minimize the deposits on the containers' bottoms. The samples were taken out after 28-day, 56-day, and 90-day exposures. The evaluation of variations in mass, strength, and appearance were the key variables investigated. Before testing compressive strength, the specimens' surfaces were washed, measured, and put under a compression test at a rate of 6.8 kN/sec.

3.8.3 Acid Resistance

This test was conducted in compliance with the guidelines indicated in (ASTM C-267). A cube size of 100x100x100mm was prepared and cured at an ambient temperature. After 28 days, the specimens were taken from the shelves by immersing them in the chemical exposure solution. The standard exposure solution was sulphuric acid (H_2SO_4) at a concentration of 5%. To achieve a 5% concentration solution, 95 g of distilled water and 5 g of sulfuric acid by mass were added to 100 g of solution. The solution was then kept at room temperature and stirred at least twice a week to ensure uniformity of solution. After 28, 56, and 90 days of exposure, the samples were removed from the containers. Following that, the surfaces of the cubes were wiped by using a soft nylon wire brush with water to remove loose material from the surface. The sample was then placed on a table to allow the surface to dry while all measurements were taken. The parameters that were assessed included changes in mass visual observation and changes in compressive strength. For the change in mass, the samples were weighted before dipping into the solution as an initial weight. Additionally, the samples were also tested 28, 56, and 90 days after being exposed to the solution. The change in compressive strength was tested by applying the pressure testing machine in the laboratory. Furthermore, the visual inspections were measured by assessing the physical damage, spalling, and expansion of the geopolymer concrete samples that were brought on by the chemical attacks.

3.8.4 Chloride Attack Test

The sodium chloride test method was performed in accordance with the guidelines in (ASTM) C1012. After 28 days of curing ambient temperature, the specimens were placed in water tanks containing a 5% sodium chloride (NaCl) salt solution. The salt solutions were made by reagent-grade chemicals dissolved in tap water, and they were stirred once a week. The parameters taken into consideration were the variations in mass, compressive strength, and visual appearance after a chosen exposure duration of up to 13 weeks. The weights before and after immersion in the solution were measured for the change in mass. The samples were immediately placed back into the sodium chloride solution after measuring the weights so they could be visually monitored for 56 and 90 days. For the measurements of change in compressive strength, the samples were crushed after removing from the solution for the crushing test machine. The average values were obtained by taking measurements from three cubes. The assessment was carried out after 28 days, 56 days, and 90 days from the date of immersion for all samples under sodium salt solution.

Table 3.6: Specimens Under Chemical Exposure Solutions for the Durability

No.	***Experimental tests***	***Age of curing days under chemical solution***	***Change in mass under chemical exposure solution specimens***					***Change in compressive strength under chemical exposure solution specimens***					***Specimens size and the grade of the concrete (mm)***
			Percentage (%) of bamboo leaf ash					***Percentage (%) of bamboo leaf ash***					
1.	*Sulfate resistance test specimens*	***Days***	***0%***	***5%***	***10%***	***15%***	***20%***	***0%***	***5%***	***10%***	***15%***	***20%***	*100x100x100 Cube with a C 25 mix ratios*
		28	3	3	3	3	3	3	3	3	3	3	
		56	3	3	3	3	3	3	3	3	3	3	
		90	3	3	3	3	3	3	3	3	3	3	
		Total samples under 5% ($MgSO_4$) salt solution = 30x3 = ***90 cubes***											
2.	*Acid resistance test specimens*	***28***	3	3	3	3	3	3	3	3	3	3	*100x100x100 Cube with a C 25 mix ratios*
		56	3	3	3	3	3	3	3	3	3	3	
		90	3	3	3	3	3	3	3	3	3	3	
		Total samples under 5% (H_2SO_4) acid solution = 30x3 = ***90 cubes***											
3.	*Chloride attack test specimens*	***28***	3	3	3	3	3	3	3	3	3	3	*100x100x100 Cube with a*
		56	3	3	3	3	3	3	3	3	3	3	
		90	3	3	3	3	3	3	3	3	3	3	

		Total samples under 5% (NaCl) salt solution = 30x3 = ***90 cubes***	*C25 mix ratios*
Total samples under 5% ($MgSO_4$, H_2SO_4, and NaCl) = 90 + 90 +90 = 270 cubes			

Figure 3.16: Preparation of specimens before soaking the chemicals

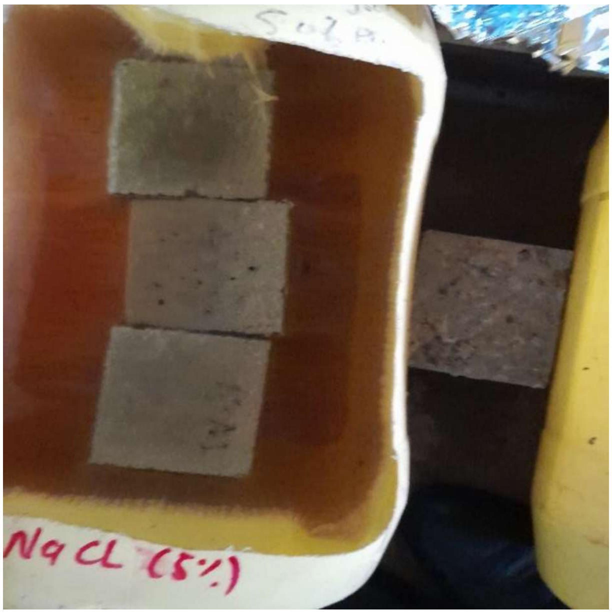


Figure 3.17: After the specimens immersed in the 5% NaCl solution

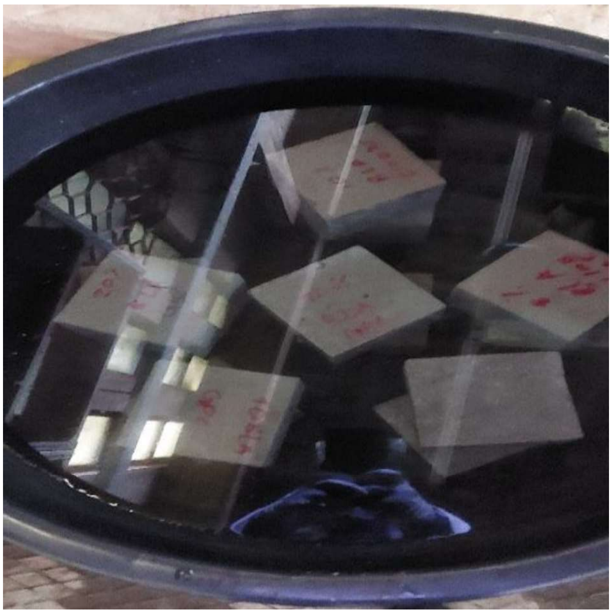


Figure 3.18: After the specimens immersed in the 5% $MgSO_4$ solution

Figure 3.19: After the specimens immersed in 5% H_2SO_4 solution

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1 Introduction

This chapter deals with the properties of geopolymer concrete with the addition of bamboo leaf ash as a partial substitute for fly ash (Class F).

4.2 Basic Aggregate Tests

The parameters covered in this section are sieve analysis, specific gravity, absorption, of course, and fine aggregates, respectively. To ensure the quality of the material and collect data for the mix design, as well as to confirm compliance with the standard specification's requirements.

4.2.1 Grading of Coarse Aggregate (14mm) Maximum Size

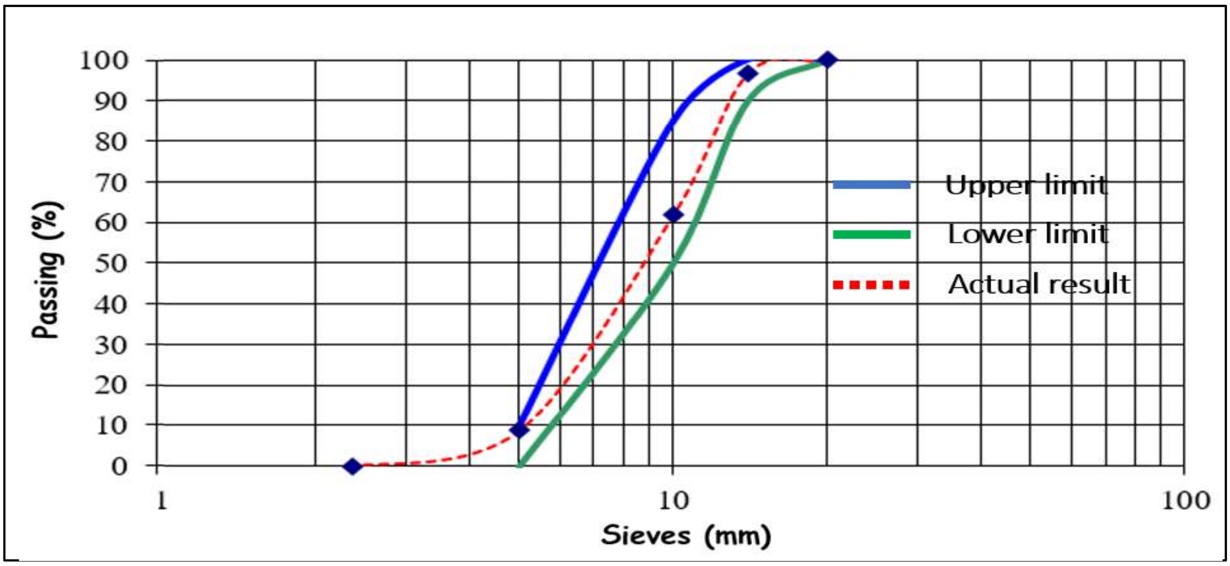


Figure 4.1: Grading curve of coarse aggregates

Figure 4.1 shows the average particle size distribution of coarse aggregate from the smallest to the greatest particle size. The cumulative passing percentage (%) of the 20 mm sieve size was 100%, whereas the 14 mm sieve size was 96.8%. The percentages for the 10- and 5-mm sieve sizes were 61.9% and 8.8%, respectively. The retained percentage mass of the 20 mm,14mm, and 10mm sieve sizes were 0%, 3.2%, and 34.9% respectively, while 5mm and 2.36mm sieve sizes were 53.1% and 8.8% respectively. This result of sieve analysis passes the grading standard of BS 882: 1992 Table 3. The aim of this test was to determine the different fractions of coarse aggregates and the paste requirement for workable concrete.

Various particle size distributions affect the performance of the concrete. For example, if the size of the aggregate is bigger or all uniform, it causes many gaps in the mix which then will require more quantity of binding materials to fill up extra spaces. So, the combination of all different sizes of coarse aggregate results is necessary to minimize voids in concrete.

These findings are similar to the results of (Ajamu & Ige, 2015). They determined that coarse aggregate size correlates to the slump of fresh concrete with a fixed water cement ratio and that concrete strength rises with coarse aggregate size. Strange and Bryant, (1979) also found that when aggregate size increases, fracture toughness of the concrete also increases. But the findings of Gettu and Shah, (1994) showed that for high-strength concrete where the coarse aggregates rupture during fracture, the size of the aggregate does not affect the fracture properties of the concrete. The test findings for the grading curve are given in Appendix A, Table A1.

4.2.2 Specific Gravity of Coarse Aggregate

The mean specific gravity of the coarse aggregate was 2.53. Generally, the specific gravity of coarse aggregates used in construction varies from 2.5 to 3.0, with an average value of around 2.68 (Olanipekun et al. 2006). The relative density of coarse aggregate is the weight of the aggregates dried to a constant weight in an oven at 105 °C divided by their absolute volume, which includes the natural voids within the aggregate particles. Specific gravity is used to calculate the solid volume of aggregates in a concrete mix design. In addition, the importance of specific gravity test is to separate deleterious particles, which are lighter than other particles, from good aggregates. Furthermore, relative density data is crucial for designing hot mix asphalt. Additionally, the specific gravity of the concrete mix is a significant factor that influences the quality and strength of materials. Lower specific gravity aggregates are often weaker than high specific gravity aggregates. Therefore, the specific gravity of coarse aggregate of 2.53 from the test output contributes to the manufacturing of good quality geopolymer concrete with bamboo leaf ash. The test calculations and the obtained results are given in Appendix A3.

4.2.3 Water Absorption of Coarse Aggregate

The result of water absorption as a percentage of dry mass was 0.98 percent. This means a less porous internal structure of coarse aggregates, which leads to higher strength and lower shrinkage during the drying of geopolymer concrete. In terms of limitations, the water absorption limit of coarse aggregates in any climatic condition ranges from 0.1 to 2%. Hence, water absorption provides information about the internal structure of the aggregates. Because aggregates with higher absorption are porous in nature, they are generally regarded as undesirable until they pass strength, impact, and hardness testing. Water absorption can also be measured as asphalt absorption. A high absorbent aggregate may result in a low-durability asphalt mix. So, if the aggregates or concrete has a high rate of absorption when the water freezes and expands, the concrete cannot accommodate the build-up of internal pressure, and pop-outs might occur. The aim of testing the absorption of coarse aggregate is to ensure the aggregates whether they absorb more or less liquid. This affects the amount of alkaline liquid required to mix the geopolymer concrete. Therefore, absorption is essential for deciding the binding to alkaline liquid ratios in geopolymer concrete mix. The result of this experiment is presented in Appendix A3.

4.2.4 Grading of Fine Aggregate

The findings of the gradation of sand particles analysis were used to plot the grain size distribution curve of river sand, as shown in Figure 4.2 below, and the result of the experiments are presented in Appendix A, Table A2.

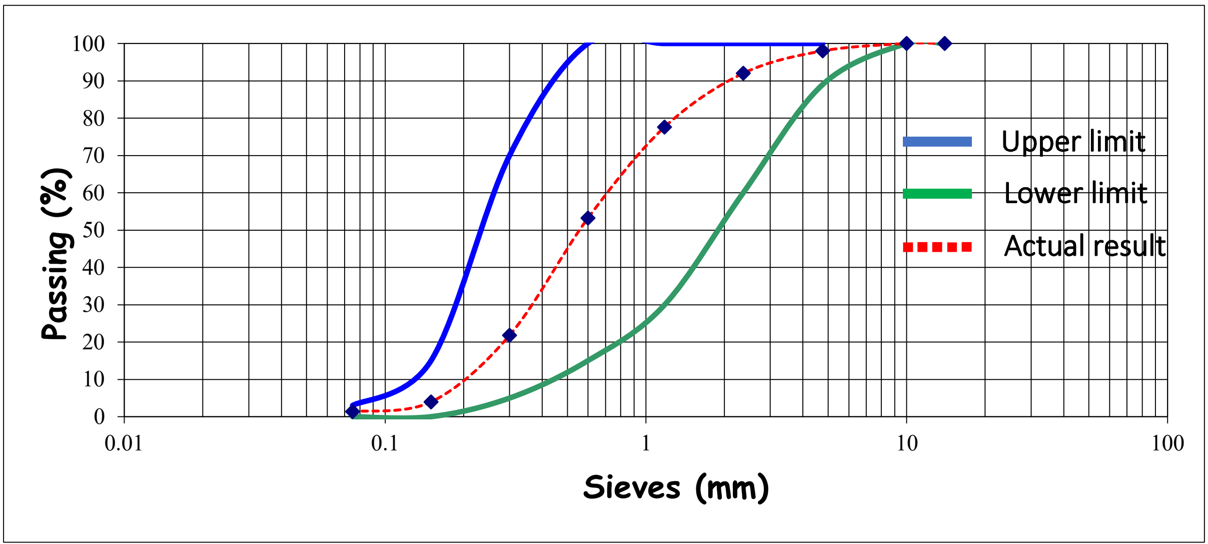


Figure 4.2: Grading curve of river sand

Figure 4.2 illustrates the fine proportion of different grain sizes in river sand. According to the Figure, the total retained percentage above 600 microns was 34.6%, while the retained percentage below 600 microns was 65.4%. This indicates that the grading curve is agreed upon between the upper and lower limits of the grading envelopes. Thus, that means the sand is categorized as zone 2 under B.S. 882-1992 Table 4. The result shows that the sand was fine-graded with a fineness modulus of 2.53. Neville, (1981) suggested that the number of particles smaller than 600 microns in size has a large effect on the workability of the mix ratio and gives a reasonably reliable index on the specific surface of fine aggregates. Good quality sand must have coarse, medium and fine grain sizes, while poorly graded sand composed in one or two of the three possible grain sizes. Meanwhile, in terms of workability well graded sand minimizes the demand for more liquid. Therefore, well-graded sand can lead to producing good geopolymer concrete.

4.2.5 Specific Gravity of Fine Aggregate

The specific gravity of the three samples was 2.65 on average. This finding indicates high specific gravity sand which is suitable for geopolymer concrete mixing and casting. When it comes to the significance of specific gravity, is regarded as an indicator of strength. Aggregates with a higher specific gravity are considered for high strength concrete, whereas aggregates with a lower specific gravity are considered for a weaker strength. The definition of specific gravity is the ratio of the weight of a given volume of aggregate to the weight of an equal volume of water. Water, at a temperature of 73.4°F (23°C) has a specific gravity of 1. On other hand, the specific gravity of the aggregate is utilized in Portland Cement Concrete to determine the percentage of voids and the solid volume of aggregates in yield calculations. The test results are shown in Appendix A, Table A4.

4.2.6 Water Absorption of Fine Aggregate

The result of fine aggregate water absorption was 1.63 percent. The results indicate that it is a suitable absorption fine aggregate in the standard specification range and that it can be used in geopolymer concrete mixing. According to BS 812-2, the absorption of aggregates should not be greater than 3%. The importance of carrying out this test is to check the absorption value of sand, whether it's a high or low absorption rate. High water absorption sand affects the performance of concrete, such as strengths and resistance to exposure conditions. In addition, the higher absorption value of sand can increase the water absorption capacity of the concrete and also influence the fresh properties of the concrete, for example consistency and workability. The result of the experiment is reported in Appendix A, Table A5.

4.3 Hydrometer Analysis of Bamboo Leaf Ash (BLA), OPC, and Fly Ash

This section covers the particle size distribution of BLA, OPC, and Fly ash class F. The particle size distribution (PSD) test of OPC cement was obtained to compare the Bamboo leaf ash (BLA), and class F fly ash particle sizes. Further, the test results were presented in Appendix C, Tables, C1, C2 and C3.

4.3.1 Particle Size Distribution of BLA, OPC, and Fly Ash

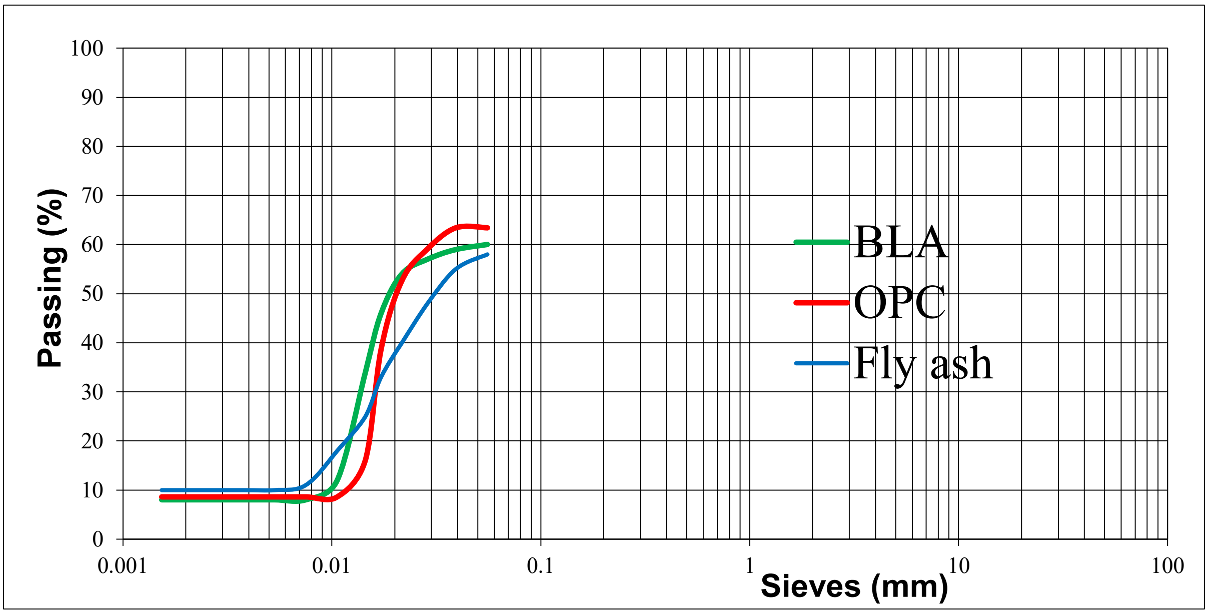


Figure 4.3: Particle size distribution of BLA, OPC, and Fly Ash

Figure 4.3 shows the particle size distribution of bamboo leaf ash, Ordinary Portland Cement (OPC), and class F fly ash. The elapsed time was 24 hours with a meniscus correction of 0.5. The diameter of fine bamboo leaf ash particles ranged from 0.056mm to 0.002mm. While the particle size distribution of fly ash ranged from 0.061mm to 0.002mm. For OPC cement, particle size distribution varied from 0.055mm to 0.003mm. Based on Figure 4.3, the test results of BLA, OPC and Fly ash demonstrates that the particles were well-graded. This means particles in the sizes of 0.06mm, 0.05mm, 0.04mm, 0.03mm, and 0.02mm were observed. The particles of fly ash and bamboo leaf ash have a significant impact on the engineering properties of geopolymer concrete, such as hardening properties, workability, and alkaline liquid-to-fly ash ratios, (Assi et al. 2018). Many articles have been published on the performance and characteristics of bamboo leaf ash (BLA) blended in concrete. However, only limited

information is available on the effect of BLA fineness. This research suggests that the fineness of bamboo leaf ash and fly ash affects the rate of strength gain and enhances the workability of geopolymer concrete. From the literature review, fly ash is classed as sandy silt or silty sand based on its grain size distribution. In particular, fly ash, as the one used in this study, is predominantly silt-sized with some clay-size fraction, according to Pandian et al. (2004).
For literature review, Jamkar et al. (2013), The compressive strength data demonstrate the critical function that fly ash fineness performs in the activation of geopolymer concrete. Workability and compressive strength both increased as the fineness increased.

4.3.1.1 Specific Gravity of Bamboo Leaf Ash (BLA)

The specific gravity of the bamboo ash obtained was 2.12, which is greater than the 1.7 reported by Umoh et al. (2013). This difference may be due to the burning process and the varying chemical compositions of the ash. While the specific gravity of OPC cement and fly ash were 2.3, and 3.14, respectively. This indicates that the specific gravity of OPC cement is more than the fly ash and BLA. The lower specific gravity of bamboo leaf ash (2.12) results in a greater volume of BLA from the mass replacement of fly ash geopolymer concrete. Consequently, the specific gravity of fly ash (2.3) met the acceptable range of class F fly ash, which is between 2.1 and 2.6, (Jala & Goyal, 2006).

According to the review of literature, fly ashes are classed as sandy silt or silty sand based on their grain size distribution. In particular, Indian coal ash is predominantly silt-sized with some clay-size fraction, according to Pandian et al. (2004). For the specific gravity of fly ash, Pandian et al. (1998) reported that the specific gravity of coal ash is commonly around 2.0, but it varies widely, ranging from 1.6 to 3.1. This variance is due to many factors, such as particle shape, gradation, and chemical makeup.

4.4 Chemical Composition of Fly ash, BLA, and OPC Cement

This section relates to the composition of raw materials in order to find detailed information on the materials' characteristics and ensure the resulting products are of the required standards. The test output was presented in Appendix B, Table B1, B2 and B3. Furthermore, the chemical composition of ordinary Portland cement (OPC) was analysed to compare the differences between the chemical molecules of pozzolanic materials and Cementitious material.

Table 4.1 Chemical Composition of Fly ash, BLA, and OPC Cement

No.	Chemical compounds	Abbreviations	Fly ash Class F (%)	Bamboo leaf ash (%)	OPC cement (%)
1.	Silicon dioxide	SiO_2	61.6	82.03	25.3
2.	Aluminium oxide	$Al2O_3$	29.88	2.65	5.0
3.	Ferric oxide	Fe_2O_3	12.7	2.63	1.2
4.	Calcium oxide	CaO	1.452	5.32	62.04
5.	Magnesium oxides	MgO	2.0	1.67	0.03
6.	Potassium oxides	K_2O	0.55	3.69	0.45
7.	Sulphur	SO_3	0.5	0.95	2.47
8.	Titanium dioxide	TiO_2	1.5	0.52	-
9.	Manganese (II) oxide	MnO	-	0.17	-
10.	Loss on ignition	LOI	1.61	-	1.27

Table 4.1 shows the chemical composition of class F fly ash, bamboo ash (BLA), and Ordinary Portland Cement. For fly ash the result of silicon dioxide (SiO_2) was 61.16%, while the aluminium oxide (Al_2O_3) was 29.88%. And the calcium oxide (CaO) content was 1.452 percent, which is less than 10 percent, indicating that class F fly ash (pozzolanic material) has a small calcium oxide content when compared to ordinary Portland cement (62.04%). The SiO_2, $Al2O_3$, and CaO contents of OPC cement were 25.3%, 5%, and 62.04% respectively. This shows the difference between pozzolanic materials and Cementous materials. It's worth noting that silica (61.6%) and alumina (29.8%) of fly ash are essential components for the production of geopolymer concrete.

The chemical makeup of fly ash, especially SiO_2, Al_2O_3 and Fe_2O_3, is important for the formation of a geopolymer concrete (GPC) network (Si-O-Al), (Mishra et al. 2022). The high aluminium silicone content affects the geopolymerization process as well as the mechanical, physical, and durability properties of GPC, Kupwade et al. (2013). The role of (SiO_2) and (Al_2O_3) in geopolymer formation is the reaction with alkaline activators (Na_2SiO_3 and NaOH) for the geopolymerisation process. Ferric oxide (Fe_2O_3) is responsible for the dark colour of fly ash. Calcium oxide (CaO) generates CSH and CASH gels during the polymerisation process of a geopolymer paste, and these gels contribute to a boost in strength and a decrease in setting time (Wattimena et al. 2017). According to Table 1 of ASTM 618, the chemical composition of pozzolanic material consists mainly of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), ferric oxide (Fe_2O_3), and magnesium (MgO). While calcium oxide, potassium, sodium, sulphur, and other molecules are present in smaller proportions. The physical characteristics and chemical makeup of fly ash are contingent upon the combustion process, type of particle ash, and coal source. The chemical makeup of different fly ashes demonstrates the considerable variation in coal used in power plants throughout the world (Malhotra & Ramezanianpour, 1994).

For bamboo leaf ash (BLA), the main constituents were SiO_2, Al_2O_3, and Fe_2O_3, CaO, MgO, and K_2O. TiO_2, MnO, and SO_3 have concentrations of less than 1%. The silicon dioxide percentage was 83.03 percent, indicating that it had a higher concentration than cement and fly ash. Silica reacts with calcium hydroxide at normal temperatures to form compounds having cementitious characteristics that contribute to the hardening of geopolymer concrete. Aluminium oxide gives the concrete rapid setting time and has a high enough acidity to support the pozzolanic reaction. The ASM 618 specifies that pozzolanic materials, whether calcined ash or industrial products, should have less than 10% calcium oxide (CaO) content. This result shows calcium oxide content of 5.32%, which is less than 10%.

This result for bamboo ash is similar to that found by Silva et al., (2021). Oxides such as SO_3, TiO2, Cl, and MnO also showed contents below 1%. This was also observed by Villar et al., (2011), who concluded that the silicone content of bamboo leaf ash ranges between 75 -84 %. Based on these test results of BLA, this study suggests that bamboo leaf ash can be used pozzolanic constituent of geopolymer concrete (GPC).

4.5 Workability of Geopolymer Concrete (GPC)

This section discusses the fresh properties of GPC evaluated employing a conventional slump cone and compaction factor apparatus. Based on visual observations, all the mixtures were typically cohesive and shiny due to the incorporation of sodium silicate, as illustrated in Figure 4.4. The ratio of alkaline liquid to binder was set to 0.6, and the ratio of (Na_2SiO_3) to (NaOH) was fixed at to 2.5. In addition, this test is essential for producing concrete with the proper consistency by assessing whether the geopolymer concrete is more or less alkaline liquid, which directly affects the strength and durability performance of GPC. The slump and compaction factor results are presented in Appendix D, Tables D1 and D2, respectively.

Figure 4.4: Appearance of geopolymer concrete mixtures

4.5.1 Slump

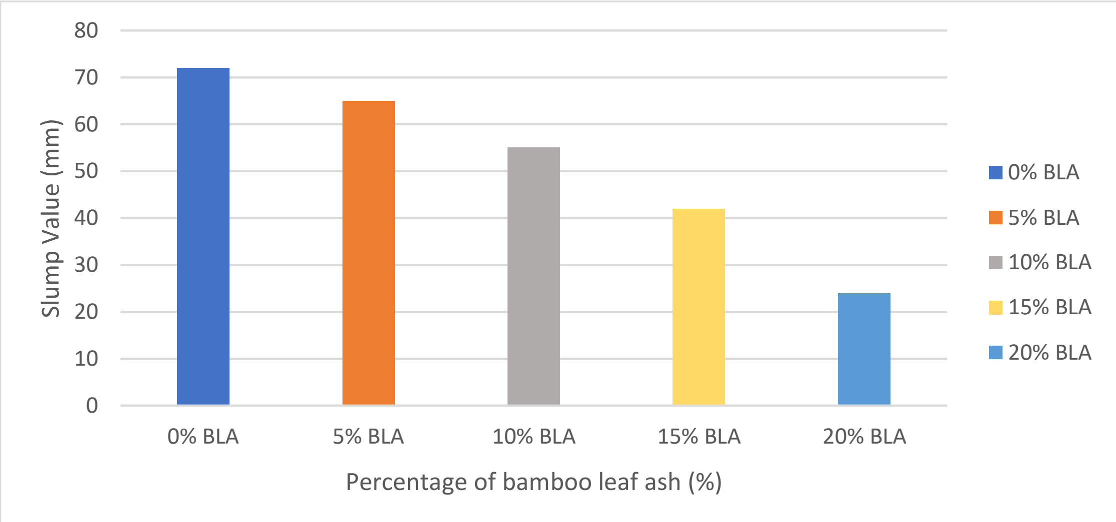


Figure 4.5: Effect of bamboo leaf ash on slump

Figure 4.5 shows the workability of geopolymer concrete with various percentages of bamboo leaf ash (BLA). The slump values at 0% and 5% BLA were 72 and 65 mm, respectively. While 10% and 15% BLA were 55 and 42 mm, respectively, and for 20% BLA, it was 24 mm. Thus, the slump results indicates that the increased percentage of bamboo leaf ash gradually reduces the slump values. This is because geopolymer concrete, which includes bamboo leaf ash requires more liquid for a given consistency. And also due to the absorbent characteristics of the cellular bamboo leaf ash particles and their high fineness which increases their specific surface area. Dhinakaran et al. (2016). The workable mixture with the highest flow was achieved when the ratio of activator to binder was 0.6 with 0% BLA. Also, it was found that the larger percentage of BLA as the partial substitute for fly ash required more alkaline liquid to attain the desired slump.

Based on limited studies on the workability of GPC, (Saloma et al., 2017), an empirical study was conducted using fly ash in combination with rice husk ash. And the workability test results indicated that the impact of using fly ash and rice husk ash as a precursor on workability decreases the flow diameter with a boost in rice husk ash (RHA) amount. For this study fly ash combined with bamboo leaf ash (BLA) demonstrated that increasing the content of BLA in geopolymer concrete made the concrete harder and less workable. Considering this, using bamboo ash on the geopolymer concrete may require the use of superplasticizers and accelerating admixtures to improve the workability. Adding superplasticizers or other admixtures that enhance the workability of geopolymer concrete containing bamboo ash represents a research opportunity and a possible research gap for further research.

4.5.2 Compaction Factor

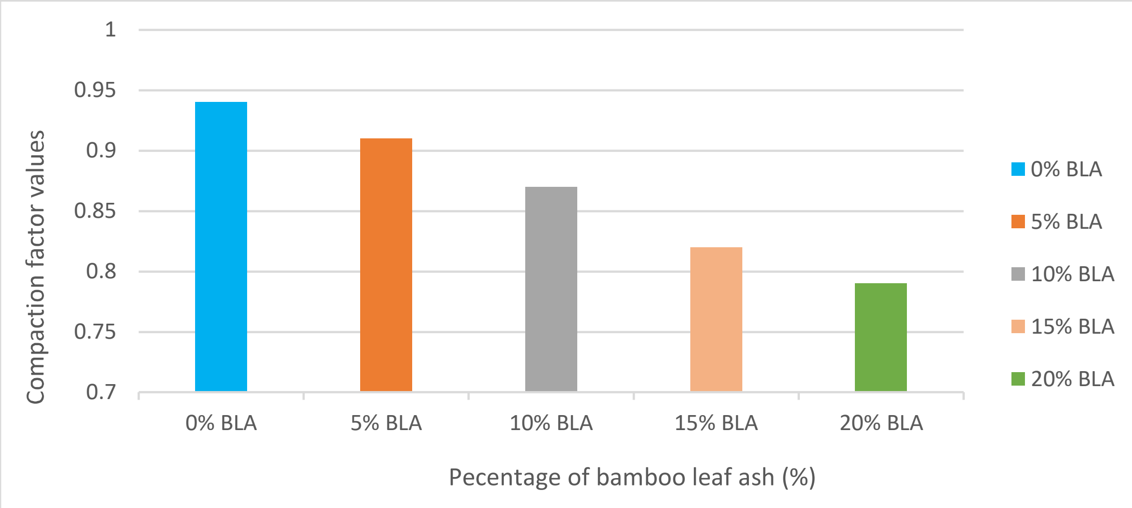


Figure 4.6: Effect of bamboo leaf ash (BLA) on compaction factor

Figure 4.6 shows the impact of bamboo leaf ash (BLA) on geopolymer concrete's compaction factor. The compaction factor value for 100% fly ash (FA) was 0.94, whereas 95%, 90% FA, plus 5%, and 10% (BLA) compaction factor values were 0.91 and 0.87, respectively. Additionally, the compacting values for 85%, 80 per cent FA, plus 15 and 20 per cent BLA were 0.82 and 0.79, respectively. As the quantity of bamboo leaf ash develops from 0% to 20%, the compaction factor values of geopolymer concrete decrease from 0.94 to 0.77 gradually. These findings of the compaction factor values demonstrate that 100% fly ash (FA) and 0% BLA have higher workability than mixes containing BLA. This could be due to the spherical-shaped particles of fly ash functioning as miniature ball bearings within the concrete mix, thereby providing a lubricant effect. It is also worth noting that this test aimed to assess how well fresh geopolymer concrete works about the external energy needed to suitably compact concrete. Mishra, (2017) reported that the compaction factor test is more useful for concrete mixes which have low workability for which the slump test is not suitable.

4.6 Mechanical Properties of Geopolymer Concrete at Ambient Curing Temperature

This section discusses the strength of hardened geopolymer concrete. The strengths attained during 28, 56, and 90 days on geopolymer with BLA concrete are investigated experimentally. In order to determine the maximum load that each sample cube and cylinder can withstand before breaking. The mean compressive and splitting tensile strength results are presented in Appendix E, Tables E1 and E2, respectively.

4.6.1 Compressive strength at Ambient Curing Temperature

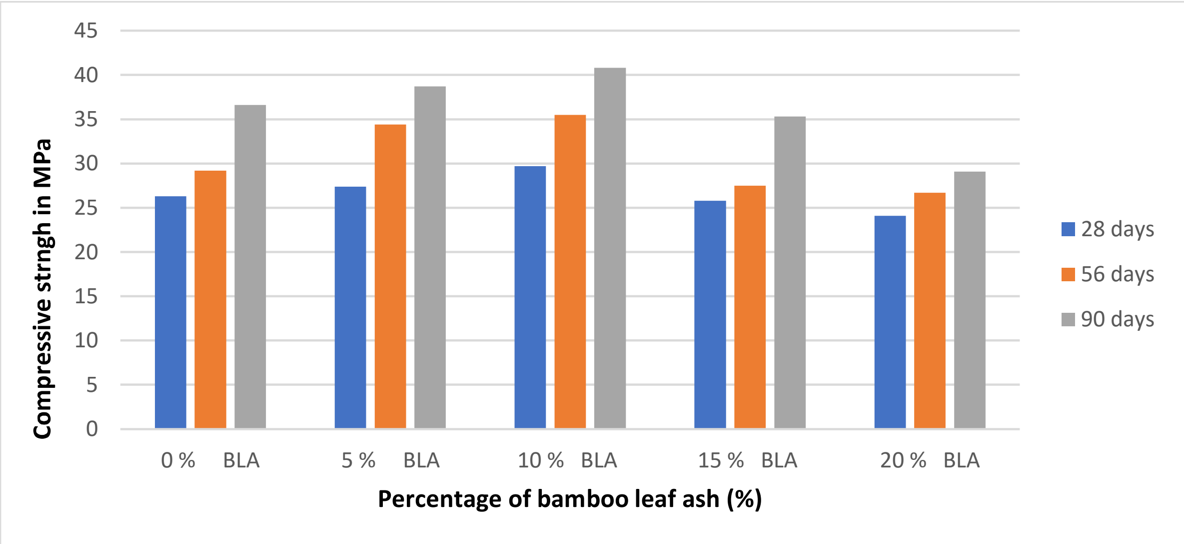


Figure 4.7: Effect of BLA on the compressive strength of GPC

Figure 4.7 demonstrates the influence of bamboo leaf ash (BLA) replacing fly ash on the compressive strength of geopolymer concrete. Compressive strength for 0%, 5%, and 10% BLA at 28 days of room temperature curing was 26.3, 27.4, and 29.7 MPa, respectively, while 15% and 20% BLA were 25.8 and 24.1 MPa. Furthermore, at 56 days for 0%, 5%, and 10% BLA, the compressive strength was 29.2, 34.4, and 35.5 MPa, respectively, while 15% and 20% BLA were 27.5 and 26.7 MPa. At 90 days, the compressive strength for 0%, 5%, and 10% BLA was 36.6, 38.7, and 40.8 MPa, whereas for 15% and 20% BLA, it was 35.3 and 29.1 MPa. The test findings show that the strength rises with the increase in curing days at ambient curing temperature. The reason behind this is the polymerization process of (alumina & silica) from the binder with the alkaline solution. (Deraman et al. 2017). This means that when alumina and silica react with an alkaline activator solution, (NaOH) and (Na_2SiO_3) create a three-dimensional network, giving the geopolymer bonding capacity and hardening. Additionally, the molarity of (NaOH) and the ratio of (Na_2SiO_3/NaOH) have a substantial impact on the increment and reduction of the strength of geopolymer concrete. For instance, previous research (Olivia et al. 2012), the higher molarity of NaOH between 12 to 16 molar exhibits an increase of strength due to the dissociation of the active species of raw material and yielding formation of more geopolymer gel network. While the lower molarity of NaOH indicates lower strength.

Meanwhile, (Değirmenci, 2017) if the ratios of (Na2SiO3/NaOH) increase by 2.5 to 3 the strength decreases due to the higher alkaline content which slows the process of the polymerization reaction. After 90 days, replacing 5% and 10% of bamboo leaf ash to fly ash exhibits a higher compressive strength of 40.8 MPa and 38.7 MPa compared to the other mix and curing days. Replacement of 0% and 20% BLA at 28 days had the smallest compressive strength, with values of 26.3 and 24.1, respectively. The compressive strength progressively increases up to 10% BLA. This is due to the higher content of silicon dioxide SiO_2 (83.03%) that contained the calcined bamboo leaf ash. Then, the strength decreases gradually as the bamboo leaf ash content exceeds 10% BLA, for instance, a mixture of 15% and 20% BLA. The main reason for this is that the large proportion of bamboo ash content in geopolymer concrete causes the absorption of more alkaline solutions, which decreases the compressive strength of GPC (Yin et al. 2022).

From previous studies, geopolymer concrete that contained fly ash class F as the primer binder had low early compressive strength at ambient temperatures curing (Nath et al. 2015). This is due to the fly ash (Class F) having a small composition of calcium oxide (CaO), which is important for the early development of strength (Hannesson et al., 2012). In this study, the lower calcium oxide (CaO) content of fly ash (1.43%) and calcined bamboo leaf ash (5.32%), curing takes place through a polymerization process with the presence of an alkaline solution to achieve the final product for the hardening and strengthening of the geopolymer concrete. Geopolymer concrete contained pozzolanic materials with a large content of (CaO) such as grand granulated blast furnace slag (GGBS) mixed with fly ash the curing occurs with both heat of hydration and polymerization process to achieve the final product of geopolymer concrete (Patarea et al. 2019). This is how this research work on geopolymer concrete differs from geopolymer concrete for the previous studies.

In order to examine the response and behaviour of geopolymer concrete with low calcium content pozzolanic materials on strength and hardening. In this research, geopolymer concrete containing fly ash (Class F) and bamboo leaf ash were used as a binding material at normal curing temperature. The higher silicon contents of fly ash (61.6%) and bamboo leaf ash (82%)

provided a significant increase in compressive strength due to the "polycondensation" of silica and alumina precursors with alkali content. This study suggests a maximum percentage of bamboo ash to replace a part of fly ash in geopolymer concrete not higher than 10% where the compressive strength is a major concern.

4.6.2 Splitting Tensile Strength at Ambient Curing Temperature

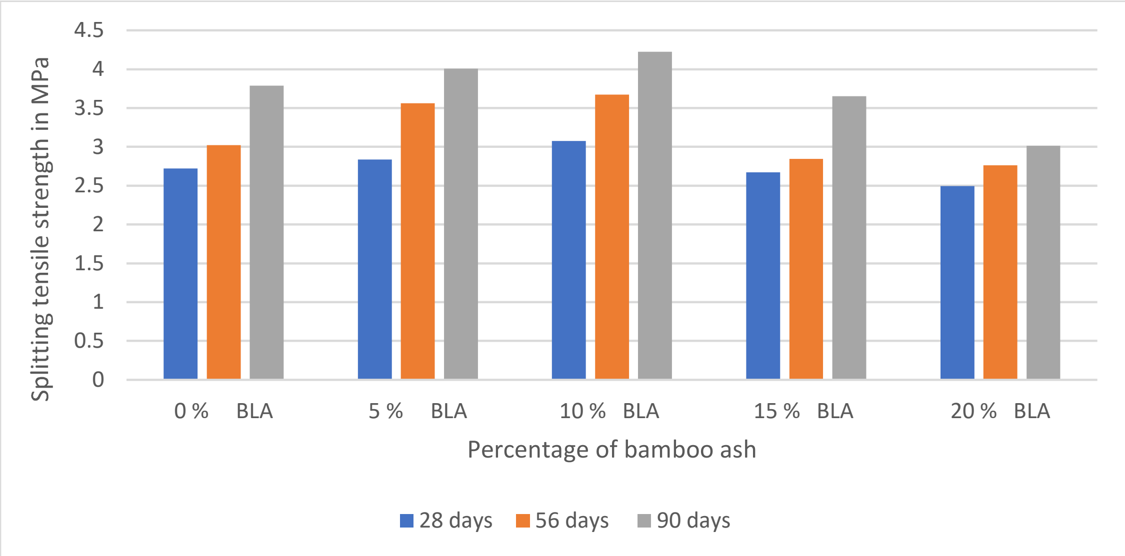


Figure 4.8: Impact of BLA on the splitting tensile strength of geopolymer concrete

Figure 4.8 shows the influence of bamboo leaf ash on the splitting tensile strength of geopolymer concrete. In 28 days, the splitting tensile strength of 100% FA and 0% BLA was 2.7 MPa, while 95%, 90% FA, and 5%, 10% BLA were 2.83 and 3.07 MPa, respectively. For 85%, 80% FA, and 15%, 20% BLA content, the splitting tensile strength was 2.67 and 2.4 MPa, respectively. The splitting tensile strength at 56 days for 0% and 5% BLA were 3.02 and 3.5 MPa, while for 10%, 15%, and 20%BLA were 3.67, 2.84, and 2.76 MPa, respectively. For 90 days, the splitting tensile strength of 0% and 5% BLA was 3.7 and 4 MPa, while, for 10%, 15%, and 20% BLA, it was 4.2, 3.65, and 3.01 MPa, respectively. The optimum strength recorded was 4.2 MPa for 90% of fly ash and 10% of bamboo ash at 90 days of ambient curing temperature. The geopolymer splitting tensile strength increases with longer curing durations. This is because of the higher content of silicon dioxide (SiO_2) in the fly ash utilised in this research (61.6%) and bamboo leaf ash (82%) which delays the polymerization process when it reacts with alkaline activators.

Pozzolanic materials that are dissolved with alkaline activators and have low calcium (CaO) content require enough time for ambient curing temperature. This is why the pozzolanic reaction strength was enhanced gradually over a longer period of time (Saha, 2018). The strength keeps improving after 90 days. Geopolymer concrete strength development depends on the chemical composition and physical properties of pozzolanic materials. From the result in Figure 4.8, the increasing percentage of split tensile strength at 90 days was 5.5% for the 5% and 10% BLA, while the decline proportion was 17.8% at 15% and 20% BLA. This is because of the high percentage of bamboo ash content in geopolymer concrete which lead to the absorption of more alkaline liquid, resulting in lower strength (Yin et al. 2022). Mixtures containing 5% and 10% BLA attained the optimum tensile splitting strength of 4 and 4.22 MPa after 90 days, whereas the lowest split tensile strength was 2.4 MPa, for the 20% BLA content at 28 day.

The geopolymer concrete strength is boosted when the sodium silicate (Na_2SiO_3) content is increased (Hardjito & Rangan, 2005; Shaikh, 2014). For this research, the (Na_2SiO_3/NaOH) ratio was 2.5 and exhibits a significant effect on the strengths of the geopolymer with bamboo leaf ash. There exists limited research on the effect of sodium silicate to sodium hydroxide (Na_2SiO_3/NaOH) ratio on the mechanical properties of geopolymer concrete based on fly ash incorporating bamboo leaf ash. Research of geopolymer concrete with bamboo leaf ash containing different Na_2SiO_3/NaOH in varying ratios may be an opportunity for future study.

4.7 Durability of Geopolymer Concrete (GPC)

This section discusses the durability performance of GPC with bamboo leaf ash (BLA). The permeability has been determined through measurements of water absorption. Additionally, the chemical attacks that have been evaluated were parameters related to sulphate resistance ($MgSO_4$), acid resistance (H_2SO_4), and chloride attack (NaCl). Sathia et al. (2008) reported that geopolymer is a new material that is being used for construction all over the world. As a new construction material, there is limited data on the durability of geopolymer concrete (GPC). Thus, ASTM (C1012), ASTM (C-267) and BS EN 1881-122(1) 1983 standard specifications and guidelines from previous studies were employed. In order to determine the effects of BLA as a replacement for fly ash in the geopolymer concrete with a Class 25 target mix proportion. The test findings were compared with samples before and after soaking in a 5% solution of $MgSO_4$, H_2SO_4, and NaCl exposure. In Appendix F, Tables F1, F2, F3, and F4 respectively are presented the test results of the durability.

4.7.1 Water Absorption

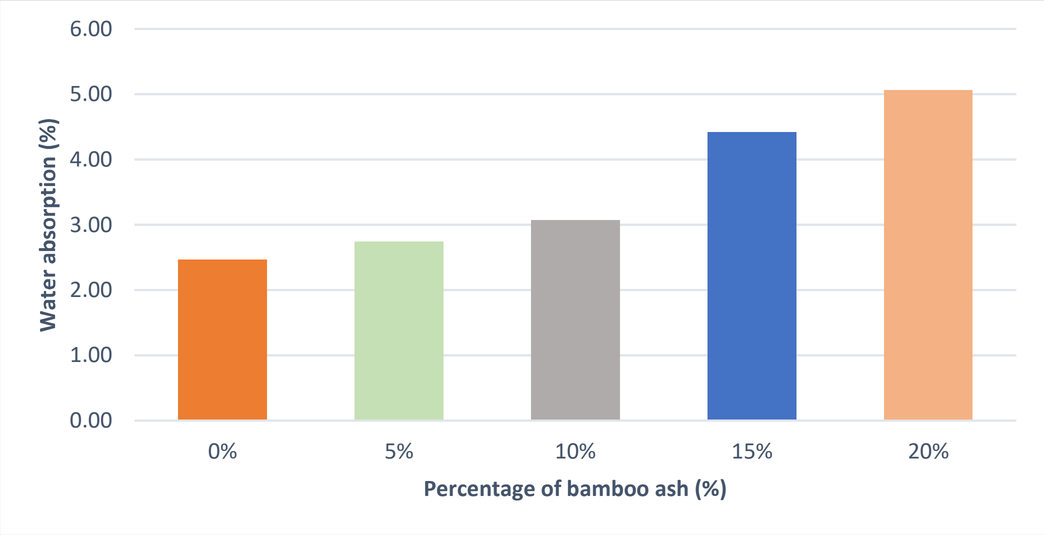


Figure 4.9: Water absorption of geopolymer concrete after 28 days

Figure 4.9 shows the effect of bamboo leaf ash on water absorption of geopolymer concrete after 28 days. The average absorption value for 0% BLA and 100% FA was 2.46%, whereas for 5% BLA and 10% BLA was 2.75% and 3.07%, respectively. Additionally, the absorption values for 15% BLA and 20% BLA were 4.42 and 5.06 %, respectively. The control sample, 0% BLA, showed the lowest absorption rate of 2.46 compared to the other mixtures containing BLA. This is because of the lower porous structure of fly ash that reduces the permeability by forming calcium silicate hydrate ($CaH2O4Si$) leading to the blocking of gel pores and consuming more calcium hydroxide (CH). Which finally results in the decrease of the breaking down of concrete (Moradikhou & Esparham, 2021). This means the higher formation of calcium silicate hydrate ($CaH2O4Si$) of the fly ash reduces the ingress of water air and other substances that influence the performance of the concrete (Deventer et al. 2003). As shown in Figure 4.9, 85% and 80% of fly ash, with 15% and 20% BLA respectively, exhibit the increased absorption values of the geopolymer concrete. This is because the specimen has a larger volume of bamboo leaf ash, which creates a number of pores that enable liquid to pass through the specimen (Gangava et al. 2016). From the test results, it can be seen that the water absorption of geopolymer concrete mixtures prepared using 0%, 5%, and 10% BLA was a lower absorption value compared to other percentages of bamboo leaf ash. This is caused by the cellular bamboo leaf ash particles' absorbent properties and high fineness (which enhances their specific surface area and leads them to absorb more liquid), according to Dhinakaran et al (2016). However, the significance of the water absorption test which indirectly reflects the permeability of geopolymer concrete is to control the water absorption rate of both the inner and outer concrete surfaces.

The capacity of concrete to hold or absorb the water is significantly affected the durability of the structure. More test results of water absorption after 28 days are shown in Appendix F, Table F1.

Based on previous water absorption of geopolymer studies, the capacity of geopolymer concrete to absorb water has a considerable impact on the durability the structure of the concrete. The ingress of water into the GPC leads the pore structure. Thus, porosity is one of the main significant parameters that directly affect the durability and strength of concrete, (Odler & Rößler, 1985). And also, as reported by Abdullah et al. (2018), the amount of water that geopolymer concrete can absorb declines a little as sodium hydroxide molarity rises. This is due to the concentration of sodium hydroxide solution increasing the leaching of silica and alumina ions as well. This indicates that enough Si^{4+} and Al^{3+} ions facilitate for the formation of additional aluminosilicate gel and the reduction of geopolymer pores, thereby lowering the raw materials' water absorption (Memon et al. 2013).

In summary, It was found that the water absorption of geopolymer concrete containing bamboo leaf ash (BLA) increases with an increase in BLA content. Therefore, the test result concluded that geopolymer concrete containing bamboo leaf has good resistance to water penetration from up to 15% compared to 20% of bamboo leaf ash.

4.7.2 Sulphate Resistance

Sulphate ions is one of the elements that contribute to the degradation and destruction of concrete structures worldwide. When sulphate salt penetrates concrete, it causes a negative impact and creates new compounds that lead to micro-cracks. The expansion and deterioration of concrete is caused by the reaction of C3A with sulphate ions in hardened cement in the presence of calcium hydroxide resulting in ettringite and gypsum (Neville, 2000). By lowering the content of calcium aluminate (C3A) and calcium hydroxide (CH), which inhibits the production of harmful chemicals like gypsum and ettringite, the application of SCMs as cement replacement materials can aid in the mitigation of sulphate attacks (Neville, 2019). This means the utilize of pozzolanic materials such as geopolymer technology can significantly lessen the impact of chemical attacks when compared to conventional concrete. According to Davidovits (1990), geopolymer has superior durability, significant early strength, and no harmful alkali-aggregate reaction. Therefore, this test was carried out to determine the effect of 5% magnesium sulphate ($MgSO_4$) solution on geopolymer concrete containing various amounts of bamboo ash. The exposure solution was a 5% solution of magnesium sulphate ($MgSO_4$). The main parameters studied included the assessment of changes in mass, variations in appearance, and versions of compressive strength after 28days, 56days, and 90 days of immersion. The test findings are summarized in Tables F2-A and F2-B in Appendix F.

4.7.2.1 Change in Mass under Magnesium Sulphate Exposure Solution

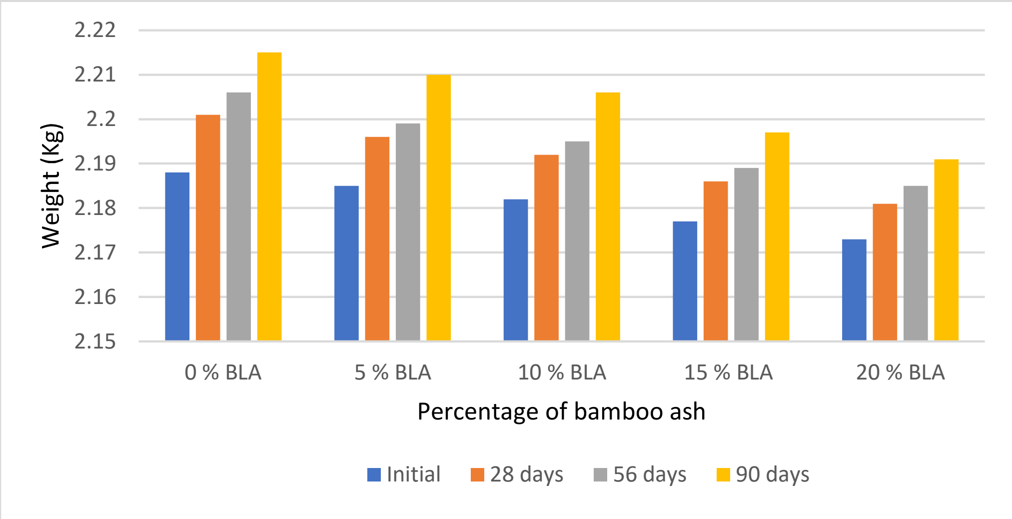


Figure 4.10 (a): Mass change after immersing in a 5% $MgSO_4$ exposure solution

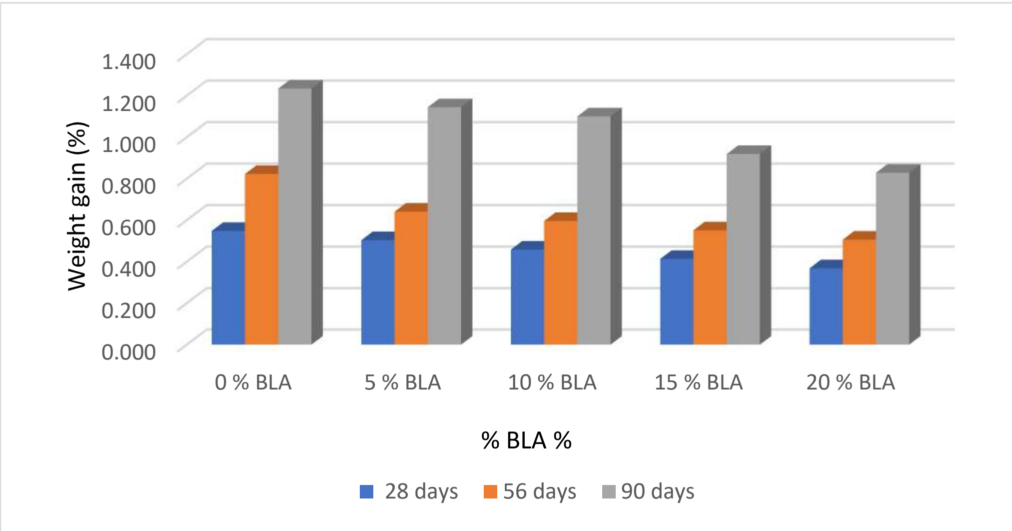


Figure 4.10 (b): Percentage of weight gain under 5% $MgSO_4$

Figure 4.10 (a) demonstrates the change of mass after immersing in magnesium sulphate ($MgSO_4$) solution. The initial weight (before exposure solution) at 28 days for 0% and 5% BLA was 2.188 and 2.185, respectively, while for 10%, 15%, and 20%, it was 2.182, 2.177, and 2.173Kg, respectively. After 28 days of immersion in solution, the change in mass at 0%, 5%, and 10% BLA was 2.201, 2.196, and 2.192kg, whereas the 15% and 20% BLA were 2.186 and

2.181kg, respectively. At 56 days, the change of mass at 0% and 5% BLA was 2.206 and 2.199kg, whereas at 10%, 15%, and 20% BLA it was 2.195, 2.189, and 2.185kg, respectively. After 13 weeks of exposure solution, the change mass at 0%, 5%, and 10% BLA was 2.215, 2.210, and 2.206kg, while the changes at 15% and 20% BLA were 2.197 and 2.191kg, respectively. As shown in Figure 4.10 (a), the test result indicates that little mass develops as the duration of exposure solution increases. This is because of the solution ($MgSO_4$) reacting with geopolymer concrete products, filling the material pores and increasing its mass due to absorption of the exposed liquid. On other hand, based on Figure 4.10 (b), the maximum weight gain recorded was 1.2% for 0% BLA at the age of 90 days of exposure solution compared to the actual weight. While the lowest weight gain recorded was 0.4 % for 28 days at 20% BLA compared to the other mixtures. Thus, the mass changes ranges after immersion the 5% $MgSO_4$ solution was ranges 0.4% to 1.2%. Thus, the observed mass change was very little, ranging from 0.4% to 1.2% compared to the actual weight. This is due to the high ratio of Na_2SiO_3 to NaOH (2.5) and the high concentration of sodium hydroxide (16 M). Both these can control sulphate attacks in external and physical damage to the geopolymer concrete. This means when external sulphate attack ions $(SO_4)^{+2}$ occur, they directly get into the geopolymer concrete samples and react with the alumina silicate network (SiO_2-AL_2O_3). So, the structure of 3D aluminium silicate chains is hence resistant to the destruction of sulphate ions $(SO_4)^{+2}$ (Davidovits 1999). In contrast, when sulphate ions attack normal concrete, they interact with C_3A and cause expansion and cracks, which increase the concrete's mass Neville (2000). Sulphate attack often occurs when aggregates of concrete, both fine and coarse, contain a high concentration of sulphates as well as sewage, seawater, marshland, and industrial influences. Because the solid sulphate salts do not interact with concrete. In a literature review, geopolymer samples exposed to magnesium sulphate surpass conventional concrete (Rajamane et al. 2012).

4.7.2.2 Strength Variation under Magnesium Sulphate ($MgSO_4$) Solution

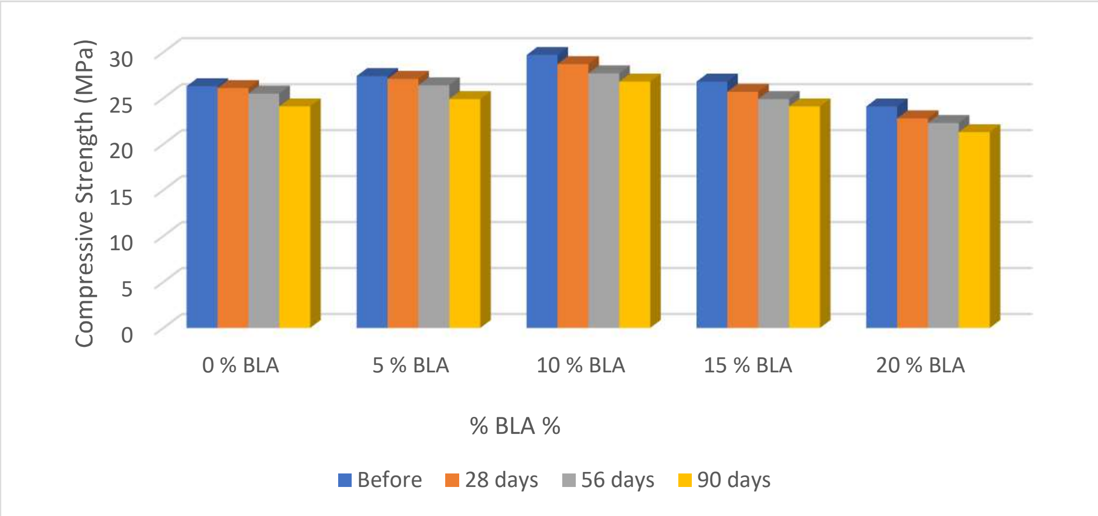


Figure 4.11(a): Variation of compressive strength after soaking in $MgSO_4$ solution

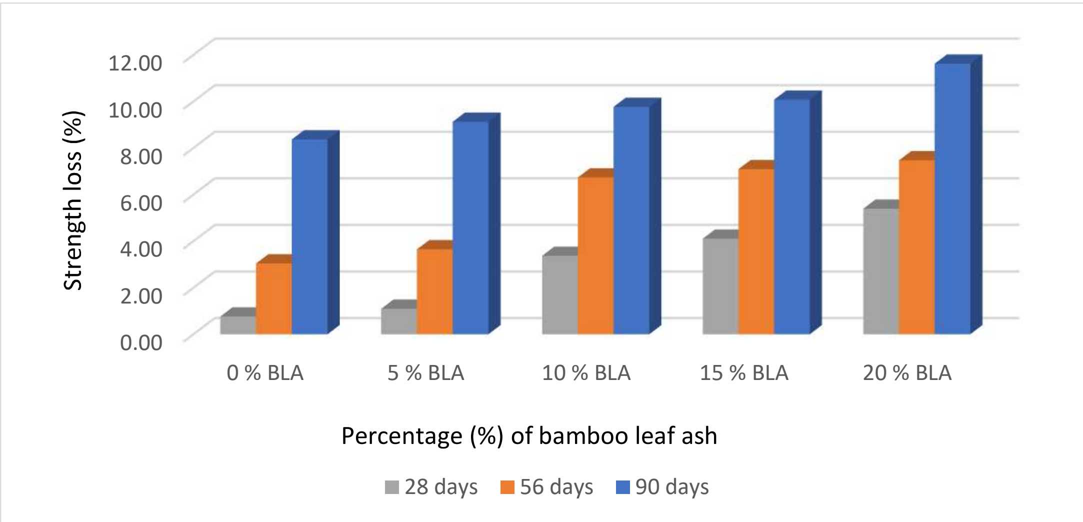


Figure 4.11 (b): Percentage loss of compressive strength under 5% $MgSO_4$

Figure 4.11 (a) depicts the variation in compressive strength under the (5% $MgSO_4$) salt solution after 28, 56, and 90 days. Before immersing the chemical exposure after 28 days, the compressive strength at 0%, 5%, 10%, 15%, and 20% BLA was 26.3, 27.4, 29.7, 26.8, and 24.1 MPa, respectively. At 28 days, after immersing in a 5% $MgSO_4$ solution, the variation of actual strength of 0%, 5%, and 10% BLA was 26.1, 27.1, and 28.7 MPa, respectively, while the 15% and 20%BLA were 25.7 and 22.8 MPa. On 56 days, the change of actual strength for 0% and 5% BLA was 25.5 and 26.4 MPa, whereas the 10%, 15%, and 20% BLA were 27.7, 24.9, and 22.3 MPa, respectively. The variation in compressive strength after 90 days for the 0%, 5%, and 10% BLA was 24.1, 24.9, and 26.8 MPa, whereas the 15% and 20% BLA changes were 24.1 and 21.3 MPa, respectively. These results in Figure 4.11(a) demonstrate the minor change in compressive strength of geopolymer concrete incorporating various percentages of bamboo leaf ash. This might be due to the strong bonding between the aggregates and alkaline liquid. It was also observed that the strength improved slightly at 10% BLA compared to the other percentages of BLA of exposure curing days. This is because of the workability of 10% BLA, and 90% of fly ash mixtures was (55mm). This means the absorption of alkaline liquid for 10% BLA mixtures was medium compared to other percentages of BLA. That is the main reason of the strength increases from 0% BLA, 5%BLA, and 10% BLA, and then decreases for 15%BLA and 20% BLA due to their higher absorption of alkaline solution.

Figure 4.11(b) shows the loss of compressive strength under a 5% magnesium sulphate salt solution. The highest percentage loss in compressive strength observed was 11.62% after 90 days for 20% BLA. While the lowest loss percentage in compressive strength under 5% $MgSO_4$ salt solution was 0.76% after 28 days for 0% BLA. Hence, the test results for Figure 4.11 (b) indicate that the loss increases with the age of curing days under 5% magnesium sulphate ($MgSO_4$) solution in the range of 0.76% to 11.62%. This is due to the intrinsic nature of aluminosilicate gels of geopolymer concrete constituent materials. This indicates that pozzolanic materials of geopolymer have less effect on the salt ions of $MgSO_4$ compared to OPC cement. This means the absence of tricalcium aluminate (C3A), which is often present if OPC is used (Bondar, 2009). Geopolymers' resistance to sulphate attack depends on the type of alkaline activator and the method of curing (Bakharev 2005; Shi et al. 2006).

Previous studies that try to find the behaviour of geopolymers subjected to sulphate-rich solutions have reported conflicting findings in compressive strength. (Bakharev, 2005), claimed that strength loss of geopolymer concrete under sulphate solution. While, Ding et al. (2004) reported that strength gain of geopolymer exposed magnesium sulphate and sodium sulphate salt solution.

4.7. 2.3 Change in Appearance under a 5% Magnesium Sulphate ($MgSO_4$) Solution

Figure 4.12 (a) Appearance before immersing the chemicals

Figure 4.12 (b) Change in appearance after 28 days under 5% $MgSO_4$ solution

Figure 4.12 (c) Change in appearance after 56 days under 5% $MgSO_4$ solution

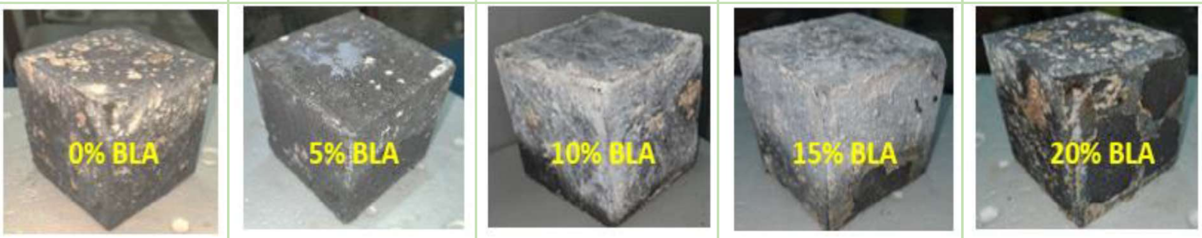


Figure 4.12 (d) Change in appearance after 90 days under 5% $MgSO_4$ solution

Figure 4.12(a) illustrates the appearance of geopolymer concrete specimens without the chemical soaking exposure solution after 28 days. In addition, the effects of 5% magnesium sulphate solution on the appearance of GPC with BLA specimens after 28, 56, and 90 days are shown in Figures 4.12(b), 4.12(c), and 4.12(d), respectively. Hence, little spalling was seen after 90 days of immersion in a 5% $MgSO_4$ on the top surface of the specimens, especially for 15% and 20% BLA. This may be due to the higher volume of bamboo ash that contained these specimens, about 15% to 20% BLA. But in general, the test result indicates that there was no significant change in the appearance of geopolymer specimens based on Figures 4.12(b), 4.12(c), and 4.12(d) appearances. This is due to the fact that geopolymer concrete does not have calcium hydroxide Ca(OH)2 which reacts with the carbon dioxide (CO_2) that causes the carbonation and deterioration of the geopolymer concrete (Temuujin et al. 2009). The salt of $MgSO_4$ solution penetrates the pores of the specimens (bug holes) and creates a new compound which causes damage to the appearance due to salt crystallization. Salt crystallization is the efflorescence of salt that comes after the long curing of solution and results scaling of concrete. So, the salt first tries to interact with the C-S-H formation of the fly ash by destroying the 3D alumina silica chain, which leads to spalling deterioration and cracking. (Singh et al. 2019) and (Metha, 2000). Thus, the greater content of high alumina and silica makes geopolymers high resistance for the impact of sulphate ions (SO_4^{2}) into the interior of the specimen.

In summary, fly ash incorporating bamboo leaf ash (BLA) content indicated minor changes in mass, strength and appearance when the samples were exposed to a 5% magnesium sulphate (MgO_4) solution. Therefore, it is suggested that bamboo leaf ash be used as a geopolymer in concrete not more than 0% to 15% BLA to replace part of fly ash if the magnesium salt attack is the major problem.

4.7.3 Acid (H_2SO_4) Resistance

The sulphuric acid resistance test of geopolymer concrete with bamboo leaf ash was evaluated in terms of weight loss, change in compressive strength, and visual appearance change. Acid attack is the chemical reaction between the acid and calcium hydroxide $Ca(OH)_2$ of hydrated cement. The damage level of an acid attack depends on the PH value, the concentration of the acid solution, and the vulnerability of concrete. Usually, acid attack occurs in the action of sewers, drainage, contaminated groundwater, and industry exposure. If the acids can penetrate the concrete through the porosity, they can cause corrosion of the steel reinforcement as well as the expansion, spalling, and swelling of the concrete structure. To mitigate this problem with the concrete structure, geopolymer concrete is the best solution due to the three-dimensional polymeric chain that can resist chemical attack. Therefore, this test was conducted using a 5% sulfuric acid (H_2SO_4) solution. Since no standard specifies the durability of the acid resistance for geopolymer concrete, ASTM (C1012) and guidelines from previous studies were utilized. The test data are provided in Tables F3-A and F3-B in Appendix F.

4.7.3.1 Change in Mass under 5 % Sulphuric Acid (H_2SO_4) Solution

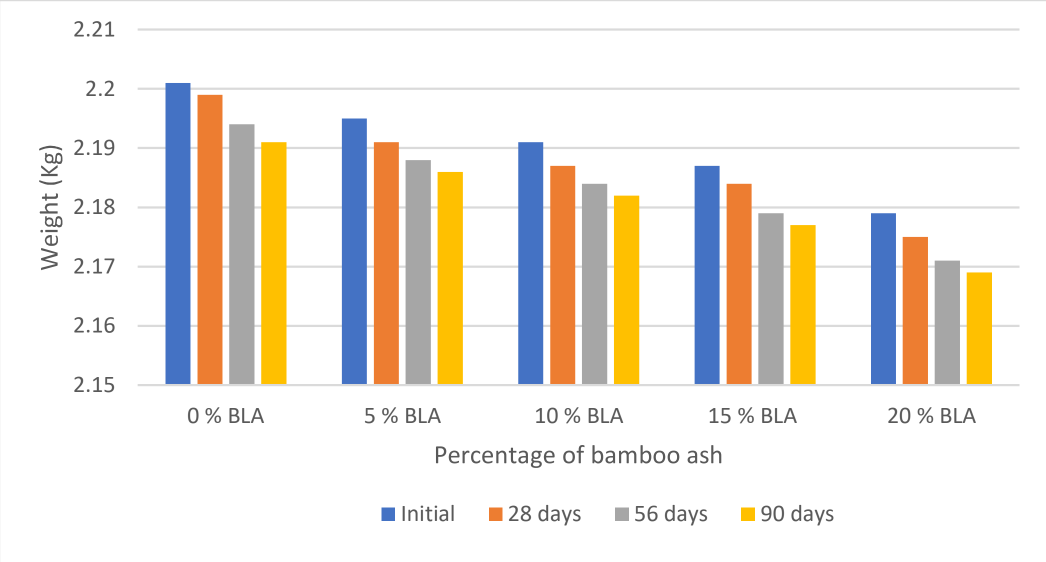


Figure 4.13 (a): Change in mass under 5 % sulphuric acid (H_2SO_4) solution

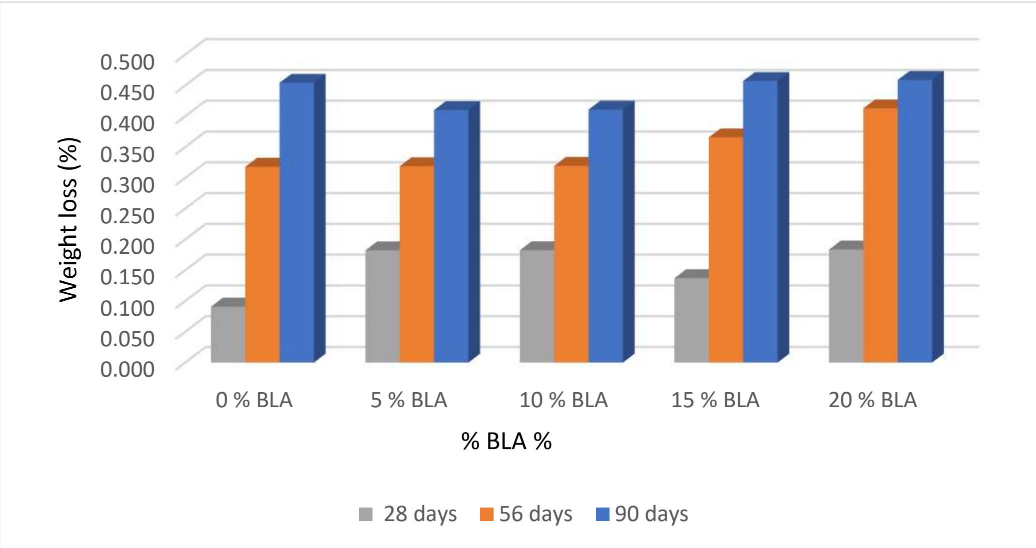


Figure 4.13 (b): Percentage loss mass under a 5 % sulphuric acid

Figure 4.13(a) represents the change in mass under sulphuric acid exposure solution after 28, 56, and 90 days. The test result indicates that the change in mass for all mixtures showed a little decrease with an increase in curing days of exposure solution. While Figure 4.13(b), shows the percentage of mass loss is less than 0.5 % for all geopolymer concrete samples under 5% sulphuric acid (H_2SO_4) exposure. This is due to the pozzolanic materials that produce a gel that fills tiny voids between fly ash particles, making concrete less porous and less likely to absorb moisture or chemical solutions that can damage the concrete. Additionally, the lower content of calcium oxide of the fly ash and bamboo leaf ash, which is about 1.4% and 5.3%, respectively, leads to a lower formation of gypsum and ettringite (Puertas et al. 2020).

This means geopolymers have excellent acid attack resistance in regard to loss of mass and strength (Thokchom et al., 2009). Furthermore, as the alkali activator concentration of geopolymer materials increases, materials with excellent compressive strength and high acid resistance are developed (Aiken et al. 2018). This indicates that alkaline activators such as sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) have a significant impact on resisting chemical attacks due to their high influence on the raw material dissolution of alumina (Al) and silica (Si) ions (Wang et al. 2009). Moreover, fly ash and bamboo leaf ash compositions, especially with higher content of SiO_2, Al_2O_3, and Fe_2O_3, are also the major reasons for the geopolymer concrete's ability to resist chemical exposure attack changes. This is due to evidence of a long-lasting pozzolanic activity, in which fly ash incorporates chemically with lime (calcium hydroxide), according to (Wardhono et al. 2015).

In the previous studies, Davidovits et al. (1990) stated that calcium alumina cement lost weight by around 30–60%, hence portland cement suffered after exposing 5% H2SO4. While geopolymers subjected to 5% sulphuric and hydrochloric acids were generally quite normal regarding mass loss in the range of 5-8%. Due to their reliance on alumina silicate network instead of calcium silicate hydrate.

4.7.3.2 Variation of Strength under Sulphuric Acid (H_2SO_4) Exposure

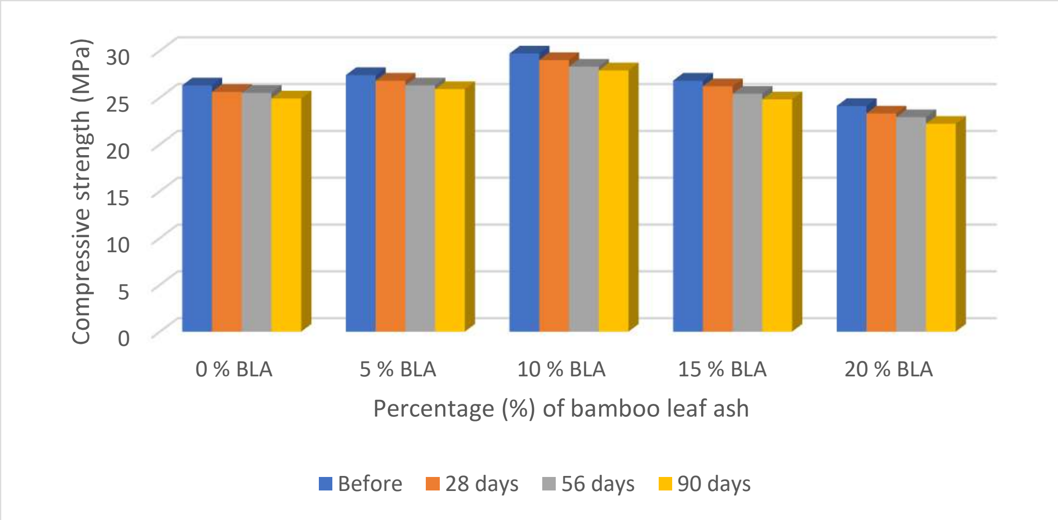


Figure 4.14 (a): Variation of compressive strength under 5 % (H_2SO_4) solution

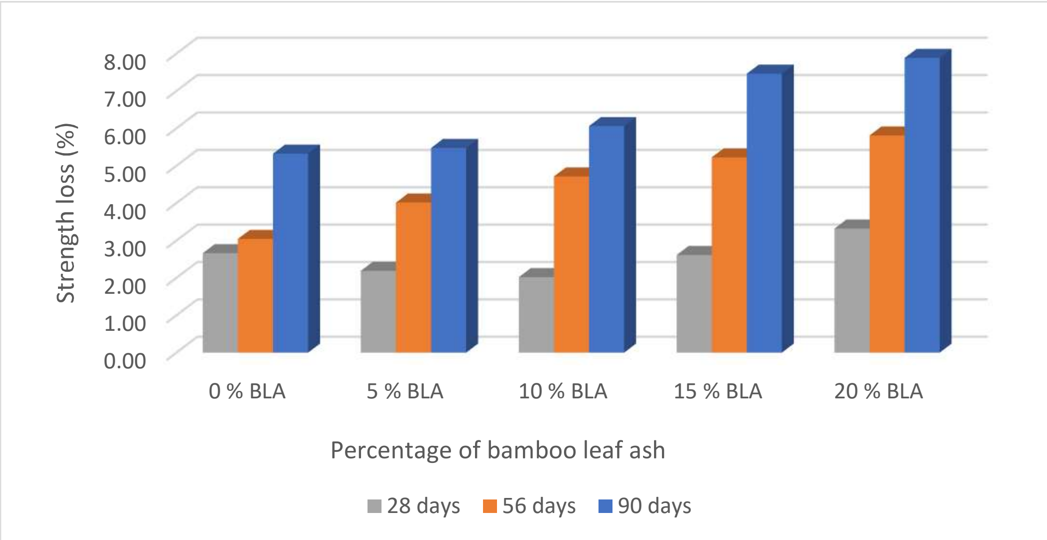


Figure 4.14 (b): Percentage loss of compressive strength under 5% (H_2SO_4) solution

Figure 4.14 (a) depicts the variation of compressive strength after immersion of a 5% sulfuric acid (H_2SO_4) solution. Before soaking in the 5% (H_2SO_4) solution, the compressive strength at 28 days for 0%, 5%, and 10% BLA was 26.3, 27.4, and 29.7 MPa, while for 15% and 20% BLA, it was 26.8 and 24.1 MPa, respectively. After 28 days of soaking in a 5% sulfuric acid (H_2SO_4) solution, for 0% and 5% BLA, the variation in compressive strength was 25.6 and 26.8 MPa, whereas, for 10%, 15%, and 20% BLA, it was 29, 26.1, and 23.4 MPa, respectively. The variation in compressive strength at 56 days for 0%, 5%, and 10% BLA was 25.5, 26.3, and 28.3 MPa, while for 15% and 20% BLA, it was 25.4 and 22.9 MPa, respectively. At the end of

90 days, for 0%, 5%, and 10% BLA, compressive changes were 24.9, 25.9, and 27.9 MPa, respectively, while the 15% and 20% BLA were 24.8 and 22.2 MPa, respectively.

According to Figure 4.14 (b), the most significant loss in compressive strength under 5% sulfuric acid solution was 7.88%, with a related 20% BLA at a 90-day exposure period compared to control samples. Conversely, the lowest loss in compressive strength recorded was 2.02%, with a matching 10% BLA at 28 days of curing in a 5% sulfuric acid solution, as indicated in Figure 4.14(b). Additionally, it was also observed that the strength declines for each mixture with the increasing curing days 28, 56, and 90 days. This due to the strong acid solution reacts with alumina-silica chain rings therefore this action leads to an increase porosity in the concrete and eventually loss of strength, (Farhana et al. 2015). So, the reaction between geopolymer pozzolanic materials and sulfuric acid (H_2SO_4) can exchange sodium (Na) and potassium (K) ions in geopolymer with hydrogen ions in an acid solution. This may be followed by an acid attack on Si-O-Al bonds, resulting in the release of aluminium ions and silicic acid.

The test results indicate that the inclusion of 10% BLA (as a substitute for fly ash) exhibits high performance in terms of compressive strength losses under a 5% sulfuric acid (H_2SO_4) solution. This is related to the workability of 10% BLA mixtures show good workable comparing to the other mixtures which results high strength concrete. This is related to the workability of 10% BLA mixtures show good workability compared to the other mixtures which results in high-strength concrete. This means the alkaline activators to fly ash ratio was 0.6 with a slump of (55mm) for 10% BLA. On other hand, for 15% and 20% BLA slump was (41mm and 24mm) which indicates more absorption of more alkaline liquid and eventually results in low strength of geopolymer concrete. All these conditions for the workability of geopolymer concrete rely upon the quantity of pozzolanic material, size of aggregates, and binder-to-alkaline liquid ratios.

In previous studies, the depolymerization of aluminosilicate polymers in acidic conditions caused alkali-activated binders to lose a significant percentage of strength (Bakharev, 2005). The polymeric gel's oxy-aluminium bridge (-Al-Si-O) is likely broken in an acidic environment, which decreases the strength of alkali-activated binders. Reduced permeability enhances the geopolymer matrix's resilience to acid attack by decreasing the amount of acid that enters it (Chindaprasirt et al. 2013).

4.7.3.3 Change in Appearance under a 5% Sulphuric Acid (H_2SO_4) Solution

Figure 4.15 (a) Appearance before immersing the chemicals

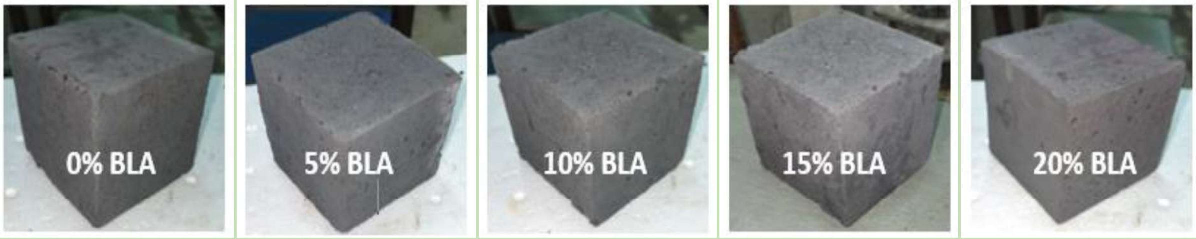


Figure 4.15 (b) Appearance after 28 days of immersing in a 5% H_2SO_4 solution

Figure 4.15 (c) Appearance after 56 days of immersing in a 5% H_2SO_4 solution

Figure 4.15 (d) Appearance after 90 days of immersing in a 5% H_2SO4 solution

Figure 4.15 (a) shows the condition of the specimen before soaking in the chemicals. Whereas Figures 4.15 (b), 4.15 (c), and 4.15 (d) represent the appearance after 28 days, 56 days, and 90 days of immersion in a 5% sulphuric acid (H_2SO_4) environment. The surface colour of geopolymer concrete specimens was slightly grey before soaking in a sulphuric acid exposure solution. While after being immersed in the acid solution, the colour changed to dark grey due to the reaction between the ferric oxide (Fe_2O_3) of both fly ash and bamboo ash with sulphuric acid (H_2SO_4) solution to form synthetic ferric sulphate trihydrate, as shown below the balanced chemical equation (Izzat et al. 2013).

$$Fe_2O_3 + 3\ H_2SO_4 \rightarrow Fe\ (SO4)_3 + 3H_2O \text{……………………………. Eq.3}$$

In general observation, the test result indicates that there were no significant variation observed in the geopolymer with BLA concrete specimens in terms of spalling cracking softening, and expansion of the concrete. This is due to the fact that geopolymer concrete does not develop calcium silicate-hydrates (CSH) for matrix formation and strength but instead utilizes a three-dimensional polymeric chain and a ring structure composed of Si-O-Al-O bonds, which helps to maintain the performance of geopolymer concrete. (Davidovits, 2008).

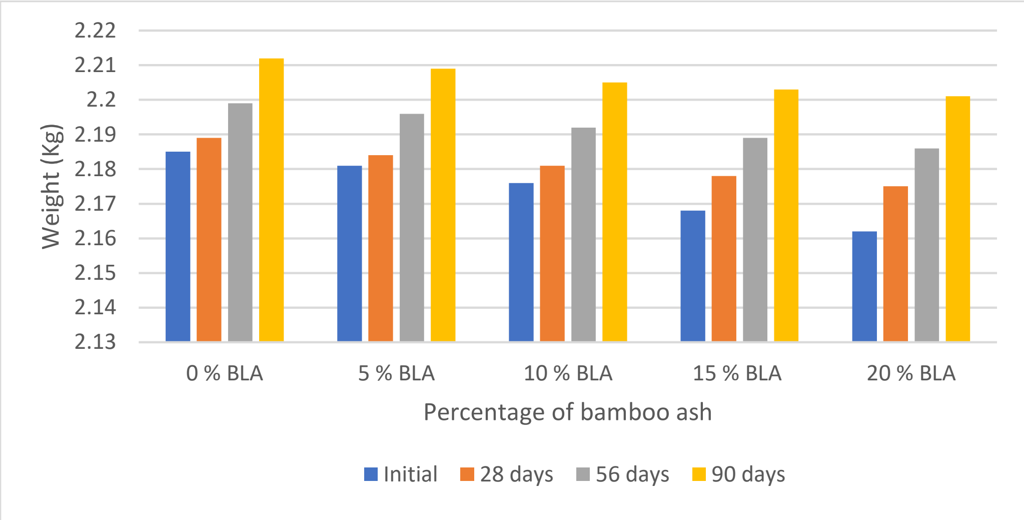
In summary, fly ash (Class F) blended with various proportions of bamboo leaf ash (BLA) ranging from (0 to 10% BLA) exhibits excellent resistance to a 5% sulfuric acid (H_2SO_4) environment in relation to mass loss, loss in strength, and change in appearance for surface disintegration. Therefore, it is recommended that bamboo leaf ash used as a geopolymer in concrete not exceed 0% up to 10% BLA to replace class F fly ash if the sulfuric acid is the main concern with regard to buried concrete structures exposed to acidic groundwater for a prolonged period and sewage pipelines.

The implication is that bamboo leaf ash used as a geopolymer in concrete should include no more than 0% to 10% BLA to replace class F fly ash if the chemical attack is the primary concern concerning buried concrete structures exposed to acidic groundwater for a long time and sewage pipelines.

4.7.4 Chloride Attack

The resistance of geopolymer with BLA against chloride attack was studied by evaluating the variations of strength, mass, and appearance after exposing a 5% sodium chloride (NaCl) solution. In terms of the durability of concrete, chloride attack is one of the major significant concerns of the concrete structure. It is the underlying cause of around 40% of structural failures in concrete, (Angst et al. 2012). In the presence of both oxygen and water, chloride attack corrodes the steel, thereby decreasing the strength of the structure. Chloride ions (Cl^-) are synthesized when elements like hydrogen chloride are dissolved in water or when the element chlorine obtains an electron. Chloride ions present in concrete in high concentrations might cause serious problems (Neville 1995). The major effect of chloride ions (Cl^-) attack is the corrosion of reinforcement. More test results are presented in Appendix F, Table F4-A, and Table F4-B.

4.7.4.1 Change in Mass under NaCl Solution



Figures 4.16(a): Change in mass under 5% sodium chloride (NaCl) solution

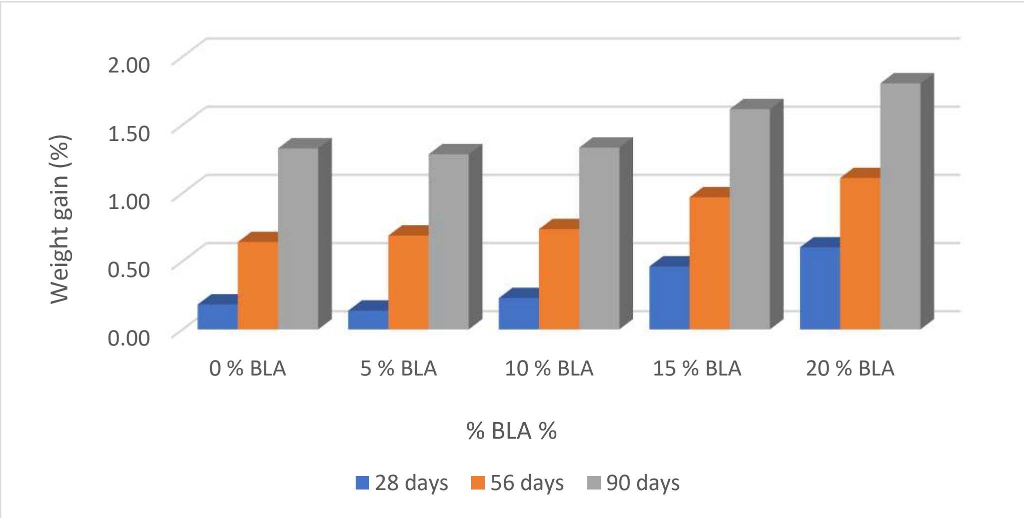


Figure 4.16 (b): Percentage loss of mass under 5% NaCl solution

Figure 4.16 (a) shows the change in mass after immersing in sodium chloride (NaCl) exposure solution. The actual mass (before immersion solution) at 28 days for 0% and 5% BLA was 2.185 and 2.181, respectively, while for 10%, 15%, and 20%, it was 2.176, 2.168, and 2.162 kg, respectively. After soaking in solution for 28 days, the change in mass with 0%, 5%, and 10% BLA was 2.189, 2.184, and 2.181 kg, while the 15% and 20% BLA were 2.178 and 2.175 kg, respectively. Additionally, at 56 days of exposure, the change of mass at 0% and 5% BLA was 2.199 and 2.1965 kg, whereas at 10%, 15%, and 20% BLA, it was 2.192, 2.189, and 2.186 kg, respectively. After 90 day of exposure to 5% NaCl solution, the change in mass at 0%, 5%, and 10% BLA was 2.212, 2.209, and 2.205 kg, while the changes at 15% and 20% BLA were 2.203

and 2.201 kg, respectively. Based on Figure 4.16 (b), shows the percentage mass gain after immersion of geopolymer specimens in a 5% sodium chloride solution. The highest mass gain recorded was 1.8%, related to 20% BLA at 90 days of exposure solution. Meanwhile, the lowest mass gain was 0.14% with relevance of 5% BLA for 28 days of immersing in the NaCl solution. The test results indicate that the mass of the geopolymer specimens gradually increased with the exposure period. This is due to the reaction between the sodium chloride (NaCl) salt and the geopolymer concrete products, which fills the material's pores and increases its bulk by absorbing the exposed liquid. It can be seen that the mass gain after 28 days of a sodium chloride (NaCl) environment for fly ash-only geopolymer mixes without bamboo leaf ash (BLA) was 0.18 percent as compared to 1.8% for the mix with 20% BLA. And this shows the change in mass in terms of increase or decrease was very low, less than 2% for all mixtures cured to a 5% NaCl solution. The main reason for this is that the combination of silicon and alkaline activators of GPC working together contributed to making less the effect of (Cl-) ions, which causes the variation of mass and strength. This means the binding capacity of geopolymer concrete is stronger than OPC cement concrete due to the cation from sodium ions (Na+) in the mixture being considered as a shield of chloride ions (Cl-) penetration (Prinya and Wichian, 2014). Based on the literature review (Oliva et al. 2011), noticed a comparable result, which concluded that the application of a higher sodium hydroxide (NaOH) concentration in the mixture contributed to a smaller pore size in concrete, which has the potential to increase water absorption.

4.7.4.2 Variation of Compressive Strength under NaCl Solution

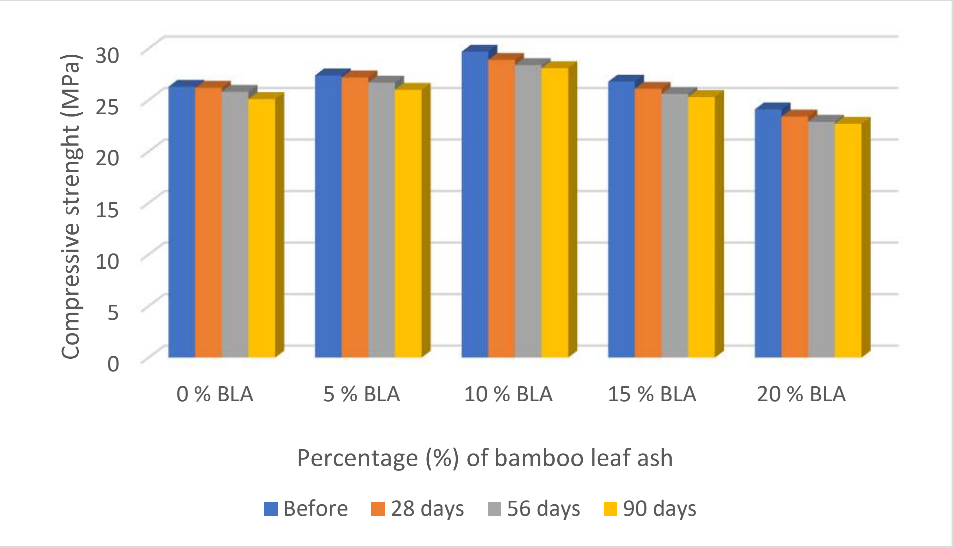


Figure 4.17 (a): Change in compressive strength under 5% NaCl

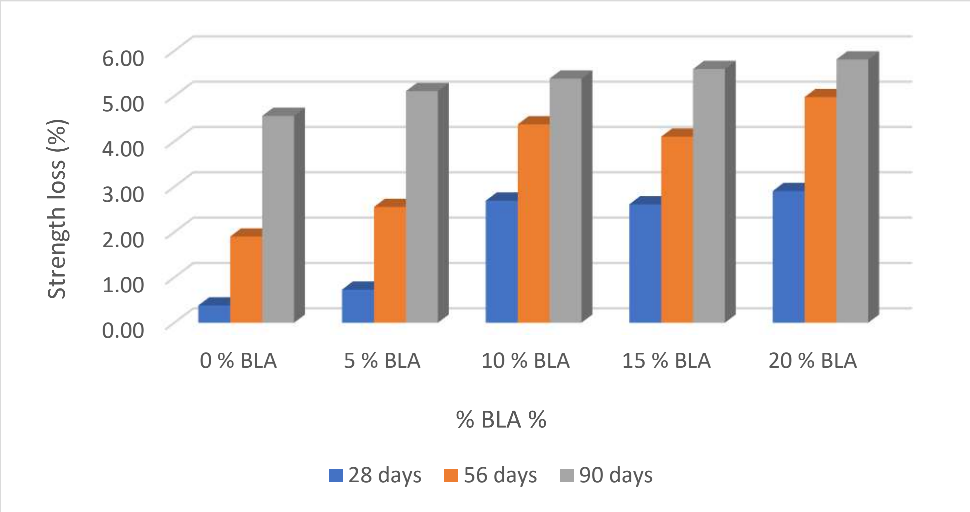


Figure 4.17 (b): Percentage loss of compressive strength under 5% NaCl solution

Figure 4.17(a) demonstrates the variation of compressive strength after soaking the NaCl salt solution for 28 days, 56 days, and 90 days of exposure. The strengths before immersing in the chemicals after 28 days for 0%, 5%, 10%, 15%, and 20% BLA were 26.3, 27.4, 29.7, 26.8, and 24.1 MPa respectively. In addition, at 28 days, after soaking in a 5% NaCl solution, the change in compressive strength of 0%, 5%, and 10% BLA was 26.2, 27.2, and 28.9 MPa, respectively, while the 15% and 20%BLA were 26.1 and 23.4 MPa. Furthermore, at the end of 56 days, the change of compressive strength for 0% and 5% BLA was 25.8 and 26.7 MPa, whereas the 10%, 15%, and 20% BLA were 28.4, 25.6, and 22.9 MPa, respectively. Moreover, the change in compressive strength after 90 days for the 0%, 5%, and 10% BLA was 25.1, 26, and 28.1 MPa, while the 15% and 20% BLA changes were 25.3 and 22.7.3 MPa, respectively.

The percentage loss of compressive strength ranges from 0.38% up to 5.81%, with a match of 0% BLA at 28 days and 20% BLA for 90 days of 5% NaCl exposure environment, as shown in Figure 4.17 (b). Additionally, the results indicate that the compressive strength slightly declines with a longer time of exposure to the solution, up to 90 days. This is due to the salt ion penetrating deep in the specimens for long curing days, which affects the geopolymer gel and final product with corrosion and internal crack. Furthermore, the geopolymers concrete made with 90% fly ash and 10% BLA cured with a 5% NaCl salt solution exhibits the highest performance for all mixtures in terms of strength reduction. The main reason for the lower decrease in compressive strength of GPC is the higher degree of polymerization as a result of the accelerated dissolution rate of silicone ion (Si^{+4}) and aluminium ion (Al^{+3}) from precursors, which in turn promotes the formation of more polymeric structures and thus leads to higher strength (Khale et al. 2007). Additionally, through the dissolution function, alkali cations also serve as charge-balancing ions in the formation of geopolymer structures. In Figure 4.17(a), the strength increases at 10% BLA mixtures and decreases at 15% and 20% BLA. This is due to a higher quantity of bamboo leaf ash above 10% BLA absorbing more alkaline solution which declines the strength.

In the literature review, (Thomas et al. 2013) reported that the porosity and connectivity of the pore structure, as well as the concrete's capacity to bind chemicals, are among the primary factors of concrete's resistance to chloride ions. The crucial durability parameters that lead to the deterioration of concrete buildings include carbonation and the penetration of chloride ions into alkali-activated materials (San Nicolas et al. 2014).

4.7.3.3 Change in Appearance under 5% Sodium Chloride (NaCl) Solution

Figure 4.18 (a) Appearance before immersing the chemicals

Figure 4.18 (b) Appearance after 28 days of immersing in a 5% NaCl solution

Figure 4.18 (c) Appearance after 56 days of immersing in a 5% NaCl solution

Figure 4.18 (d) Appearance after 90 days of immersing in a 5% NaCl solution

Figure 4.18(a) demonstrates the appearance of geopolymer concrete specimens before immersing in the 5% sodium chloride (NaCl) solution. In addition, the appearance of geopolymer concrete samples after being immersed in a 5% sodium chloride salt solution can also be seen in Figures 4.18(b), 4.18(c), and 4.18(d).. The test result indicates a less significant effect on the appearance of GPC specimens exposed to a 5% NaCl solution for 28, 56 and 90 days. This is due to the strong chain silica reaction between fly ash (FA), bamboo leaf ash (BLA), and alkaline activators which lowers the penetration or diffusion of chloride ion (Cl-). The reaction mechanisms and products of alkali-activated materials are different from OPC concrete systems. Calcium-aluminosilicate-hydrates (C-A-S-H) and sodium-aluminosilicate-hydrate (N-A-S-H) are the major reaction gels in geopolymer concrete (GPC) while the main hydration product in OPC system is the Calcium-silicate-hydrate (C–S–H). Additionally, due to the difference in reaction phases between pozzolanic materials and OPC concrete, the materials that were activated with alkaline solutions had better durability properties (Malhotra & Mehta, 2004). For example, the hydrotalcite-type phase in alkali-activated materials indicates significant chloride immobilization ability, which contributes to the higher resistance against chloride ingress of pozzolanic materials (Memon et al., 2013) and (Yang et al., 2020).

Based on the literature review, pozzolanic materials were proven to have better durability qualities in terms of mechanism, and possible enhancements are still unclear in previous studies (Puertas et al. 2000) and (Juenger et al.2 011).

In summary, the results indicate that the geopolymer concrete has strong resistance to sodium chloride salt, with less than 2% mass change and compressive strength loss below 5%. However, the inclusion of bamboo leaf ash as a partial substitute of fly ash in geopolymer concrete adversely affects the change in mass, the variation of compressive strength, and visual appearance. Therefore, if sodium chloride (NaCl) salt attack is the biggest concern, it is advised that bamboo leaf ash be utilized as a replacement for fly ash in geopolymer concrete at a percentage that does not exceed 10% BLA.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

This research presents an evaluation of the properties of geopolymer concrete with the Addition of bamboo leaf Ash as a natural pozzolanic material. The properties that were investigated are the workability, mechanical, and durability performance. Due to this research work the following conclusions were made:

1. Bamboo leaf ash is suitable for blending materials in the production of geopolymer concrete.
2. Geopolymer concrete workability decreases with the increasing percentage of bamboo leaf ash up to 20% BLA.
3. The compressive strength of geopolymer concrete with bamboo leaf ash increases with the increase in curing days at ambient temperature. Furthermore, 5 to 10% BLA replacement of fly ash improves the compressive strength of geopolymer concrete. In contrast, when bamboo leaf ash content exceeds 10%, the compressive strength of geopolymer concrete decreases steadily.
4. Durability performance:
   a) Water absorption value of geopolymer concrete increases with the increasing the amount of bamboo leaf ash. In addition, geopolymer concrete containing bamboo leaf has good resistance to water penetration from 0% up to 15% compared to 20% of bamboo leaf ash.
   b) fly ash incorporating bamboo leaf ash (BLA) content indicated minor changes in mass, strength and appearance when the specimens were exposed to a 5% magnesium sulphate (MgO_4) solution.
   c) fly ash (Class F) blended with various proportions of bamboo leaf ash (BLA) ranging from (0 to 10% BLA) exhibits excellent resistance to a 5% sulfuric acid (H_2SO_4) environment in terms of mass loss, loss in compressive strength, and change in appearance for surface disintegration.
   d) The results confirmed that geopolymer concrete is highly resistant to sodium chloride salt in terms of mass change, less than 2%, and loss of compressive strength, below 5%. However, the inclusion of bamboo leaf ash (BLA) as a

partial replacement of fly ash class F in geopolymer concrete adversely affects the change in mass, the change in compressive strength, and visual appearance.

5.2 RECOMMENDATION

5.2.1 Recommendation from this work

1. For this research, the Na2SiO_3/NaOH ratio was 2.5 and exhibits a significant effect on the strengths of the geopolymer with bamboo leaf ash. Additionally, there are very little research on the effect of sodium silicate to sodium hydroxide (Na_2SiO_3/NaOH) ratio on the mechanical properties of geopolymer based on fly ash incorporating bamboo leaf ash. Therefore, using geopolymer concrete with bamboo leaf ash containing different Na_2SiO_3/NaOH ratios may be an opportunity for future research gaps that need to be studied.

5.2.2 Recommendations for Further Work

1. More research is needed to investigate the performance of geopolymer concrete incorporating bamboo leaf ash, such as fracture toughness and creep based on the various mix ratios of fly ash blended bamboo leaf ash geopolymer needs to be studied.
2. There is a need to check whether more alkaline solutions would result in better strength beyond 10% BLA.
3. Geopolymer concrete with different percentages of bamboo leaf ash under chemical attack for long periods of 360 days at high concentrations needs to be investigated.

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APPENDICES

Appendixes A: Basic aggregate tests

Table A1: Results of sieve analysis of course aggregate (14mm) size maximum

Sieve size	*Retained mass (gm)*	*Percentage aggregate retained (%)*	*Cumulative passed percentage (%)*	*Criteria of Acceptance*	
				Min (%)	*Max (%)*
20	0	0	100	100	100
14	201	3.2	96.8	90	100
10	2198.2	34.9	61.9	50	85
5	3342	53.1	8.8	0	10
2.36	552	8.8	0		
	4078				

Table A2: Results of sieve analysis of river sand

Sieve size (mm)	*Retained mass (gm)*	*% Retained (%)*	*Cumulative passed percentage (%)*	*Cumulative percentage retained*	*Acceptance Criteria*	
					Min (%)	*Max (%)*
14	0	0.0	100.0	0	100	-
10	0	0.0	100.0	0	100	-
4.76	10	2.0	98.0	2	89	100
2.36	30	6.0	92.0	8	60	100
1.18	72	14.4	77.6	22	30	100
0.6	122	24.4	53.2	47	15	100
0.3	157	31.4	21.8	78	5	70
0.15	89	17.8	4.0	96	0	15
0.075	13	2.6	1.4		0	3
	7	1.4	0.0	Total = 253		

	500			$F.m = \frac{253}{100} = 2.53$		

A3: Calculation of specific gravity and water absorption of course aggregate

Mass of saturated surface dry sample in air (A) = 685.1 gram

Mass of vessel containing sample and filled with water (B) = 1581.6 gram

Mass of vessel filled with water only (C) = 1166.4 gram

Mass of oven-dried sample in the air (D) = 678.4 gram

Relative density on an oven-dried basis = $\frac{D}{A-(B-C)} = \frac{678.4}{685.1-(1581.6-1166.4)} = \mathbf{2.51}$

Relative density on saturated and surface dried basis = $\frac{A}{A-(B-C)} = \frac{685.1}{685.1-(1581.6-1166.4)} = \mathbf{2.53}$

Apparent relative density = $\frac{D}{D-(B-C)} = \frac{678.4}{678.4-(1581.6-1166.4)} = \mathbf{2.57}$

Mean result = $= \frac{2.51+2.53+2.57}{3} = \mathbf{2.53}$

Water absorption (percent of dry mass) = $\frac{100(A-D)}{D} = \frac{100(685.1-678.4)}{678.4} = \mathbf{0.98}$

Table A4: Calculation of the specific gravity of river sand

Sample number	**1**	**2**	**3**
Bottle number	A	B	C
Mass of empty bottle (W1)	57.7	55.48	55.3
Mass of bottle + Soil (W2)	80.5	91.1	91.3
Mass of bottle + Soil + Water (W3)	177.9	175	174.2
Mass of bottle full of water (W4)	163.7	152.82	151.9
Mass of water used (W3-W2)	97.4	83.9	82.9
Mass of Soil used (W2-W1)	22.8	35.62	36
Volume of soil (W4-W1) -(W3-W2)	8.6	13.44	13.7
Specific gravity of soil (Gs) = $\frac{(W2-W1)}{(W4-W1)-(W3-W2))}$	2.651	2.648	2.627
Average Gs.	(2.651+2.648+2.627)/3=2.64		

Table A5: Water absorption of river sand

Saturated surface dried weight (A)	466.7 gram
Oven-dried weight (B)	459.2 gram

Water absorption = $\frac{\mathbf{A-B}}{\mathbf{B}}\ \mathbf{x\ 100 =}\ \frac{\mathbf{466.7-459.2}}{\mathbf{459.2}}\mathbf{x100 = 1.63}\%$

Appendix B: XRF (X-ray fluorescence) analysis

Table B1: XRF analyses of fly ash class F

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FOR DIRECTOR OF GEOLOGICAL SURVEYS
24 FEB 2022
P. O. Box 30009-00100 NAIROBI

00093-GeoChem.pdz	AssayTime: 2/24/2022 1:08:34	ElapsedTime: 23
Alloy 1:	Match No:	

Field Info			
Operator	SUPERVISOR	Sender name	HASSAN SAID MOHAMED
Sample type	POWDER	Sender ref	FLY ASH CLASS F

Element Name	Min	%	Max	+/- [*3]
MgO	0	1.935	0	2.007
Al2O3	0	29.880	0	0.923
SiO2	0	61.644	0	0.944
P2O5	0	0.231	0	0.064
S	0	0.046	0	0.027
Cl	0	0.041	0	0.030
K2O	0	0.930	0	0.030
CaO	0	1.452	0	0.033
Ti	0	0.819	0	0.014
V	0	0.011	0	0.005
Cr	0	0.000	0	0.004
Mn	0	0.054	0	0.010
Fe	0	2.748	0	0.043
Co	0	0.000	0	0.000
Ni	0	0.003	0	0.003
Cu	0	0.008	0	0.002
Zn	0	0.008	0	0.002
As	0	0.001	0	0.001
Se	0	0.000	0	0.001
Rb	0	0.006	0	0.001
Sr	0	0.016	0	0.001
Y	0	0.008	0	0.002
Zr	0	0.035	0	0.002
Nb	0	0.003	0	0.001
Mo	0	0.001	0	0.002

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BRUKER

00093-GeoChem.pdz	AssayTime: 2/24/2022 1:08:54	ElapsedTime: 25
Alloy 1:	Match No:	

Element Name	Min	%	Max	+/- [*3]
Pd	0	0.000	0	0.005
Ag	0	0.000	0	0.002
Cd	0	0.000	0	0.004
Sn	0	0.000	0	0.015
Sb	0	0.000	0	0.007
Ba	0	0.057	0	0.032
La	0	0.053	0	0.070
Hf	0	0.000	0	0.006
Ta	0	0.002	0	0.002
W	0	0.000	0	0.001
Pt	0	0.001	0	0.002
Au	0	0.001	0	0.002
Hg	0	0.000	0	0.002
Tl	0	0.000	0	0.001
Pb	0	0.005	0	0.003
Bi	0	0.000	0	0.003
Th	0	0.000	0	0.005
U	0	0.000	0	0.010

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Table B2: XRF (X-ray fluorescence) analyses of natural bamboo leaf ash

BRUKER

00092-GeoChem.pdz	AssayTime: 2/24/2022 1:07:27	ElapsedTime: 25
Alloy 1:	Match No:	

Field Info			
Operator	SUPERVISOR	Sender name	HASSAN SAID MOHAMED
Sample type	POWDER	Sender ref	BAMBOO LEAF ASH

Element Name	Min	%	Max	+/- [*3]
MgO	0	1.679	0	1.085
Al2O3	0	2.656	0	0.472
SiO2	0	82.033	0	1.185
P2O5	0	1.664	0	0.105
S	0	0.263	0	0.033
Cl	0	0.318	0	0.038
K2O	0	3.698	0	0.056
CaO	0	5.328	0	0.062
Ti	0	0.149	0	0.009
V	0	0.004	0	0.002
Cr	0	0.000	0	0.003
Mn	0	0.561	0	0.028
Fe	0	1.535	0	0.036
Co	0	0.000	0	0.000
Ni	0	0.003	0	0.004
Cu	0	0.017	0	0.004
Zn	0	0.038	0	0.005
As	0	0.002	0	0.002
Se	0	0.000	0	0.001
Rb	0	0.010	0	0.002
Sr	0	0.019	0	0.003
Y	0	0.000	0	0.002
Zr	0	0.012	0	0.002
Nb	0	0.002	0	0.001
Mo	0	0.000	0	0.002

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00092-GeoChem.pdz	AssayTime: 2/24/2022 1:07:27	ElapsedTime: 25
Alloy 1:	Match No:	

Element Name	Min	%	Max	+/- [*3]
Rh	0	0.000	0	0.002
Ag	0	0.000	0	0.003
Cd	0	0.000	0	0.008
Sn	0	0.000	0	0.006
Sb	0	0.000	0	0.007
Ba	0	0.000	0	0.048
La	0	0.000	0	0.103
Hf	0	0.000	0	0.004
Ta	0	0.000	0	0.002
W	0	0.000	0	0.003
Pt	0	0.000	0	0.002
Au	0	0.001	0	0.004
Hg	0	0.000	0	0.002
Tl	0	0.001	0	0.002
Pb	0	0.008	0	0.006
Bi	0	0.000	0	0.005
Th	0	0.000	0	0.008
U	0	0.000	0	0.016

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Table B3: XRF (X-ray fluorescence) analyses of OPC cement

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FOR DIRECTOR OF GEOLOGICAL SURVEYS
24 FEB 2022
P. O. Box 30009-00100 NAIROBI

00094-GeoChem.pdz	AssayTime: 2/24/2022 1:09:57	ElapsedTime: 24

Alloy 1:	Match No:

Field Info			
Operator	SUPERVISOR	Sender name	HASSAN SAID MOHAMED
Sample type	POWDER	Sender ref	OPC - CEMENT

Element Name	Min	%	Max	+/- [*3]
MgO	0	0.000	0	1.912
Al2O3	0	5.018	0	0.557
SiO2	0	25.342	0	0.667
P2O5	0	0.472	0	0.137
S	0	3.263	0	0.081
Cl	0	0.000	0	0.029
K2O	0	0.637	0	0.034
CaO	0	62.040	0	0.208
Ti	0	0.199	0	0.017
V	0	0.000	0	0.008
Cr	0	0.000	0	0.006
Mn	0	0.045	0	0.013
Fe	0	2.822	0	0.070
Co	0	0.000	0	0.006
Ni	0	0.000	0	0.005
Cu	0	0.014	0	0.005
Zn	0	0.022	0	0.003
As	0	0.000	0	0.002
Se	0	0.000	0	0.001
Rb	0	0.005	0	0.002
Sr	0	0.092	0	0.004
Y	0	0.002	0	0.002
Zr	0	0.027	0	0.002
Nb	0	0.000	0	0.002
Mo	0	0.000	0	0.002

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00094-GeoChem.pdz	AssayTime: 2/24/2022 1:09:57	ElapsedTime: 24
Alloy 1:	Match No:	

Element Name	Min	%	Max	+/- [*3]
Pd	0	0.000	0	0.004
Ag	0	0.000	0	0.004
Cd	0	0.000	0	0.007
Sn	0	0.000	0	0.019
Sb	0	0.000	0	0.012
Ba	0	0.000	0	0.044
La	0	0.000	0	0.128
Ce	0	0.000	0	0.032
Hf	0	0.000	0	0.004
Ta	0	0.000	0	0.002
W	0	0.000	0	0.002
Pt	0	0.001	0	0.002
Au	0	0.000	0	0.004
Hg	0	0.000	0	0.003
Tl	0	0.000	0	0.002
Pb	0	0.000	0	0.004
Bi	0	0.000	0	0.005
Th	0	0.000	0	0.008
U	0	0.000	0	0.013

Appendix C: Hydrometer Analysis

Table C1: Hydrometer analysis of fly ash class F

Wet & Dry Sieve Analysis to BS 1377				Hydrometer Analysis to BS 1377								
Sieve size (mm)	Retained mass (gm)	% Retained (%)	Cumulative passed percentage (%)	Date	Time in min	Temp o C	Rh1	Rh	HR	D(mm)	K %	K(corrected)
20	0	0.0	100.0	10 AM	0.5	20	25	25.5	10.2	0.06116	*58*	*58*
10	0	0.0	100.0									
5	0	0.0	100.0									
2.36	0	0.0	100.0		1	20	23.5	24	10.8	0.0445	55	55
1.18	0	0.0	100.0		2	20	20.5	21	11.9	0.03303	48	48
0.6	0	0.0	100.0		4	20	17.5	18	13.1	0.0245	40	40
0.425	0	0.0	100.0		8	20	14.5	15	14.3	0.0181	33	33
0.3	0	0.0	100.0		15	20	11	11.5	15.7	0.01385	25	25
0.15	0	0.0	100.0		30	20	8	8.5	16.9	0.01016	18	18
0.075	0	0.0	100.0		60	20	5	5.5	18	0.00742	11	11
<0.075	50	100.0			240	20	4.5	5	18.3	0.00374	10	10
TOTAL	50				480	20	4.5	5	18.3	0.00264	10	10
					1440	20	4.5	5	18.3	0.00153	10	10

Table C2: Hydrometer analysis of bamboo leaf ash

Wet & Dry Sieve Analysis to BS 1377				*Hydrometer Analysis to BS 1377*								
Sieve size (mm)	*Retained mass (gm)*	*% Retained (%)*	*Cumulative passed percentage (%)*	*Date*	*Time in min*	*Temp o C*	*Rh1*	*Rh*	*HR*	*D(mm)*	*K %*	*K(corrected)*
20	0	0.0	100.0	11. AM	0.5	20	29	29.5	8.6	0.05615	60	60
10	0	0.0	100.0									
5	0	0.0	100.0									
2.36	0	0.0	100.0		1	20	28.5	29	8.8	0.04017	59	59
1.18	0	0.0	100.0		2	20	27.5	28	9.2	0.02904	57	57
0.6	0	0.0	100.0		4	20	26	26.5	9.7	0.02109	54	54
0.425	0	0.0	100.0		8	20	22	22.5	10.3	0.01536	46	46
0.3	0	0.0	100.0		15	20	16.5	17	13.1	0.01265	34	34
0.15	0	0.0	100.0		30	20	6	6.5	17.5	0.01034	12	12
0.075	0	0.0	100.0		60	20	4.5	5	18.3	0.00748	8	8
<0.075	50	100.0			240	20	4.5	5	18.3	0.00374	8	8
TOTAL	50				480	20	4.5	5	18.3	0.00264	8	8
					1440	20	4.5	5	18.3	0.00153	8	8

Table C3: Hydrometer analysis of OPC cement

Wet & Dry Sieve Analysis to BS 1377				*Hydrometer Analysis to BS 1377*								
Sieve size (mm)	**Retained mass (gm)**	**% Retained (%)**	**Cumulative passed percentage (%)**	**Date**	**Time in min**	**Temp o C**	**Rh1**	**Rh**	**HR**	**D(mm)**	**K%**	**K(corrected)**
20	0	0.0	100.0	11 AM	0.5	20	**30**	**30.5**	**8.4**	**0.0555**	*127*	*63*
10	0	0.0	100.0									
5	0	0.0	100.0									
2.36	0	0.0	100.0		1	20	**30**	**30.5**	**8.4**	**0.03924**	127	63
1.18	0	0.0	100.0		2	20	**28**	**28.5**	**9**	**0.02872**	118	59
0.6	0	0.0	100.0		4	20	**25**	**25.5**	**10.2**	**0.02162**	105	53
0.425	0	0.0	100.0		8	20	**18.5**	**19**	**12.9**	**0.01719**	77	39
0.3	0	0.0	100.0		15	20	**8**	**8.5**	**17.1**	**0.01446**	32	16
0.15	0	0.0	100.0		30	20	**4.5**	**5**	**18.5**	**0.01063**	17	9
0.075	0	0.0	100.0		60	20	**4.5**	**5**	**18.5**	**0.00752**	17	9
<0.075	50	100.0			240	20	**4.5**	**5**	**18.5**	**0.00532**	17	9
TOTAL	50				480	20	**4.5**	**5**	**18.5**	**0.00376**	17	9
					1440	20	4.5	**5**	18.5	0.00153	17	9

Appendix D: Workability of fresh geopolymer concrete

Table D1: Slump value results of geopolymer concrete

No.	*percentage of bamboo leaf ash*	*Slump values*	*Standard of Workability*	*Type of Slump*
1.	*0% BLA*	72	Medium	*True slump*
2.	*5% BLA*	65	Medium	*True slump*
3.	*10% BLA*	55	Medium	*True slump*
4.	*15% BLA*	41	low	*True slump*
5.	*20% BLA*	24	Very low	*True slump*

Table D2: Compaction factor test results of geopolymer concrete

No.	*percentage of bamboo leaf ash*	*Compaction Factor Values*	*Standard of Workability*
1.	*0% BLA*	0.94	High
2.	*5% BLA*	0.91	Medium
3.	*10% BLA*	0.87	Medium
4.	*15% BLA*	0.82	low
5.	*20% BLA*	0.79	Very low

Appendix E: Mechanical Properties of Geopolymer Concrete

Table E1: Compressive Strength

No.	Percentage of Bamboo leaf ash	Compression load maximum at failure (KN)			Compressive strength (Mpa) after room-temperature curing		
		28 days	56 days	90 days	28 days	56 days	90 days
1.	0 % BLA	263	292	366	26.3	29.2	36.6
2.	5 % BLA	274	344	387	27.4	34.4	38.7
3.	10 % BLA	297	355	408	29.7	35.5	40.8
4.	15 % BLA	268	275	353	26.8	27.5	35.3
5.	20 % BLA	241	267	291	24.1	26.7	29.1

Table E2: Splitting tensile strength

No.	Percentage of Bamboo leaf ash	Breaking load of splitting tensile strength (KN)			Splitting tensile strength (Mpa) after curing at room temperature		
		28 days	56 days	90 days	28 days	56 days	90 days
1.	0 % BLA	190.85	213.47	267.19	2.7	3.02	3.78
2.	5 % BLA	197.92	251.64	283.45	2.8	3.56	4.01
3.	10 % BLA	219.13	261.54	296.88	3.1	3.7	4.2
4.	15 % BLA	183.78	200.75	258.00	2.6	2.84	3.65
5.	20 % BLA	169.65	195.09	212.76	2.4	2.76	3.01

Appendix F: Durability of Geopolymer concrete

Table F1: Water absorption of geopolymer concrete

No.	% BLA %	Mass of oven-dried samples after 28 days			Average mass (W2)	Mass of saturated samples after 28 days			Average (W1)	Water absorption (%)
		W1(g)	W2(g)	W3(g)		W1(g)	W2(g)	W3(g)		
1.	0 %	2136	2145	2133	2138	2167	2195	2210	2191	2.46
2.	5 %	2122	2130	2123	2125	2164	2215	2171	2183	2.75
3.	10 %	2085	2144	2119	2116	2262	2140	2141	2181	3.07
4.	15 %	2077	2108	2081	2089	2152	2254	2137	2181	4.42
5.	20 %	2019	2073	2015	2036	2049	2183	2184	2139	5.06

Table F2: Sulphate resistance

Table F2 –A Change in mass under 5% magnesium sulfate ($MgSO_4$)

No.	Percentage of bamboo ash content (%)	Initial weight (Kg) after 28 days before immersing in chemicals	Weight (Kg) After soaking in 5% magnesium sulfate ($MgSO_4$)			Weight gain (%) between the initial weight and weights of 28, 56, and 90 days		
		Actual weight	28 days	56 days	90 days	28	56	90
1.	0 % BLA	2.188	2.201	2.206	2.215	0.548	0.82	1.23
2.	5 % BLA	2.185	2.196	2.199	2.210	0.503	0.64	1.14
3.	10 % BLA	2.182	2.192	2.195	2.206	0.458	0.60	1.10
4.	15 % BLA	2.177	2.186	2.189	2.197	0.413	0.55	0.92
5.	20 % BLA	2.173	2.181	2.185	2.191	0.368	0.51	0.83

Table F2 –B Change in compressive strength under ($MgSO_4$) Solution

No.	Percentage of bamboo ash content (%)	Compressive strength before immersing chemicals after 28 days	Compressive strength (MPa) after immersing in 5% magnesium sulfate ($MgSO_4$) solution			Loss (%) of compressive strength (MPa) between the initial strength and 28, 56, and 90 days after soaking		
		Initial	28 days	56 days	90 days	28 days	56 days	90 days
1.	0 % BLA	26.3	26.1	25.5	24.1	0.76	3.04	8.37

2.	*5 % BLA*	27.4	27.1	26.4	24.9	1.09	3.65	9.12
3.	*10 % BLA*	29.7	28.7	27.7	26.8	3.37	6.73	9.76
4.	*15 % BLA*	26.8	25.7	24.9	24.1	4.10	7.09	10.07
5.	*20 % BLA*	24.1	22.8	22.3	21.3	5.39	7.47	11.62

Table F3: Sulphuric acid resistance

Table F3 –A Change in mass under 5% (H_2SO_4) solution

No.	*Percentage of bamboo ash content (%)*	*Initial weight (Kg) after 28 days before immersing in chemicals*	*Weight (Kg) After soaking in 5% Sulphuric acid (H_2SO_4)*			*Weight loss (%) between the initial weight and weights of 28, 56, and 90 days*		
		Initial	*28 days*	*56 days*	*90 days*	*28 days*	*56 days*	*90 days*
1.	*0 % BLA*	2.201	2.199	2.194	2.191	0.548	0.82	1.23
2.	*5 % BLA*	2.195	2.191	2.188	2.185	0.503	0.64	1.14
3.	*10 % BLA*	2.191	2.187	2.184	2.180	0.458	0.60	1.10
4.	*15 % BLA*	2.187	2.184	2.179	2.177	0.413	0.55	0.92
5.	*20 % BLA*	2.179	2.175	2.171	2.168	0.368	0.51	0.83

Table F3 –B Change in compressive strength under 5% (H_2SO_4) solution

No.	Percentage of bamboo ash content (%)	Initial compressive strength after 28 days before immersing in 5% (H_2SO_4) solution	Compressive strength (MPa) after immersing in a sulphuric acid (H_2SO_4) solution			Loss (%) of compressive strength (Mpa) between the initial strength and 28, 56, and 90 days after soaking		
		Initial	28 days	56 days	90 days	28 days	56 days	90 days
1.	0 % BLA	26.3	25.9	25.5	24.9	1.52	3.04	5.32
2.	5 % BLA	27.4	26.8	26.3	25.9	2.19	4.01	5.47
3.	10 % BLA	29.7	29.1	28.3	27.9	2.02	4.71	6.06
4.	15 % BLA	26.8	26.1	25.4	24.8	2.61	5.22	7.46
5.	20 % BLA	24.1	23.3	22.9	22.2	3.32	5.81	7.88

Table F4: Chloride resistance

Table F4 –A Change in mass under 5% (NaCl) solution

No.	Percentage of bamboo ash content (%)	Initial weight (Kg) after 28 days before immersing in chemicals	Weight (Kg) After soaking in 5% sodium chloride (NaCl))			Weight loss (%) between the initial weight and weights of 28, 56, and 90 days		
		Initial	28 days	56 days	90 days	28 days	56 days	90 days
1.	0 % BLA	2.185	2.189	2.199	2.212	0.18	0.64	1.33
2.	5 % BLA	2.181	2.184	2.196	2.209	0.14	0.69	1.28
3.	10 % BLA	2.176	2.181	2.192	2.205	0.23	0.74	1.33
4.	15 % BLA	2.168	2.178	2.189	2.203	0.46	0.97	1.61
5.	20 % BLA	2.162	2.175	2.186	2.201	0.60	1.11	1.80

Table F3 –B Change in compressive strength under 5% (NaCl) solution

No.	*Percentage of bamboo ash content (%)*	*Initial compressive strength after 28 days before immersing in 5% (NaCl) solution*	*Compressive strength (MPa) after immersing in a 5% sodium chloride (NaCl) solution*			*Loss (%) of compressive strength (MPa) between the initial strength and 28, 56, and 90 days after soaking*		
		Initial	*28 days*	*56 days*	*90 days*	*28 days*	*56 days*	*90 days*
1.	*0 % BLA*	26.3	26.2	25.8	25.1	0.38	1.90	4.56
2.	*5 % BLA*	27.4	27.2	26.7	26	0.73	2.55	5.11
3.	*10 % BLA*	29.7	28.9	28.4	28.1	2.69	4.38	5.39
4.	*15 % BLA*	26.8	26.1	25.6	25.3	2.61	4.10	5.60
5.	*20 % BLA*	24.1	23.4	22.9	22.7	2.90	4.98	5.81

Appendix G: Materials for the experimental tests

G1: Mechanical properties tests

Table G1-A: Compressive strength

No.	*Percentage of Bamboo leaf ash*	*Curing days at ambient temperature*			*Specimens size (mm) and mix ratio*
		28 days	*56 days*	*90 days*	
1.	*0 % BLA*	3	3	3	*Cube size of 100x100x100 Class 25 target mix ratio*
2.	*5 % BLA*	3	3	3	
3.	*10 % BLA*	3	3	3	
4.	*15 % BLA*	3	3	3	
5.	*20 % BLA*	3	3	3	
Total samples of compressive strength = 3 x 15 = ***45 cubes***					

Table G1-B: Splitting tensile strength

No.	*Percentage of Bamboo leaf ash*	*Curing days at ambient temperature*			*Specimens size (mm) and mix ratio*
		28 days	*56 days*	*90 days*	
1.	*0 % BLA*	3	3	3	*Cylinder size of 300x150 mm Class 25 target mix ratio*
2.	*5 % BLA*	3	3	3	
3.	*10 % BLA*	3	3	3	
4.	*15 % BLA*	3	3	3	
5.	*20 % BLA*	3	3	3	
Total samples of compressive strength = 3 x 15 = ***45 cubes***					

G2: Durability performance tests

Table G1: Water absorption test

No.	*Percentage of Bamboo leaf ash*	*Curing days at ambient temperature*	*Specimens size (mm) and mix ratio*
		28 days	
1.	*0 % BLA*	3	*Cube size of 300x150 mm Class 25 target mix ratio*
2.	*5 % BLA*	3	
3.	*10 % BLA*	3	
4.	*15 % BLA*	3	
5.	*20 % BLA*	3	
*Total samples of water absorption= 3 x 5 = **15 cubes***			

Table G2: Specimens under chemical exposure solutions for the durability

No.	*Experimental tests*	*Age of curing days*	*Change in mass specimens*					*Change in compressive strength specimens*					*Specimens size (mm)*
			Percentage (%) of bamboo leaf ash					*Percentage (%) of bamboo leaf ash*					
1.	*Sulphate resistance test specimens*		*0%*	*5%*	*10%*	*15%*	*20%*	*0%*	*5%*	*10%*	*15%*	*20%*	*100x100x100 cube*
		28	3	3	3	3	3	3	3	3	3	3	
		56	3	3	3	3	3	3	3	3	3	3	
		90	3	3	3	3	3	3	3	3	3	3	
		*Total samples under 5% ($MgSO_4$) salt solution = 30x3 = **90 cubes***											

2.	Acid resistance test specimens	28	3	3	3	3	3	3	3	3	3	3	100x100x100 cube
		56	3	3	3	3	3	3	3	3	3	3	
		90	3	3	3	3	3	3	3	3	3	3	
		*Total samples under 5% (H_2SO_4) acid solution = 30x3 = **90 cubes***											
3.	Chloride attack test specimens	28	3	3	3	3	3	3	3	3	3	3	100x100x100 cube
		56	3	3	3	3	3	3	3	3	3	3	
		90	3	3	3	3	3	3	3	3	3	3	
		*Total samples under 5% (NaCl) salt solution = 30x3 = **90 cubes***											

Table G3: list of all the experimental test samples and their volumes

No	Experimental tests of the study	Size of cubes (mm)	No. of samples	Volume (m^3)	Total volume (m^3)
1	Compressive strength	100x100x100	45	0.001	0.045
2	Splitting tensile strength	300x150 Cylinder	45	0.0053	0.24
3	Water absorption	100x100x100	15	0.001	0.015
4	Sulfate Resistance	100x100x100	90	0.001	0.09
5	Acid resistance	100x100x100	90	0.001	0.09
6	Chloride attack	100x100x100	90	0.001	0.09
			375 specimens		**0.57 m3**
*The total volume of all specimens = **0.57 m^3***					
*For wastage, it is factored by 1.1, which is equal to **0.57 x1.1 = 0.627 m^3***					

Table G4: Mix design of geopolymer concrete with bamboo leave ash (BLA)

No.	*Constituents' materials of geopolymer concrete*	*Percentage of bamboo leaf ash as a replacement for fly ash class (F)*				
		0 %	*5 %*	*10 %*	*15 %*	*20 %*
1.	*Fly ash (Kg)*	*54.55*	*51.83*	*49.10*	*46.37*	*43.64*
2.	*Bamboo leaf ash (kg)*	*0*	*2.73*	*5.46*	*8.18*	*10.91*
3.	*Fine Aggregate (kg)*	*81.82*	*81.82*	*81.82*	*81.82*	*81.82*
4.	*Coarse Aggregate(kg)*	*163.64*	*163.64*	*163.64*	*163.64*	*163.64*
5.	*Solution/binder*	*0.6*	*0.6*	*0.6*	*0.6*	*0.6*

Table G5: Material Required for C 25 Mix Ratio of Geopolymer Concrete

Ingredients of GPC	*Bamboo leave ash*	*Fly ash class F*	*Fine Aggregate*	*Coarse Aggregate*	*Na_2SiO_3 (SS)*	*NaOH (SH)*	*SS/SH (117/46.8)*
Quantity (kg)	*27.3*	*245.5*	*409.1*	*818.2*	*117*	*46.8*	*2.5*

Appendix H: Calculation of mixture proportion of geopolymer concrete

Unit weight of Geopolymer concrete	***= 2400 kg/m3***
Class 25 (1:1.5:3)	
Total volume of 5 batches from Appendix G, Table G3	***= 0.627 m3***
Fly ash (Batch 1) = 1/5.5 x (0.625/5) x 2400 kg/m3	*= 54.55 kg*
Total (fly ash + BLA)	***= 273 kg***
Batch 1 (BLA)= 54.55 x 0%	*= 0*
Batch 2 (BLA) = 54.55 x 5%	*=2.73 kg*
Batch 3 (BLA)= 54.55 x 10%	*= 5.46 kg*
Batch 4 (BLA) = 54.55 x15%	*= 8.18 kg*
Batch 5 (BLA)= 54.55 x 20%	*=10.91 kg*
Total bamboo leaf ash (BLA),	***=27.3 kg***
Total (FA +BLA) =	***= 273 kg***
Total fly ash class F = 273 kg – 27.3 kg	***= 245.5 kg***
Fine aggregate = 1.5/5.5 x 0.627 x 2400kg/m3	*= 410 kg*
Coarse aggregate = 3/5.5 x 0.627 x 2400kg/m3	*= 820 kg*

Calculation of Alkaline Liquid

Mass of binding materials (fly ash, BLA)	***= 273 kg***
Alkaline liquid / fly ash ratio by mass	*= 0.6*
Alkaline liquid = 0.6 x mass of fly ash	
Alkaline liquid = 0.6 x 273kg	*= 163.8 kg*

Ratio of sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) = 2.5

Na2SiO3 / NaOH = 2.5

Na_2SiO_3 = 2.5 NaOH ……………………………………………………………………………. (i)

NaOH + Na2SiO3 = Total alkaline liquid ………………………………………………. (ii)

NaOH + Na2SiO3 = 163.8 kg

Substitute (Na_2SiO_3) to equation 1

NaOH + 2.5 NaOH = 163.8 kg

NaOH (1 + 2.5) = 163.8 kg

$$NaOH = \frac{163.8\ kg}{(1\ +\ 2.5\ )}$$

$$NaOH = \frac{163.8\ kg}{3.5} = \mathbf{46.8kg}$$

Sodium silicate (Na_2SiO_3) from equation (ii):

Na_2SiO_3 = 163.8 kg – NaOH

Na_2SiO_3 = 163.8 kg – 46.8

*Na_2SiO_3 **= 117 kg***

Checking the ratio of Na2SiO3/ NaOH of 2.5;

$$\frac{117\ kg}{46.8\ kg} = 2.5 \quad ok$$

Preparation of sodium hydroxide (NaOH):

NaOH = 16 molar,

First, let's calculate the molar mass of NaOH:

Na = 22.98 g/mole, O = 16 g/mole, H = 1 g/mole

Molecular Weight of (NaOH) = (22.98 +16 +1) = 40 g/mole

1 mole of NaOH = 40 gram

Hence,

1 mole NaOH = 40 gram

16 moles = X

NaOH = 16 x40 = 680 grams

f or preparing 16 molars (M) of sodium hydroxide (NaOH) solution = 16 x 40 gram

680 grams of NaOH was dissolved in 1000 ml of distilled water.