EFFECT OF MICRO LIME ON THE ENGINEERING PROPERTIES OF AMBIENT TEMPERATURE-CURED SUGARCANE BAGASSE ASH-BASED GEOPOLYMER CONCRETE

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A thesis submitted to the School of Engineering and Built Environment in partial fulfillment of the requirement for the award of the Degree of Master of Science in Structural Engineering of Masinde Muliro University of Science and Technology

October 2024

DECLARATION

I declare that this thesis is my original work and has not been submitted for the award of any degree or other award in this institution or any other university to the best of my knowledge.

Sign…………………………………… Date……………………………………

Thuku Keithy Kamau

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CERTIFICATION

The undersigned certify that they have read and hereby recommend for approval of Masinde Muliro University of Science and Technology a research thesis titled **"Effect of Micro Lime on the Engineering Properties of Ambient Temperature-Cured Sugarcane Bagasse Ash-Based Geopolymer Concrete."**

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DEDICATION

I dedicate this thesis to Mr. and Mrs. Thuku.

ACKNOWLEDGEMENT

I truly appreciate Dr Benard Omondi and Dr Janet Oyaro, who served as my supervisors, for their dedication to providing me with the essential direction in all facets of the research. Their remarks provided excellent information and provocative questions on which I could base my in-depth research.

Prof. David Koteng, the Director of Civil and Resource Engineering, at Technical University of Kenya, was extremely generous in allowing the research to be conducted at their Concrete Laboratory. Mr Leonard Simiyu, a member of the laboratory team, provided crucial assistance. I would also like to thank Indoor East Africa in Nairobi for providing a superplasticizer using sodium naphthalene formaldehyde (SNF), which was used in the tests.

I sincerely thank you! The Technical University of Kenya's Mr. Brian Otieno, Miss. Cynthia Nziva, Mr. Joseph Ng'ang'a, and Miss. Mercy Lovi contributed significantly. Mr. Frank Odero and Miss Linda Akoth, fellow students who were excellent sources of support and constructive criticism, must also be thanked.

My parents, I truly appreciate your encouragement and assistance during the demanding period of the study project. God is going to bless you richly. The Almighty God, in Whom I live and have my being, is the one to whom I owe the greatest obligation of gratitude. He beheld His outstretched hand of provision and unwavering grace, giving me the courage to pursue knowledge.

ABSTRACT

The use of cement in the building sector is environmentally unsustainable due to significant carbon emissions. Advancing concrete technology places geopolymer concrete as a potential green concrete by completely replacing Ordinary Portland Cement. However, the geopolymerization process is initiated at elevated temperatures, which demands that curing at elevated temperatures be conducted for several hours, limiting its application. Calcium ions in Geopolymer concrete (GPC) allow the formation of Calcium Aluminate Silicate and Calcium Silicate Hydrate gels, allowing ambient temperature curing. To study the effect of micro lime on the engineering properties of ambient temperature-cured sugarcane bagasse ash-based GPC, this research used Sugarcane Bagasse Ash (SCBA) as source material; one part of sodium Hydroxide 16M solution and two parts of sodium silicate were used as the alkaline activator. Crushed stones and river sand were utilized as the coarse and fine aggregates, respectively. A sodium naphthalene formaldehyde (SNF) based superplasticizer was added at 3% of the SCBA. Micro lime was added as an admixture in varying proportions as a percentage weight of SCBA. In the fresh state, it was found that the workability decreased with the increase of micro lime content. The ambient temperature curing of the SCBA-based GPC was achieved at a 1% addition of the micro lime. The SCBA-based GPC's compressive strength increased with the micro lime increase, up to 7%. The ambient temperature-cured SCBA-based GPC at 3% had the best water absorption resistance. The SCBA-based GPC had no significant weight loss on 2.5% sulfuric acid exposure. The 5 and 7% micro lime mix had no significant change in compressive strength under the condition of sulfuric acid, unlike the 0,1 and 3%. The results from this research contribute to the body of knowledge on ambient temperature-cured SCBA-based geopolymer concrete. It reveals the possibility of expanding the applications of GPC made from the locally available source material, SCBA.

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ABBREVIATIONS, ACRONYMS AND SYMBOLS

AAS	Alkaline Activator Solution
ACI	American Concrete Institute.
ASTM	American Society for Testing and Materials
BBA	Bottom Bagasse Ash.
BS EN	British Standard European Norm.
C-A-S-H	Calcium Aluminate Silicate Hydrate
CO_2	Carbon (iv) Oxide.
CRMs	Cement Replacement Materials.
C-S-H	Calcium Silicate Hydrate
DMDA	Densified Mix Design Algorithm.
FBA	Filter Bagasse Ash
FM	Fineness Modulus
GGBS	Ground Granulated Blast Furnace Slag.
GPC	Geopolymer Concrete
LOI	Loss on Ignition.
MAS	Maximum Aggregates size.
MPa	Megapascals.
Na_2SiO_3	Sodium Silicate.
NaOH	Sodium Hydroxide.
N-A-S-H	Sodium Aluminosilicate Hydrate
OPC	Ordinary Portland Cement
SC	Solarcure Curing
SCBA	Sugarcane Bagasse Ash.
SP	Superplasticizer.

XRD	X-ray Diffraction.
XRF	X-ray Fluorescence.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

There is evidence of increased concern about global warming. Thus, finding sustainable, environmentally friendly methods of infrastructural expansion is critical (Wong, 2022). Concrete is a significant component of diverse infrastructure development, second only to water consumption (Gagg, 2014). Ordinary Portland Cement (OPC) is a significant component of cement concrete used as a binder (Okoye, 2017). Concrete will continue to be in demand due to the rising demand for infrastructure development. In engineering history, cement has been the most often used element in concrete as a binding agent for aggregates.

Some environmental issues caused by cement production include depleting natural reserves such as fossil fuel supplies, lack of raw materials and escalated environmental concerns affiliated with climate change. Cement manufacturing has a significant carbon footprint, uses excessive energy, and contributes significantly to the global human Carbon (iv) Oxide (CO_2) emissions (Ahmed et al., 2022). About one ton of carbon dioxide is released during cement production (Worrell et al., 2001). Cement production requires a lot of energy; the energy requirement for producing 1 kilogram of cement is about 1.76 Megaloules (Soomro et al., 2023).

Using pozzolanic admixtures like fly ash in place of Ordinary Portland Cement clinker makes it possible to mitigate the CO_2 emissions from cement manufacture (Al-Bakri et al., 2023), which is proving more environmentally sustainable. This is also part of a sustainable environment, achieved by inter-grinding Portland cement clinker with natural pozzolana to lower the carbon footprint (Koteng', 2019). The natural pozzolana, including recycled materials and wastes (industrial, agricultural, and domestic) as substitutes or, in some cases, replacements in cement, have been the focus of many researchers. Cement Replacement Materials such as Fly Ash, Ground Granulated Blast Furnace Slag (GGBS), Metakaolin, Rice Husks Ash (RHA), Sugarcane Bagasse Ash (SCBA), and others enhance the binder's long-term strength and durability (Davidovits, 2013).

Industrial by-products rich in aluminosilicates, such as fly ash, blast furnace slag, and silica fume, are widely used as substitutes for OPC binders because they have cement-like binding capabilities when combined with aqueous alkali-metal solutions such as Sodium Hydroxide (NaOH), Potassium Hydroxide (KOH) and Sodium Silicate (Na_2SO_3) (Davidovits, 2013). When amorphous aluminosilicate elements dissolve and quickly condense in an alkaline environment, they produce vast networks of polymeric gel, thus geopolymer binder (Nawaz et al., 2020). Geopolymer cement is produced by treating raw materials, which are essentially industrial or agricultural wastes, that contain aluminosilicate with alkali hydroxide and alkali silicate. Concrete that contains geopolymer binder is known as geopolymer concrete (Singh et al., 2020). Thus, geopolymer concrete (GPC) is concrete that is based on source material and an alkaline solution to replace cement in conventional cement-based concrete fully.

The source material for geopolymers should be rich in alumina and silica. Examples include natural minerals such as Kaolinite clay, by-product materials such as fly ash, silica fumes, Ground Granulated Blast Furnaces (GGBS), Rice Husks Ash (RHA) and Sugarcane Bagasse Ash (SCBA). The cost, accessibility, type of application, and individual end-user requirements all influence the decision. The sodium- or potassium-based soluble alkali metals are the source of the alkaline liquids. The most typical alkaline solution contains Sodium Silicate, Potassium Silicate, Potassium Hydroxide, or both. The sodium hydroxide-prepared material has superior sulfate attack resistance because of the stable, interconnected aluminosilicate polymer structure (Karthiyaini, 2016). In dissolving the source materials, OH ions break the aluminosilicates (Waqas et al., 2021). Therefore, ensuring enough OH ions are in the geopolymer matrix for the geopolymerization process is crucial. Furthermore, it can be inferred that the NaOH solution's molarity influences the geopolymer matrix's compressive strength.

Like any other geopolymer concrete without Calcium ions as part of the mix, elevated temperatures are required for several hours for curing. Elevated temperature curing is expensive and limited due to a lack of geographical electrical connectivity and the high cost of electricity. Steam curing also requires electricity. Solarcure involves exposure of the GPC to 90^{o}C for three days with an 8-hour exposure to the sun in a fabricated box (Zahid et al., 2018). Elevated curing, achieved by continuous oven curing, steam curing, and solarcure, is restricted to precast elements and laboratory-scaled works, limiting the prudent application of SCBA geopolymer concrete. In contrast, the binder ought to be able to be set at ambient temperature for regular concrete. The commercial usage of concrete built with geopolymer SCBA is constrained by high-temperature curing. It is necessary for SCBA-based geopolymer concrete to cure in ambient conditions to expand its range of applications.

The need to advance the application and versatility of GPC is based on its durability properties. This technology is employed in sewage systems, mining industries, sulfate-rich soils, marine habitats, environments with high amounts of carbon dioxide, and panels for walls with exceptional fire resistance (Karthiyaini, 2016).

Sulfate ions interact chemically with the constituents of hardened concrete in a series of reactions known as sulfate attack. Since these reactions could result in the cracking, spalling, or loss of strength of concrete structures, appropriate test methodologies are needed to determine the resilience of concrete under sulfate exposure. Geopolymer concrete can be utilized for structures subjected to sulfate assault because of its excellent resistance to sulfate damage (Xie et al., 2019).

According to (Hassan et al., 2020), an alkaline silicoaluminate gel containing cross-linked silicon and aluminium tetrahedra is the primary reactivity product produced by a fly ash-based geopolymer. Sodium Aluminosilicate Hydrate, or N-A-S-H gel, is the gel formed when NaOH is used to serve as the alkaline activator for this geopolymer. In another research (Garcia-Lodeiro et al., 2011), as long as calcium ions are available, N-A-S-H is converted into Calcium Aluminosilicate Hydrate (C-A-S-H) and Calcium Silicate Hydrate (C-S-H) at high pH. Concrete made of geopolymer can harden at room temperature because C-S-H gel forms in the matrix. GGBS's calcium ions would encourage C-S-H nucleation. Therefore, the mechanical and microstructural qualities of the Fly Ash – GGBS blend-based geopolymer mix will be better the more significant the fraction of GGBS in the mixture (Karuppannan et al., 2020). They referred to the increased accumulation of Calcium Aluminate Silicate Hydrates, C-A-S-H reaction gel, as the main product of geopolymerization. C-A-S-H gel eliminates the need for high temperatures to cure the geopolymer concrete.

One common industrial byproduct that is readily available locally is sugarcane bagasse ash (SCBA). Because bagasse has a high calorific value, it can be burned in huge quantities in a sugar-producing region to produce electricity for milling, clarifying, evaporation, and crystallisation equipment. The byproduct of this incineration process is SCBA. Despite the fact that the amount of ash in the bagasse is only about 3% of its initial mass, the volume of burned bagasse can produce a significant amount of SCBA, which needs to be managed in an environmentally responsible and cost-effective manner

(P. Zhang et al., 2020). The SCBA is pozzolanic due to its substantial Silica presence in the amorphous state (Yadav et al., 2020).

The mineral analysis of SCBA from various countries shows a varying percentage of Calcium Oxide ranging from 1.69% to 10.07% (Abdalla et al., 2022). SCBA has a lower calcium oxide percentage when compared to GGBS (41.37%) (Puertas et al., 2011).

In an effort to obtain ambient temperature-cured GPC, researchers have proposed the use of additional material such as quick lime to accelerate polymerization. Quick lime, commonly known as calcium oxide, grows the early strength of geopolymer concrete but diminishes its workability. Using the calcium ion in the SCBA-based geopolymer concrete would allow ambient cured geopolymer concrete, avoiding elevated temperature curing in geopolymer concrete. Micro lime is the microscopic particle size of the quicklime. The particle size of micro lime is of 5 micrometer or less (Zhu Minjie et al., 2023).

Several questions must be addressed: Can the SCBA-based geopolymer concrete be cured at room temperature when micro lime is added? Can SCBA-based geopolymer concrete made using micro lime have good compressive strength and maintain its excellent durability? Therefore, this research aimed at investigating the effect of micro lime on the engineering properties of SCBA geopolymer concrete.

1.2 Problem Statement

Eco-friendly Geopolymer Concrete (GPC) composed of SCBA as source material is cured at temperatures between 50°C and 100°C for a minimum of 6 to 8 hours, continuous oven curing. Elevated temperature curing is expensive and limited due to a lack of geographical electrical connectivity and the high cost of electricity. Steam curing also requires electricity. Solarcure involves exposure of the GPC to 90°C for three days with an 8-hour exposure to the sun in a fabricated box. Elevated curing, achieved by continuous oven curing, steam curing, and solarcure, is restricted to precast elements and laboratory-scaled works, limiting the prudent application of SCBA geopolymer concrete. In contrast, the binder should be able to be set at room temperature for regular concrete. Geopolymer concrete increasingly includes reactive calcium to permit curing at room temperature, although SCBA-based geopolymer concrete has gotten less attention. A possible remedy is using micro lime due to its higher reactivity power than the coarse-grained quicklime. However, there is limited data on the effect of micro lime on ambient temperature cured SCBA-based GPC in terms of strength and durability. It is against this background that this research aimed to investigate the effect of micro lime on the engineering features of SCBA-based geopolymer concrete because the precise amount of reactive calcium in SCBA-based polymer concrete is unclear. Furthermore, the dosage of micro lime should also be verified.

1.3 Objectives

1.3.1 Main Objective

To investigate the effect of micro lime on the engineering properties of ambient temperature-cured sugarcane bagasse ash-based geopolymer concrete.

1.3.2 Specific Objective

1. To evaluate the workability of the SCBA-based geopolymer concrete with varying proportions of micro lime.
2. To evaluate the compressive strength of the SCBA-based geopolymer concrete with varying proportions of micro lime and cured at ambient temperature.

3. To evaluate the water absorption on the SCBA-based geopolymer concrete with varying proportions of micro lime and cured at ambient temperature.
4. To evaluate the chemical attack of the SCBA-based geopolymer concrete with varying proportions of micro lime and cured at ambient temperature.

1.4 Research Questions

1. How do varying proportions of micro lime affect the workability of SCBA geopolymer concrete?
2. What is the effect of micro lime in varying proportions on the compressive strength of SCBA geopolymer concrete?
3. What is the effect of micro lime in varying proportions on the water absorption of SCBA geopolymer concrete?
4. What is the effect of micro lime in varying proportions on the chemical attack of SCBA geopolymer concrete?

1.5 Justification

Utilizing industrial and agricultural waste for engineering applications is a sustainable disposal technique for disposing of vast amounts of garbage. Geopolymer concrete efficiently uses industrial waste to produce eco-friendly concrete. This work will help to greater sustainability by substituting SCBA for cement in concrete manufacturing. Multiple environmental benefits will result, including a reduction in CO_2 emissions that will help mitigate the consequences of climate change.

Leveraging on the superior benefits of geopolymer concrete, SCBA-based geopolymer concrete proves to be a sustainable construction material. The SCBA-based GPC, like other types of GPC, is cured under elevated temperatures. It must be cured under ambient temperature to allow wide application of SCBA-based GPC in the construction industry.

Thus, the research investigates the effect of micro lime on the engineering properties of SCBA-based geopolymer concrete.

1.6 Scope and Limitations

This study focused on examining the mechanical and durability properties of concrete. The workability of fresh concrete was also analyzed. The study specifically looked at the compressive strength of the concrete and its ability to resist water absorption and chemical damage from acid attack. The tested concrete was SCBA geopolymer concrete with micro lime addition, and it was cured under ambient conditions.

1.7 Outline of the Thesis

This thesis contains Five Chapters. Chapter one (Introduction) provides an introduction to concrete and geopolymer concrete. The chapter also explains the problem being tackled by the research, the objectives of the research, research questions based on the specific objectives, and the limitations of the research.

Chapter two (Literature Review) contains reviewed literature on geopolymer concrete. The constituents of geopolymer concrete are the source material, i.e., sugarcane bagasse ash, micro lime, and alkaline activator. The reaction mechanism, the curing and the mix design of geopolymer concrete are also reported. After the review of the literature review, the research gap and conceptional framework were are presented comprehensively.

Chapter three (Methodology), highlights the material that were used and their various sources, the laboratory procedures followed to get their material properties and the relevant standards to determine their suitability for the manufacture of concrete. The mix design is described in section 3.3. The constituents of geopolymer concrete were machine mixed, tested for workability, cast of cubes, and demoulded. Some were cured in an oven at 100^{o}C for 24 hours, and some were left at room temperature to be cured for up to 56 days. The tests were done at 7 and 14-day intervals. This chapter also highlights the ANOVA and descriptive method of analysis.

Chapter four (Results and Discussion) reports and discusses the properties of fine and coarse aggregates used in this study from laboratory experiments. Characterization of sugarcane bagasse ash by determining its chemical properties. It also discussed the results of workability, compressive strength, water absorption and chemical resistance test in a bid to determine the effect of micro lime on ambient temperature-cured geopolymer concrete and that without micro lime, cured in an oven.

Finally, Chapter Five (Conclusion and Recommendations) presents the conclusions and recommendations based on the results discussed in Chapter Four.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter contains reviewed literature from various scholars in the concrete and narrowing down to geopolymer concrete. The constituents of geopolymer concrete, are the source material i.e., sugarcane bagasse ash, the micro lime, and alkaline activator. The reaction mechanism, curing, and geopolymer concrete mix design are also reported. After the review of the literature review, the research gap and conceptual framework were presented comprehensively.

2.2 Geopolymer Concrete

Geopolymer concrete has developed due to the ongoing substitution of pozzolanic material for cement clinker, forming the ideal replacement of Ordinary Portland Cement (OPC) in the production of green concrete. The binder in geopolymer concrete is a cementitious paste made from amorphous aluminosilicate and activated by an alkaline solution. A solid, long-lasting alumino-silicate substance known as a geopolymer is typically created by activating a solid powder precursor with either alkaline hydroxide or alkaline silicate (Davidovits, 2013; Provis & Van Deventer, 2009). It has an amorphous structure. The reaction between an alkaline liquid acting as an activator and an aluminosilicate powder serving as the source material results in the solid mineral. Geopolymers are structurally composed of the gel phase that contains chains of silicon-oxygen and oxidoperoxy alumane tetrahedra that are randomly arranged. Charge balance is provided by a significant number of interstitial alkali and alkali earth cations once the complex geopolymerization process is finished, which involves recondensing the silica-alumina tetrahedra into a gel phase while simultaneously releasing water molecules and destroying the raw silicate structure by the alkali solution. The unreacted aluminosilicate raw materials, the coarse and fine aggregates, and this gel phase form a constant mass of binder (Nawaz et al., 2020).

Traditional cement and geocements can set and harden at ambient temperature due to the formation of Calcium Silicate Hydrate (C-S-H) gel. The source of its strength, though, is aluminum-silicate polycondensation. The geopolymerization reaction typically needs to start at an elevated temperature, thus the elevated temperature curing (Adam & Horianto, 2014; Triwulan et al., 2017; Zahid et al., 2018). Due to challenges with heating on-site, heat-cured geopolymer concrete is less economically viable and only suitable for precast members, limiting the application of geopolymer concrete for infrastructural development (Nuaklong et al., 2020).

Materials widely utilized to create geopolymer concrete include fly ash, granulated blast furnace slag (GGBS), sugarcane bagasse ash, and calcined kaolin (metakaolin). Depending on the source material, several types of geopolymer concrete can be categorized, including metakaolin, slag, fly ash, rice husks, and sugarcane bagasse (Ryno, 2014). The various source materials impact the final concrete product. The key factors determining the source material to be utilized are its accessibility, affordability, nature of application, and any particular demands of the end users (Baskar et al., 2014).

In the geopolymerization chemical reaction, aluminosilicate oxide (Si_2O_5 and Al_2O_2) reacts with polysilicates to create a three-dimensional polymeric link (Si-O-Al-O) under alkaline conditions. The method of chemically integrating minerals is more accurately described by the term "geosynthesis." The final product of this process is the geopolymer mineral's essential constituents (Khale & Chaudhary, 2007).

Chemical companies produce sodium or potassium silicates, which have a crystalline, glassy structure or a non-crystalline, amorphous structure (Davidovits, 1991). The main variables influencing the geopolymer process are the alkaline solution concentration, water/solid ratio, curing time, and curing temperature. The chemical and mineral content of the binder is an additional crucial element (Khale & Chaudhary, 2007).

The concentration of the alkaline solution, the curing temperature, the curing duration, and the chemical makeup of the source material all have an impact on the silica-to-aluminum ratio, which directly influences the strength of geopolymer concrete (Fernández-Jiménez et al., 2005). The characteristics of geopolymers are significantly influenced by the abundance of aluminium (Provis, 2009). Perhaps more importantly, the rate at which Aluminium is released throughout the reaction affects the strength, setting characteristics, acid resistance, microstructure, and most notably, the strength development profile of the geopolymer.

2.3 Alkaline Activator

The alkaline activator participates in condensation and acts as a solvent for the silica and aluminium's dissolution. It is necessary to use a strongly alkaline solution. Potassium Hydroxide, Sodium Silicate, Potassium Hydroxide, and Sodium Hydroxide are the most often used activators in geopolymer concrete (Ryno, 2014).

The qualities of the geopolymer concrete binder are influenced by the type of alkaline solution employed, even though sodium compounds also exhibit good compressive strength and workability for the same binder concentration and alkali-to-silicate ratio as potassium compounds (Sabitha et al., 2012). Compared to their sodium counterparts, potassium compounds are more expensive.

The required reactivity and the cost of the solution influence the choice of alkaline solution (Ryno, 2014). When combined with sodium silicate, sodium hydroxide is an effective alkaline activator that improves the reaction between the binder and the alkaline activator, producing good mechanical properties (Fernández-Jiménez et al., 2005).

The activator effectiveness depends on activator dosage, ambient temperature, molarity, and water-to-binder ratio (Kabir et al., 2015),. They also discovered that silica and alumina released from high molarity increase compressive strength. A solution with a high concentration of sodium hydroxide promotes polymerization, thereby increasing compressive strength. However, regarding molarity, a higher concentration of Sodium Hydroxides reduces the workability. A high molarity of Sodium Hydroxide (NaOH) results in a higher concentration of the NaOH solution, which promotes quick dissolution of the aluminosilicates, forming stronger bonds (Waqas et al., 2021).

Potable water is less viscous than the alkaline solution (Pavithra et al., 2016). Consequently, workability will be hindered when utilising an alkaline solution to make GPC, while workability will be improved when Portland concrete is made with the same amount of water. As a result, it has been discovered that attempts to improve the workability of GPC by including more water resulted in the specimens bulging and losing strength. Instead of adding water, a superplasticizer based on naphthalene was suggested to make GPC more workable. Superplasticizer was found to have a major effect on the behaviour of fresh GPC without appreciably altering its compressive strength or other properties.

According to (Kabir et al., 2015; Pavithra et al., 2016; Ryno, 2014), in order to allow for complete crystal dissolution of the sodium hydroxide pellets and heat dissipation, sodium hydroxide was made the day before and maintained at room temperature.

2.4 The Reaction Mechanism of Geopolymer Concrete

A destruction-condensation transformation occurs in the initial solid precursor to produce coagulated structures that condense during the creation of geopolymer concrete to create the binder, as described in (Puligilla, 2007). During poly-condensation events, water is expelled, and the gel reorganizes to form a rigid three-dimensional network.

2.4.1 General Characteristics of Geopolymer Concrete Gel

During the production of geopolymer concrete, Portland Cement (PC) as a binder is replaced with two types of materials. These consist of an activator and a source material high in alumina and silica, including fly ash, rice husk ash and granulated blast furnace slag. When slag is incorporated as part of the source material, Calcium Silicate Hydrate (CSH) is the primary by-product identical to Calcium Silicate Hydrate (CSH), a byproduct of Portland Cement hydration as shown in Figure 2.1 (Duque-Redondo et al., 2022; Kar, 2013).

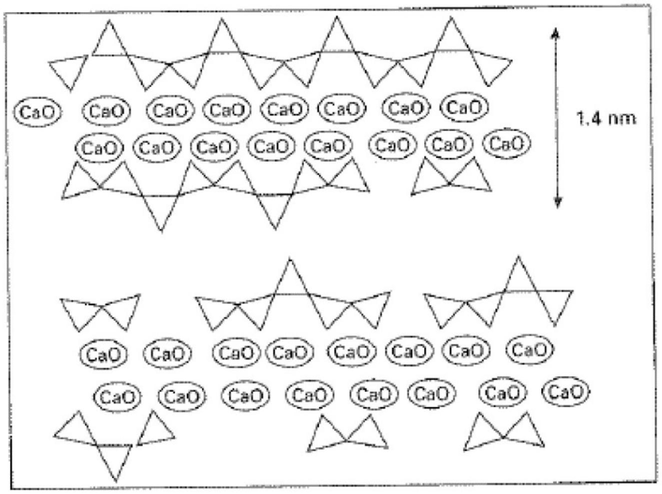

Figure 2. 1 PC CSH Gel Structural Model (Duque-Redondo et al., 2022)

Fly ash alongside alkaline solution reaction products differ from PC chemically and microscopically. Fly ash activated by an alkaline solution yields an alkaline aluminosilicate as a reaction product. It comprises three-dimensionally arranged silicon aluminium tetrahedra (Davidovits, 1991; Fernández-Jiménez et al., 2005), as shown in Figure 2.2. The network's cavities can incorporate alkaline cations to make up the difference for the imbalance charges resulting from the substitution of Al (III) for Si (IV).

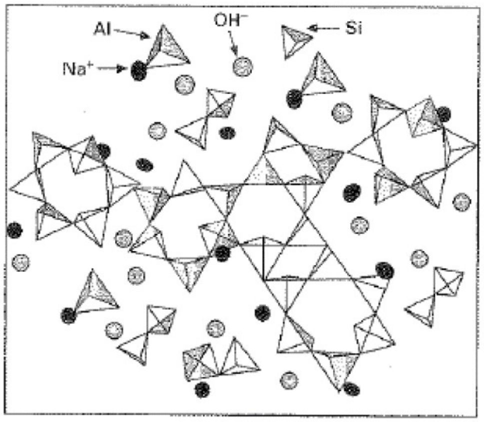

Figure 2. 2 Two-Dimensional Model of Structure for N-A-S-H Gel (Fernández-Jiménez et al., 2005)

The chemistry and nanostructure of alkaline aluminosilicate gel are influenced by the alkali, its concentration, the length of the curing process, and the temperature. Unlike geopolymer (Fernández-Jiménez & Palomo, 2005) created the acronym N-A-S-H for sodium aluminosilicate. Geopolymers are more well-known commercially, while N-A-S-H is commonly known among cement specialists and scholars (Provis & Van Deventer, 2009).

2.4.2 Function of Silicon in the N-A-S-H Gel Framework

In geopolymer concrete, the level of reaction, the curing circumstances, and—most significantly—the inclusion of soluble silica within the alkali activator all affect the structural makeup of the N-A-S-H gel (Puligilla, 2017). Since silica in N-A-S-H does not always originate from the source material, the final factor must be considered. It could also be due to the alkaline activator. Sodium silicate's silica is dispersible and combines with the N-A-S-H matrix. The amount of silica polymerization in the activating solution is determined by the sodium silicate solution's SiO_2/Na_2O ratio, which impacts the intermediate structural phases in forming the N-A-S-H matrix (Provis & Van Deventer, 2009).

Additionally, indefinitely increasing the Si/Al ratio in the N-A-S-H could be ineffective. To utilize binders with low CO_2 emissions, the optimal SiO_2/Na_2O ratio for the N-A-S-H gel matrix in the geopolymer concrete is 2 (Kar, 2013).

2.4.3 Aluminium's Contribution to N-A-S-H Gel

Alkaline silicate solutions with high concentrations are usually metastable and have a pH of around 5.5. Therefore, soluble silicates being present alone cannot result in the formation of a substance that has been chemically hardened. The compounds derived from silicates dissolve back into the water. Aluminium initiates condensation processes in alkaline aluminosilicates through chemical means. As a result, the quantity of aluminium in the precursor substance considerably impacts how the N-A-S-H matrix develops, affecting the mechanical properties of geopolymer concrete.

2.4.4 Sodium's Function in N-A-S-H Gel Structure

AlO^{4+} tetrahedral units absorb the negative charge that alkaline cations balance to create hydrated aluminosilicate gel. By being connected to aluminium internal to the gel structure and available in the solution that fills up the pores, sodium cation can counter the negative charge created by AlO^{4-} and the charge on the $Al(OH)^{4-}$ groups. Si/Al ratios lower than 1.40 were found in aluminosilicates, where this was observed (Provis, 2009).

2.4.5 The Function of Calcium in C-A-S-H/C-S-H

The readily available cations significantly impact the amount of condensation in geopolymer concrete (Puligilla, 2007). Because calcium strongly polarizes the alkali metal ions with a greater charge, such as sodium and potassium ions, calcium participates in complexing silicates and aluminosilicates. Alkaline earth metals (Ca) are more effective than alkaline metals at stabilizing non-bridging oxygen (Na, K). Incorporating calcium ions would thereby limit the generation of polymerized species.

When GGBFS is activated in a mildly alkaline environment to produce alkali-activated slag binders, like the gel produced by the hydration of OPC binders, the principal reaction produced is a 2D C-S-H/C-A-S-H gel. The slag contains 35-40% CaO and other cementitious materials, which qualifies it as a pozzolana (Puligilla, 2017). The slag provides Ca^{2+} for the formation of -S-H/C-A-S-H gel.

Geopolymer concrete created from precursor (aluminosilicate sources) having some calcium contains C-A-S-H, (C, N, K)-A-S-H, and (N, K)-A-S-H, that have been shown to exist together as reaction byproducts in fly ash/metakaolin geopolymers in the presence of any soluble form of calcium (Garcia-Lodeiro et al., 2011). The primary phase supplying strength in OPC containing high-aluminum-containing ingredients and geopolymer concrete is a C-(N-A-S-H) gel.

Diagrammatically, more product enters the pore space on the outermost layer of slag particles when hydroxide-activated binding (C-S-H/C-A-S-H gels) is present, as shown in Figure 2.3(Puligilla, 2007).

One of the best activators, sodium metasilicate, was found to produce quick hardening and Portland cement-like compressive strength (Provis & Van Deventer, 2009).

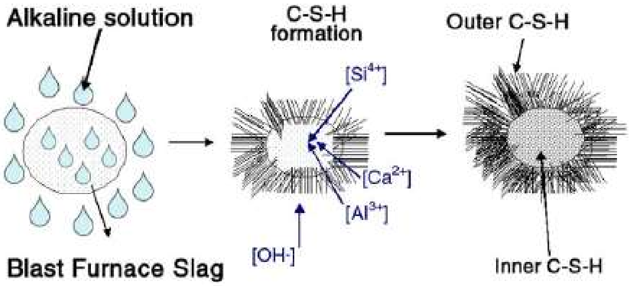

Figure 2. 3 Reaction Mechanism of Hydroxide-Activated Slag Particle (Puligilla, 2017)

In the porous region far from the raw materials, calcium ions that dissolve from the slag particles and silicate ions in the activator combine to create a foil-like C-S-H phase whenever alkaline silicate solutions rapidly accelerate slag (Puertas et al., 2011). The microstructure of pastes of activated sodium silicate slag is a gel-like material between slag particles. They further stated that the microstructure of hydrogen-activated pastes is uniformly hardened with distributed voids, indicating that the product has grown from the outermost layer of particles into the space between them.

2.5 Sugarcane Bagasse Ash Geopolymer Concrete

2.5.1 Sugarcane Bagasse Ash

After the juice obtained from sugarcane is extracted, sugar refineries produce sugarcane bagasse. After being cleaned and dried, sugarcane bagasse normally has the following composition: 45%–55% cellulose, 20%–25% hemicellulose, 18%–24% lignin, and 1%–4% ash (Payá et al., 2018).

Due to the high calorific content, sugar cane bagasse is used as biofuel in sugar factories, converting it to ash, sugarcane bagasse ash (SCBA), which is around 0.3% of the total processed sugar cane bagasse (Abdalla et al., 2022). Due to the presence of contaminants and the burning conditions, several different chemical compositions can be found in the SCBA. The SCBA is pozzolanic due to its substantial silica (SiO_2) presence in the amorphous state (Payá et al., 2018; Yadav et al., 2020). The SCBA could be used to replace clinker content for cement production, giving use to SCBA and providing a solution to the issue of the disposal of the ash. Consequently, numerous researchers have investigated its application in the cement industry.

In a study (Akbar et al., 2021), they found that the total sum of ($SiO_2 + Al_2O_3 + Fe_2O_3$) was higher than 70%, at 77.47%, in sugarcane bagasse ash and thus satisfies the (*ASTM C618*, 2008) standard for pozzolana for Class N Fly Ash. According to a mineral analysis by Arasa et al. (2017), the total amount of SiO_2, Al_2O_3, and Fe_2O_3 in the SCBA obtained from West Kenya Sugar Company meets the standard for pozzolana without additional processing. Several researchers (Akbar et al., 2021; Amin et al., 2022; Arasa et al., 2017; Ferreira et al., 2016) investigated the ability of bagasse ash in cement-like substances to enhance the qualities of concrete and mortar while lowering emissions of carbon dioxide for long-term growth.

The SCBA from the sugar factories and other boilers are categorized into Filter Bagasse Ash (FBA) and Bottom Bagasse Ash (BBA). In a study by (Frías et al., 2011, 2017), they compared the composition and cementitious qualities of FBA and BBA to an SCBA made in a laboratory-controlled burning, Laboratory Bagasse Ash (LBA) (as a benchmark). The total concentration of acidic oxides in the three ash (SiO_2, Al_2O_3, and Fe_2O_3) exceeds 75%, per the mineral analysis. Among the ash, the lowest silica content was 56%, and the highest Loss On Ignition was 18%. The mineralogy of the three ashes is comparable based on XRD analysis, with SiO_2 being the most abundant. Where the boiler temperature exceeds 800 degrees Celsius, the SCBA crystalizes and ceases being amorphous.

The impact of the combustion environment was examined by (Cordeiro et al., 2009) those who calcined SCBAs in a muffle furnace for three hours with temperatures between 400 and 900 degrees Celsius. The pozzolanic activity index for the samples obtained at low temperatures was only 28% because of the sample's high carbon content. Only samples calcined at 600 degrees Celsius contained 77% of the pozzolanic reactivity index.

SCBA reburning's effect on pozzolanic activity was studied (Ferreira et al., 2016). The authors chose to reburn the bagasse due to the disadvantages of using "natural" or "untreated" SCBA. The most noticeable change after reburning is a reduction in loss on Ignition (LOI). As a consequence of reburning or treatment, SCBA reactivity increased. This is because amorphous silica is present, and the surface area has increased. However, (Abdalla et al., 2022) found that the raw SCBA directly from a sugar factory in Kenya met the bare minimum requirement as a pozzolanic material; further treatment in a furnace reduced the total composition of Al_2O_3, SiO_2, and Fe_2O_3. The chemical composition for various SCBA sourced locally, in western Kenya, is as tabulated in Table 2.1.

Table 2. 1 Chemical Composition of the SCBA in Kenya.

Sugar Factory	**Nzioa sugar**		**West Kenya**
Reference	(Abdalla et al., 2022)		(Arasa et al., 2017)
Nature	**Raw**	**Processed**	**Raw**
SiO_2	80.005	76.18	62.3
Al_2O_3	8.923	3.62	4.25
Fe_2O_3	3.19	8.71	3.69
CaO	1.482	2.88	1.02
K_2O	2.705	5.495	2.70
MgO	2.372	0.00	0.43
P_2O_5	0.537	1.422	2.70
TiO_2	0.464	0.937	0.32
MnO	0.16	0.456	0.23
LOI	15.08	5.82	15.28
$SiO_2 + Al_2O_3 + Fe_2O_3$	92.12	88.51	70.24

2.5.2 SCBA-based Geopolymer Concrete

When mixed with the alkaline solution, the amorphous aluminosilicate source material dissolves the Silica and Alumina species. Their dissolution is very much dependent on the concentration of the alkaline solution (Yadav et al., 2020). The geopolymer mortar developed by (Saloma et al., 2016) was tested for the effect of NaOH concentration and found that varying the molarity of NaOH affected the slump value, setting time of fresh concrete, as well as the hardened concrete's density and strength in compression. While the setting time lengthened, the value of the slump shrank. As the molarity of NaOH rose, so did the density and compressive strength of concrete that had been hardened. A mortar geopolymer mixture with a concentration of 16M obtained the most significant compressive strength. However, the samples were heated to high temperatures for curing.

According to another study, adding polypropylene (PP) fibres to sugarcane bagasse geopolymer concrete increased flexural and tensile strength (Akbar et al., 2021). The results demonstrated that limiting the PP fibre content to 1% enhanced the flexural properties and the compressive strength by providing a denser microstructure. Even with a higher superplasticizer dosage, the SCBA-based geopolymer mortar hydrates faster, according to Akbar et al. (2021). The samples were cured at high temperatures. The superior cementitious material of SCBA-based geopolymer composite concrete was demonstrated by the Ultrasonic Pulse Velocity test conducted on cured samples.

In separate research (Mermerdaş et al., 2017) on how aggregates affect geopolymer concrete. Geopolymer mortar was made using natural sand, crushed limestone, and sand-limestone mixes. According to test results, natural sand-containing geopolymer mortar flowed better than other aggregates; coarser sand grading also improved flow. Crushed limestone possessed the greatest compressive and shear tensile strengths. For flowability, it was recommended to use natural sand.

According to (Joshaghani & Moeini, 2017), as the amount of SCBA in concrete increases, its workability is reduced. When SCBA's silica concentration is raised, the strength of geopolymer concrete also rises.

The composition mineral of SCBA is essential for the pozzolanic reaction. Silica is the primary mineral found in SCBA. Calcium Silicate Hydrate (C-S-H) is the major hydrated byproduct that results from the chemical interaction involving SCBA and calcium oxide (Payá et al., 2018). The micro lime provided the calcium ions.

2.6 Micro Lime

Micro lime is a type of lime that has been processed into microparticles. Micro lime has many advantages over conventional lime: pure, weightless, bright, and without salts and impurities (Salama et al., (2019). Micro lime: Compared to coarse-grained limestone, fine-grained limestone yields quicklime with a higher reaction activity much more easily (Zhu Minjie et al., 2023). The micro lime chemical composition is summarized in Table 2.2 (Azarhoosh et al., 2019)

Table 2. 2 Chemical Composition of Micro Lime.

Composition	Micro lime (%)
CaO	86.44
MgO	6.32
SiO_2	2.26
Al_2O_3	1.15
Fe_2O_3	0.35
Na_2O	0.23
MnO	0.11
TiO_2	0.04
K_2O	0.17

Source: (Azarhoosh et al., 2019)

The particle size for micro lime is 2.255+/-1.994 micrometers, (Komabayashi et al., 2009) and less than 5 micrometers (Zhu Minjie et al., 2023). Microparticles work as a filler and help to improve the bond between the particles in the concrete. The micro fly and micro lime combination boost early compressive strength in contrast to the control sample. The most significant improvement in compressive strength above the control specimen, 14.81 per cent, was achieved by incorporating 2.5% nano fly ash and nano lime (Tudjono et al., 2014).

A research carried out by (Temuujin et al., 2009) on the effect of calcium compounds on geopolymer concrete; Fly Ash was used as the source material. The calcium compound partially replaced the Fly ash by 1%,2%, and 3%. The addition enhanced the mechanical characteristics of the samples that were cured at room temperature while lowering the qualities of those cured at high temperatures. Calcium hydroxide was found to be more effective than calcium oxide. (Antiohos & Tsimas, 2004) also found that the optimal dosage of quicklime to be 5% in the Fly ash with low calcium content. The effect was accelerated hardening and improved early compressive strength.

A research by (Adam et al., 2016) on investigating how adding lime to ambient-cured fly ash-based geopolymer concrete affects its strength and setting time. The lime was added between 1% and 10% by weight of the binder. It was found that the mechanical properties of the geopolymer concrete cured at room temperature increased with the addition of lime. After the curing period of 28 days, the compressive strength ranged from 8 to 12 N/mm^2.

The effects of lime quantity on ambiently cured geopolymer concrete's compressive strength were carried out by (Adam et al., 2019). In order to achieve sufficient strength at an early stage, Class F fly ash and slaked lime were used as the binding agent, with the percentage of lime to the binder being 4, 5, 6, and 7%. The ideal range value was between 6% and 7%. Class F fly ash was partially replaced with 4%–7% slaked lime for ambient curing.

In a research study, the effectiveness of geopolymer concrete using a blend of slag and fly ash as the source material was examined by (Kalaivani et al., 2020). Lime was used in an amount of 5%. Concrete is helped to geopolymerize by the heat produced when lime is introduced to the geopolymer. The mechanical qualities of geopolymer concrete that had been ambiently cured increased, according to their study of the material's water absorption. Slaked lime was added to replace 5% of the fly ash to accomplish ambient curing.

The chemical makeup of the source material determines how much calcium should be used in geopolymer concrete (Matalkah et al., 2020). It was discovered that adding calcium oxide up to 10% increased compressive strength; when more of the same material was added than 10%, the compressive strength was lowered.

According to (Salama et al., 2019), pozzolanic nanomaterials exhibit high pozzolanic reactions, resulting in additional C-S-H gel formation and enhanced mechanical strength. Compared to the known (bulk) material, nanomaterials have numerous advantages, including being pure, light, bright, and free of salts and impurities.

The dosage of micro lime is determined to range between 1% and 7%, not as a substitute but as an additive (Adam et al., 2019; Antiohos & Tsimas, 2004; Kalaivani et al., 2020; Matalkah et al., 2020; Temuujin et al., 2009).

2.7 Curing of Geopolymer Concrete

The effect of curing temperature on GPC cured at elevated temperatures was studied by (Triwulan et al., 2017) with fly ash as the source material. This was achieved through steam curing at 40^oC, 60^oC, and 80^oC for 24 hours. The compressive and tensile strength were optimum at 60^oC for 24 hours. The curing temperatures enhanced the percentage of closed porosity.

The impact of the curing environment and curing time was examined by (Adam & Horianto, 2014) with fly ash as the source material. Geopolymer mortar was created by adjusting the constant oven temperatures for curing of 80, 100, and 120 degrees Celsius for 4, 6, and 20 hours, respectively. The findings indicated that the ideal curing conditions of 120°C and 20 hours led to the greatest compressive strength of 33.10N/mm^2 at 20 hours against 14.30N/mm^2 at 4 hours. The polymerization process was improved by a more extended curing period, leading to better compressive strength.

In order to avoid reliance on electricity to achieve curing of the GPC. (Zahid et al., 2018) proposed using solarcure on GPC concrete, exposing the sample to 90^{o}C for each cycle. This was achieved by exposing the GPC to the sun for three cycles for a maximum solar duration of eight hours. The solarcure technique increased compressive strength by 56% to the samples cured under the Continuous Oven curing method. The microstructure properties of the GPC also improved.

Grounded Granulated Blast Furnace Slag can be used to partially replace Fly Ash in order to achieve ambient temperature curing (Davidovits, 2013; Puertas et al., 2014).. This was made possible by the slag's high calcium level. There are other uses for the ambient cure GPC in the building sector. Two reaction processes, polymerization and hydration, linked to the development of C-A-S-H and C-S-H are produced when calcium is added to GPC for ambient cured concrete (Adam et al., 2020). The author found that putting the samples in an airtight container is the most efficient way to cure them so they may be used in both processes. This makes it easier for the water to be trapped for hydration and polymerization at room temperature.

The choice of curing method will depend on various factors such as the mix design, production schedule, and project specifications. Geopolymer concrete's mechanical characteristics, durability, and general performance can all be considerably improved by adequately curing the material.

2.8 Mix Design

In terms of its constituents, geopolymer concrete differs from Portland Cement Concrete (Pavithra et al., 2016). In contrast to cement concrete, geopolymer concrete's binder is not a single substance. GPC water is released during the polymerization process, but water plays a significant role in cement concrete during the hydration phase. This makes the standardized cement concrete mix design not applicable in geopolymer concrete. Thus, according to the design procedure proposed by (Pavithra et al., 2016), GPC was designed for a specific strength by employing the correlating Alkaline Activator solution to Fly Ash ratio derived from the modified American Concrete Institute, ACI strength vs. water-to-cement ratio curve, as shown in Fig. 2.4. The proposed mix design considers the specific gravity of the material used—utilization of the proposed mix design for SCBA based GPC.

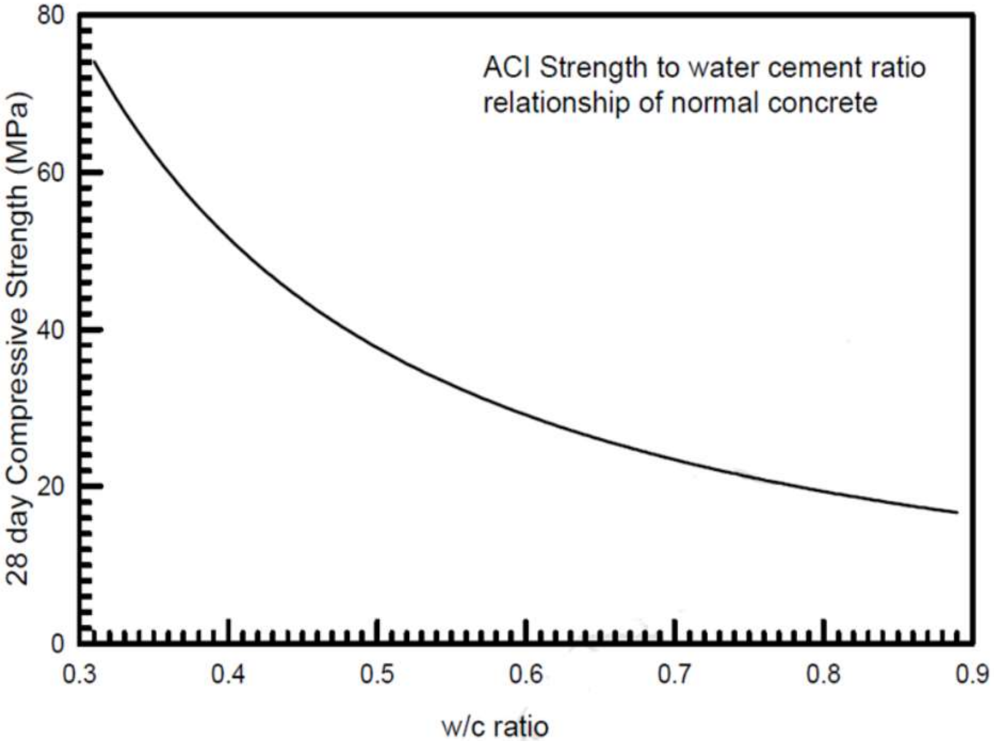

Figure 2. 4 Compressive Strength - Water - Cement Ratio Curve (Pavithra et al., 2016)

The fine and coarse aggregate content was determined using the absolute volume method in the proposed mix design (Pavithra et al., 2016). This was based on the (*DIN 1045 : 1988*) combined aggregate grading, which has since been superseded. As a result, the Densified Mix Design Algorithm (DMDA), an approved approach to mix design, method was used based on the premise that concrete comprises aggregates of varying sizes bound together with cementitious paste to determine the fine and coarse aggregate content. In order to achieve the highest density of concrete in DMDA, all solid particles of various sizes were closely packed into a dense framework (Huynh et al., 2017). Thus, the DMDA utilizes Fine Aggregates to fill the voids between aggregate particles, increasing aggregate system density (Huynh et al., 2017).

Using coarse aggregates with low maximum aggregate size (MAS) increases the surface area that bonds with the binder paste and minimizes stress concentration around the particles caused by differences in aggregate and pastes moduli of elasticity (Koteng', 2013). A low MAS allows concrete to flow easily through heavily fortified structural members. As per (ACI 363, 2005), coarse aggregates should have a MAS of 12.7mm.

2.9 Research Gap

Sugarcane is one of the crops that is grown in Kenya. It is cultivated to produce sugar. The by-product of the processed sugarcane is sugarcane bagasse. Due to high calorific content of the sugarcane bagasse, it is used as a biofuel in the sugar factories for the boilers. Sugarcane bagasse Ash is a residue from the boilers. When SCBA is disposed of in landfills, air, water, and land pollution results. SCBA is a pozzolanic material and can be used in concrete production. This research sought to use the SCBA as the source material in geopolymer concrete. However, the SCBA GPC requires elevated temperatures for curing. This limits its application in the construction industry.

Therefore, there is a need to research on ambient temperature-cured SCBA-based GPC to expand its applicability. In order to achieve this, the foregoing has revealed that micro lime can be used. However, there is a need to verify the effectiveness of micro lime to achieve ambient temperature-cured SCBA-based GPC. Furthermore, there is a need to develop comprehensive data on the effect of micro lime on ambient temperature-cured SCBA-based GPC in terms of workability, compressive strength, and durability.

2.10 Conceptional Framework

The independent variables are the variables that cause the effect, whereas the dependent variable is the effect. In this research, the cause is the varying proportion of micro lime, whereas the engineering properties such as workability, compressive strength, water absorption, and chemical resistance are the effect.

Other influencing variables include the ratios of the alkaline activator, the characteristics of the coarse and fine aggregates and the nature of the SCBA.

The inter-relationship between the variables is shown in Figure 2.5

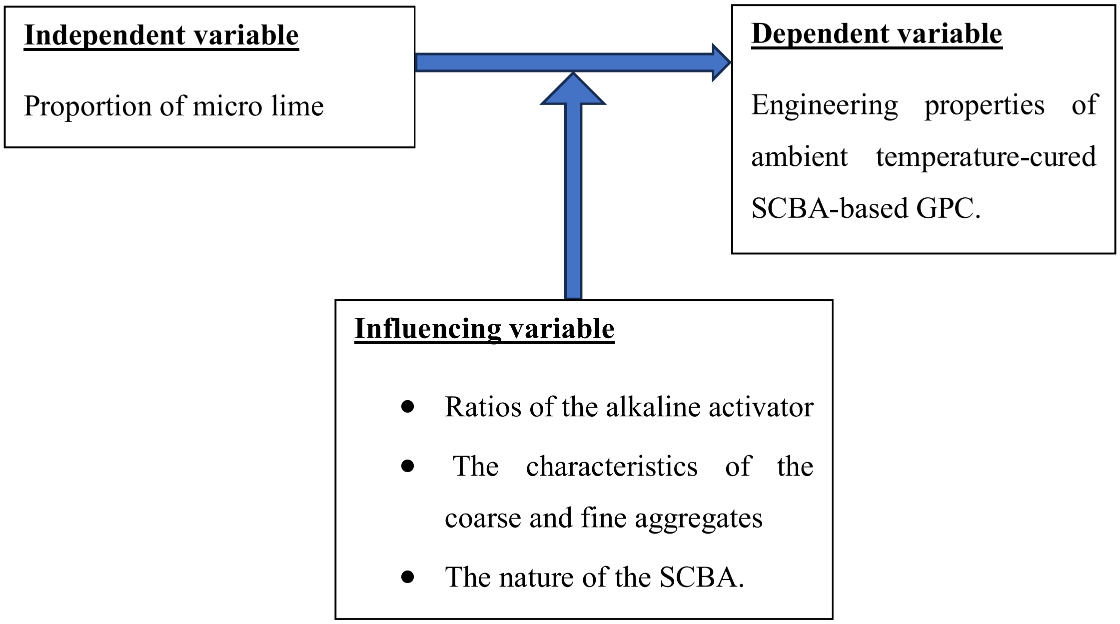

Figure 2. 5 Conceptional Framework

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter explains the chosen methodology for carrying out the study's objectives. This section describes the procurement, preparation, and suitability testing of the materials, as shown in Figure 3.1. Additionally, it provides information on the tools used at each stage in preparing and handling the test samples. It also directs collecting data and displays for simple analysis.

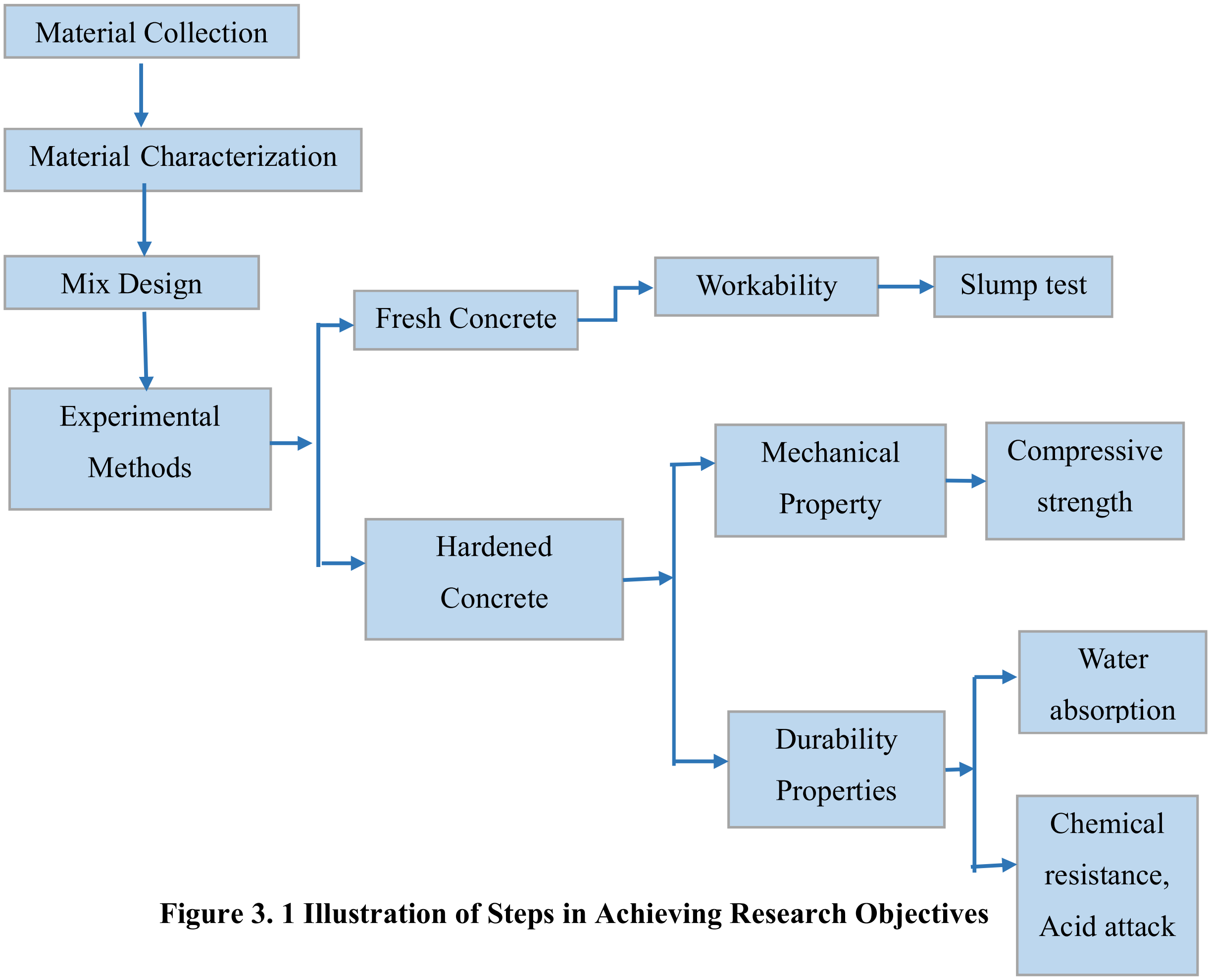

Figure 3. 1 Illustration of Steps in Achieving Research Objectives

3.2 Materials

The West Kenya sugar company was the source of raw or untreated sugarcane bagasse ash. Crushed stone of Maximum Size Aggregate (MAS) of 12.7mm was used as the coarse aggregates, and river sand of fineness modulus (FM) of 2.71 was used as the fine aggregates. Sodium Hydroxide pellets (98% purity and with a specific gravity of 2.13), Sodium silicate gel (Na_2O=8% and SiO_2=26%), and micro lime were bought from scientific Laboratory supplies. A sodium naphthalene formaldehyde (SNF) based superplasticizer, a high range water reducing admixture for high slump, produced by Indoors East Africa in Nairobi, was used. Potable water from the Nairobi County water supply was used.

3.3 Material Preparation and Characterization

All tests were carried out at the Technical University of Kenya in the Concrete laboratory.

3.3.1 Coarse Aggregate

Crushed coarse aggregates were washed through a sieve size 3.18 mm to remove any fine particles, then oven-dried at 105℃ for 24 hours to remove any entrained moisture. After cooling, the aggregates were sieved through BS sieve sizes 12.7mm, 9.35mm, 6.35mm, and 4.76mm, as shown in Figure 3.2. The Aggregate Crushing Value (ACV) was carried out per BS 812-110:1990, and the Aggregate Impact Value (AIV) to conform to BS 812-112:1990. All were carried out at the Technical University of Kenya Concrete Laboratory. The AIV is the resistance to sudden shock or impact. A lower value indicates that the aggregates are more resistant to impact, thus high quality. A 10% and 20% value indicates that the aggregates are strong. The ACV measures the resistance of aggregates to crushing under a gradually applied compressive load. The lower value indicates better strength; a limit is 45%.

9.35 - 12.70mm 6.35 - 9.35 mm 3.18 - 6.35 mm

Figure 3. 2 Physical Images of Aggregates

3.3.2 Fine Aggregates

River sand was used as fine aggregates and obtained from a local supplier in Nairobi. The river sand was washed through a sieve size of 0.150mm to remove dust particles, followed by oven drying at 105□ for 24 hours to remove any entrained moisture. It is assumed that the properties of the aggregates will not be interfered with while drying at 105□. After cooling, the fine aggregates were sieved through sieve sizes 2.36mm, 1.18mm, 0.600mm, 0.300mm, and 0.150mm to ascertain that grading and fineness modulus (FM) conformed to the limits recommended by ASTM C33. Three sieving tests were carried out with different samples of fine aggregates.

3.3.3 Alkaline Activator

An alkaline activator in this study is Sodium Hydroxide and Sodium Silicate, sourced locally from Scielab Chemical supplier. One part of Sodium Hydroxide 16 M solution and two parts of sodium silicate were used as the alkaline activator. To account for complete crystal dissolution and heat dissipation, sodium hydroxide was prepared one day ahead of time according to the recommendations by (Kabir et al., 2015; Pavithra et al., 2016). The physical properties of sodium silicate and sodium hydroxide are shown in Table 3.1, which is sourced from the technical datasheet in Appendix A3 and A4.

Table 3. 1 Physical Properties of Sodium Hydroxide and Sodium Silicate

Alkaline Activator	Appearance	Assay		Specific Gravity
Sodium Hydroxide	White Powder	97.58%		2.13
Sodium Silicate	Viscous clear Liquid	Na_2O = 8.01%	SiO_2 = 27.99%	1.53

Source: Certificate of Analysis of both Sodium Silicate, Appendix A3

The percentage of solids in Sodium silicate liquid is 42.66% and 39.02% for 16M Sodium Hydroxide.

3.3.4 Micro Lime

The micro lime was obtained from Scielab Chemical suppliers. The particle size of micro lime, according to (Komabayashi et al., 2009,) should be of size 2.255 ± 1.994 micrometer (μm).

This research used micro lime as an admixture in SCBA-based geopolymer concrete to provide the reactive calcium ions. Based on the discussed literature review, the micro lime was varied by 1%, 3%, 5%, and 7% by SCBA weight. The chemical composition and physical properties are shown in Table 3.2, sourced from the technical datasheet in Appendix A5.

Table 3. 2 Chemical Composition and Physical Properties

Calcium Hydroxide	
Assay	95.64%
Appearance	White Light powder
pH	12.4
Specific Gravity	2.24
Particle size	2.255+/-1.994 µm

3.3.5 Sugarcane Bagasse Ash

The raw SCBA was sourced from West Kenya Sugar Company, Kakamega County, Kenya, as shown in Figure 3.3 (a). The SCBA was dried in an oven and sieved through a 150-micron sieve to remove larger and unwanted materials, as shown in Figure 3.3 (b). The SCBA was calcined in a muffle furnace, at 750^oC, in the Technical University of Kenya Chemistry Laboratory to determine the loss of ignition (LOI). The mineral composition of the SCBA was analyzed using X-ray fluorescence (XRF) at the Ministry of Mines Laboratory, Machakos, Nairobi, and tabulated. The sieved ash was stored in a polythene bag to maintain constant moisture content.

(a) SCBA before Sieving **(b) SCBA after Sieving**

Figure 3. 3 SCBA Sample

3.3.6 Superplasticizer

The viscous nature of sodium silicate and 16M sodium hydroxide which makes the concrete mix less workable, necessitating the addition of a superplasticizer. Therefore, a sodium naphthalene formaldehyde (SNF) based superplasticizer, a high range water reducing admixture for high slump produced by Indoors East Africa in Nairobi, was used. The SP was used according to the manufacturer's 3% cementitious material dosage, i.e., SCBA. The superplasticizer had a specific gravity of 1.20 and a brown liquid in appearance.

3.4 Concrete Mix Design

The mix design procedure proposed by (Pavithra et al., 2016) was used in this study. It involves calculating the paste content based on the specific gravity of each ingredient. The maximum water content was based on the maximum aggregate size. The SCBA content was based on the ACI strength vs. water-to-cement ratio curve, as shown in Figure 2.4.

The paste content included SCBA, Sodium Hydroxide and Sodium Silicate and was determined using Equations 3.1 and 3.2.

$V_{paste} = V_{SCBA} + V_{NaOH} + V_{Na_2SiO_3}$ …………………………… Equation 1.1

$V_{paste} = [\frac{MSCBA}{Gs\ SCBA} + \frac{MNaoH}{Gs\ NaoH} + \frac{MNa_2SiO_3}{Gs\ Na_2SiO_3}]$………………….. Equation 2.2

Where V- volume

M- Mass and

Gs- Specific gravity

A Densified Mix Design Algorithm (DMDA) was used to determine the percentages of the fine and coarse aggregates. DMDA is based on the assumption that concrete is made up of aggregates of varying sizes bound together by the cementitious paste; the composition of the aggregates is determined from the relative amounts of the different sizes, making up the Maximum Dry Density, MDD.

The maxima density was carried out by the hand-rodding method, where smaller coarse aggregates (9.53 mm- 6.35 mm) are gradually packed into the larger aggregates (12.7 mm – 9.53 mm) conforming to (*ASTM - C29*). After which, a packing curve was obtained. The MDD was obtained at a certain percentage and the fine aggregates are packed into the coarse aggregates. The new MDD was found at a certain percentage and used to compute the proportions of the fine and coarse aggregates. The packing curves are shown in Figures 3.4, 3.5 & 3.6.

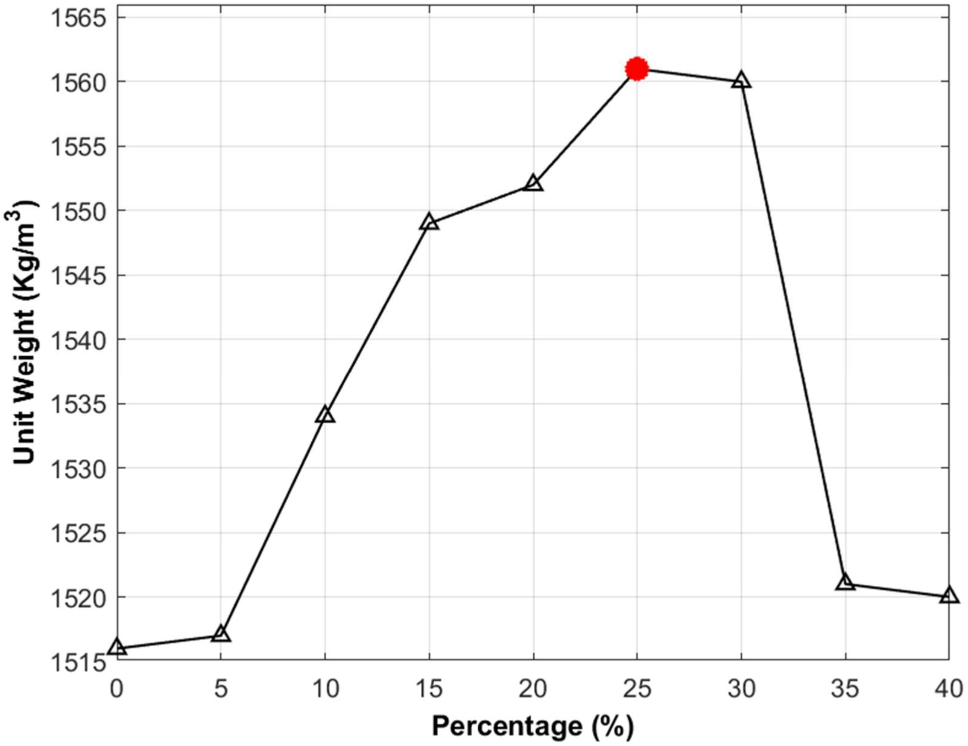

Figure 3. 4 Packing Curve of 6.35mm into 12.7mm Aggregate Size

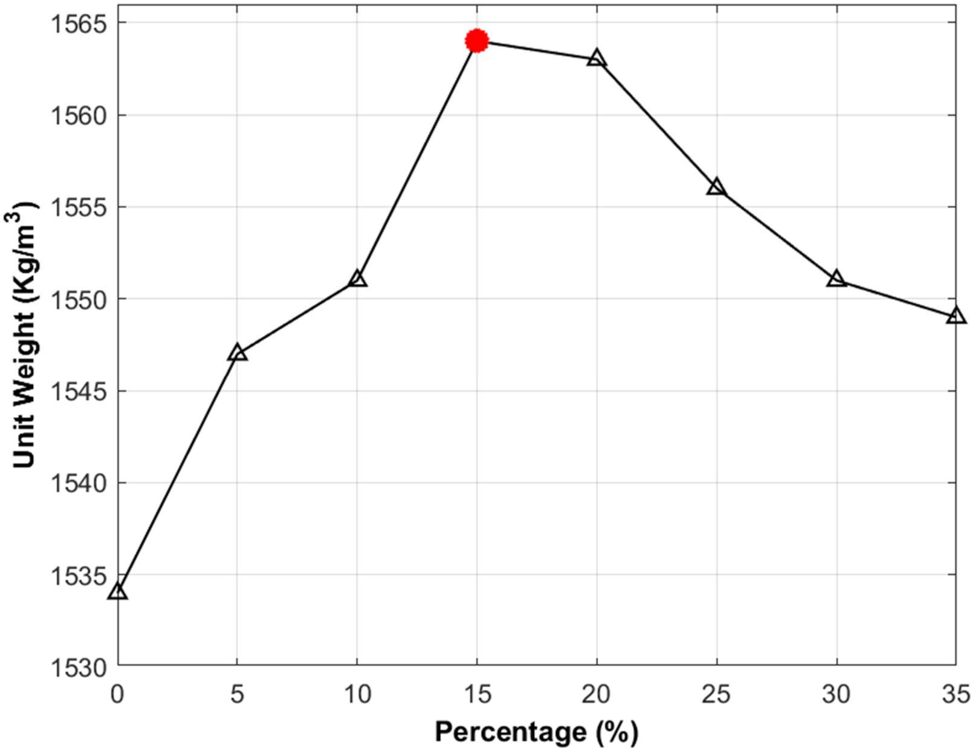

Figure 3. 5 Packing Curve 3.18mm into 25% of 6.35mm and 12.7mm Aggregates Size

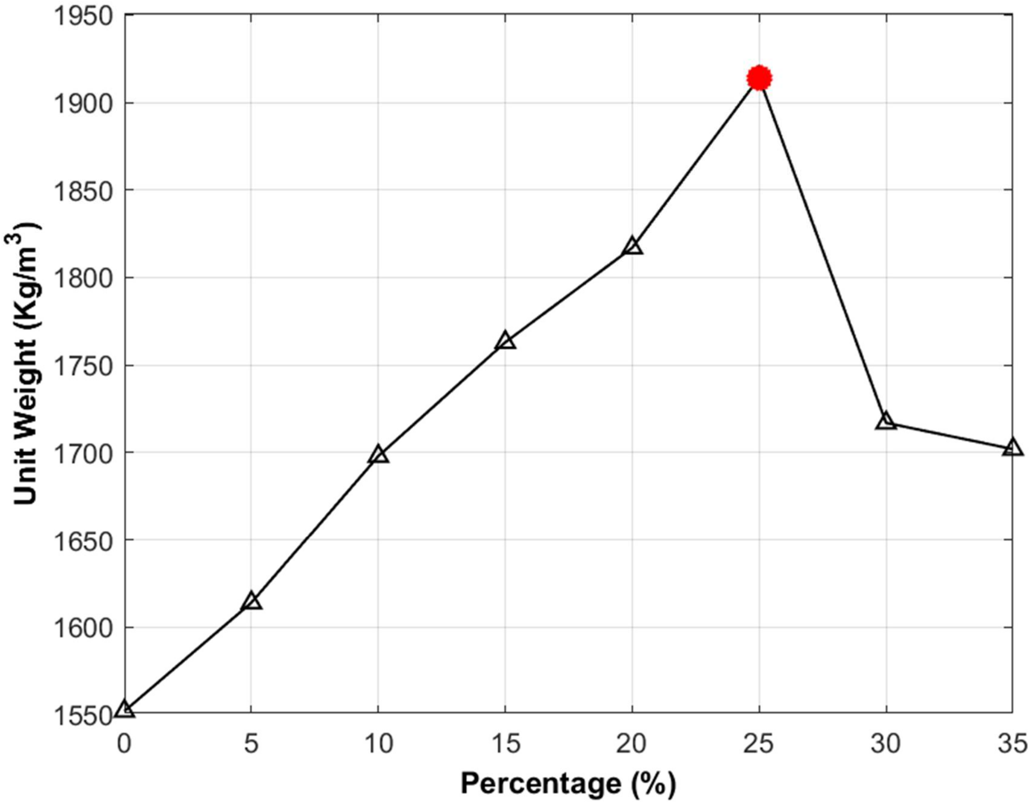

Figure 3. 6 Packing Curve of River Sand into 15% of 3.18mm and 25% of 6.35mm and 12.7mm Aggregates Size

The quantities of materials for 1 m^3 of concrete are presented in Table 3.3

Table 3. 3 Concrete Mix Proportion.

Mix Type	CA 1 (kg)	CA 2 (kg)	CA 3 (kg)	FA (kg)	SCBA (kg)	Na_2SiO_3 (kg)	NaOH (kg)	H_2O (kg)	SP (kg)	ML (kg)
Mix 1	847.92	282.05	200.45	435.26	400	133.34	66.67	128.65	12	0
Mix 2	847.92	282.05	200.45	435.26	400	133.34	66.67	128.65	12	4
Mix 3	847.92	282.05	200.45	435.26	400	133.34	66.67	128.65	12	12
Mix 4	847.92	282.05	200.45	435.26	400	133.34	66.67	128.65	12	20
Mix 5	847.92	282.05	200.45	435.26	400	133.34	66.67	128.65	12	28

Legend: (Coarse Aggregates) CA 1- 9.35-12.7mm, CA 2- 6.35-9.35mm, CA 3- 6.35-3.18mm, FA-Fine Aggregates, SP- Superplasticizer, ML- Micro Lime

3.5 Concrete Mixing

A $0.02m^3$ paddle mixer Katerina model B200A made in China was used for concrete mixing, as shown in Figure 3.7. The mixing sequence entailed mixing the SCBA with NaOH for 30 seconds, followed by Na_2SiO_3 for 1 minute. The mixing water and the SP were added until a paste formed. The fine aggregates were added and allowed a mixing time of 1 minute. The coarse aggregates were added from the small size to the 12.70mm size. This was then allowed to mix until a homogenous mix was obtained. This was added before the fine and coarse aggregates were added for the 1, 3, 5 and 7% micro lime as admixture. A longer mixing duration significantly improves workability, mechanical strength, and durability. Therefore, after adding all the ingredients, five minutes was allowed as the mixing time.

Figure 3. 7 Mixer

3.6 Workability

A slump cone test determined the concrete workability conforming to BS EN 12350-2:2009. A slump cone of galvanized steel or iron, with a standard base diameter of 200mm, top diameter of 100mm, and a height of 300mm, a base plate, a compacting rod of 16mm diameter and 600mm length, and a rule, graduated from 0mm to 300mm, at 5mm intervals. The test was done on freshly prepared concrete within 2 minutes after mixing. The inner surface of the cone was cleaned and oiled evenly before filling with concrete. Once a uniform workable concrete-mix was obtained, the slump cone shall be firmly held down at the middle of the base plate and filled with concrete in three layers and tamped 25 blows after each layer. The excess concrete was removed and the surface levelled off. The cone was the lifted off gently in vertical direction and inverted against the cone moulded concrete, and the slump was read by the ruler and recorded.

3.7 Preparation and Curing of Cubes

Once a uniform concrete mix was achieved, it was poured into the concrete cube mould. 100 mm x 100 mm x 100 mm cube moulds that are compliant with BS EN12390-1:2012 were used, and the specimen was cast to BS EN 12390-2:2000. The control samples, with 0% micro lime, were placed in the oven for curing at 100^{o}C for 24 hours after which it was allowed to cool, demoulded and ready for the test.

The cubes with varying percentages of the micro lime were cast and left in the moulds for 24 hours before the moulds were removed. The samples were marked and left in an undisturbed area, at ambient temperature, for curing to the required age of 7, 14, 28 and 56 days. Extra cubes were moulded, cured for 28 days, and subjected to water absorption and chemical attack.

3.8 Test on Hardened Concrete

3.8.1 Compressive Strength

The compressive strength was tested with a universal compression-testing machine with a 150kN load capacity, as shown in Figure 3.8. Compressive tests conforming to BS EN 12390-2:2019, were undertaken at 7, 14, 28, and 56 days. The cured samples were placed centrally between the batten, and the top batten touched the top surface of the sample. A constant loading rate was applied until the cubes were crushed, and the load at failure was recorded. Three cubes were cast for each testing age, and the percentage of micro lime addition and the average strength were reported for further analysis. A plot was created by graphing the compressive strength versus concrete's age.

Figure 3. 8 Compressive Test Machine

3.8.2 Durability

The ability of concrete to withstand weathering, chemical erosion, abrasion, and other deterioration processes is known as durability. Durable concrete maintains its inherent shape, quality, and utility even after exposure to environmental conditions. The following tests were carried out to determine the durability of SCBA-based GPC;

i. Water Absorption

One technique used to gauge the durability of concrete is water absorption. This indicates the pores in the concrete. A high-water absorption rate indicates that the concrete is more vulnerable to chemical attack, moisture degradation, and freeze-thaw cycles. Estimating the water absorption rate is crucial to ensure that the concrete can endure external conditions and preserve its structural integrity over time.

Concrete cubes cured for 28 days were tested for water absorption, according to (*BS 1881-122:2011*). A total of 3 cubes were cast for each variation of the micro lime. The specimen was oven-dried for 72 hours at 105^{0}C. After the samples had been removed from the oven, they were allowed to cool for 24 hours in an airtight vessel. The specimen was weighed and recorded. The specimen was then immersed entirely in potable water for 30 minutes, at 125mm deep, at room temperature. The specimen was then removed, shaken to remove the bulk of the surface water, and dried with a cloth to remove the surface water. Weighing the sample and recording its mass was done. The subsequent cumulative immersion times were used to calculate the water absorption rate: 10 minutes, 30 minutes, 60 minutes and 120 minutes.

ii. Chemical Attack

Chemical attacks can happen when aggressive chemicals like acids, sulfates, and chlorides are present in concrete. These chemicals react with the components of the concrete and degrade the structure. The type and concentration of the chemicals, exposure period, and temperature affect how severe the attack will be.

This was carried out according to (*ASTM C1898*). The key indicators were the visual inspection, percentage mass change, and change in compressive strength of the sample.

For each variation of micro lime, three sets of concrete cubes were cast and tested on day 28. With 2.5% of sulfuric acid, the cubes were fully immersed. At the interval of 7 days, the cubes were washed, and the acid was replaced. The cloth-dried samples were weighed and returned to the acid bath. This was carried out for a total of 7 weeks. The weight change was tabulated for further analysis. At the end of the 7 weeks, the residual compressive test was conducted, and recorded for further analysis.

3.9 Data Analysis

Data analysis is useful for drawing conclusions or comparing investigations involving multiple variables. The goal was to determine how a factor or independent variable affects a dependent variable. The collected data were subjected to descriptive analysis and Analysis of Variance (ANOVA). The descriptive analysis involves the description of the basic features of the data. The analysis of variance test also known as ANOVA. It is applied whenever more than two groups need to be measured. The generic linear model framework is employed. The degree of confidence indicates the degree of assurance the research has in its conclusion based on the comparison of the two sets of data. In addition to the degree of confidence, the significance level is used.

The (α) significance level of 0.05 is typically adopted in several studies. The value of 0.05 means that only 5% of the test group with no real difference will not be significantly, whereas the real difference will be significantly different in the data groups. The ANOVA was done using a MATLAB code, as shown in Appendix C1.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter represents the test results on the materials and other parameters to achieve the main objective. These include workability, compressive strengths, water absorption and chemical attack. It also puts forward scientific explanations for the results.

4.2 Material Properties

4.2.1 Coarse Aggregates

The sieve analysis results are shown in Figure 4.1. The properties of the aggregates were determined and tabulated in Table 4.1

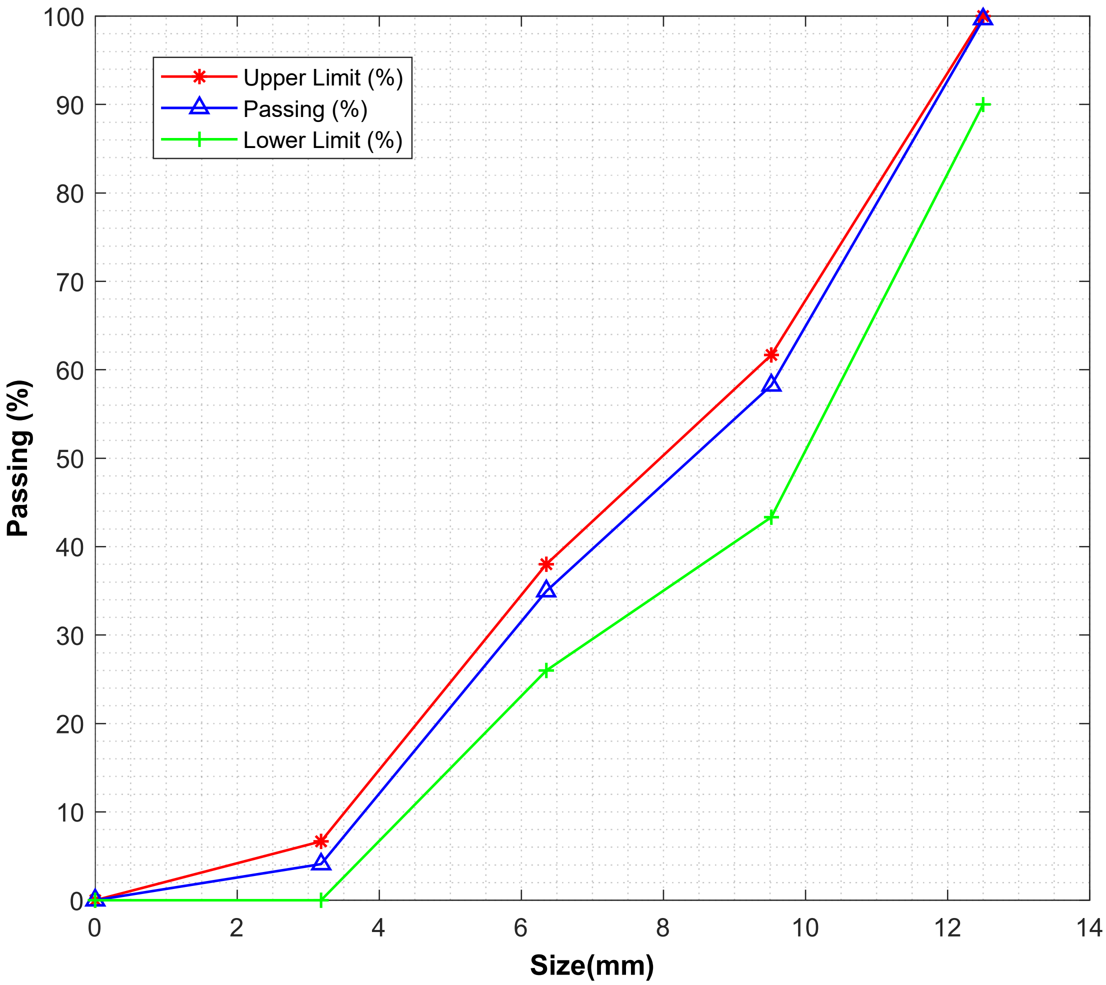

Figure 4. 1 Coarse Aggregates Sieve Analysis

Table 4. 1 Properties of Coarse Aggregates

Specific gravity	Water Absorption (%)	AIV (%)	ACV (%)
2.70	2.90	12.04	17.23

Legend: AIV-Aggregate Impact Value, ACV-Aggregate Crushing Value.

The different aggregate sizes were mixed proportionally based on the packing curves, and riffled and sieve analysis was performed. A well-graded coarse aggregate improves the concrete's pore structure, compaction, and interlocking of the aggregates (Ogundipe et al., 2018). Figure 4.1 shows that the aggregates used in the study were well-graded and fit between the upper and lower limits, implying the coarse aggregates were suitable for concrete.

ACV is only helpful when working with unknown-performing aggregates, especially when there is a suspicion that the aggregate may be weaker. The material that satisfies the standards for AIV will also reasonably meet the needs of crushing and abrasion qualities because AIV is an indicator of toughness.

AIV of 12.04% and ACV of 17.23% falls below the 45% defined upper limit (M.S. Shetty, 2005). Concrete with high compressive strength is produced using aggregates with strong mechanical qualities, such as AIV.

The specific gravity of the coarse aggregates was 2.70. The value lies within the ranges of the specific gravity of aggregates from rock fragments, which is 2.6 and 2.8 (M.S. Shetty, 2005)

4.2.2 Fine Aggregates

The aggregate grading is an essential characteristic as it affects the workability and packing density of the concrete mix. The particle size distribution also known as sieve analysis results of the river sand are shown in Figure 4.2.

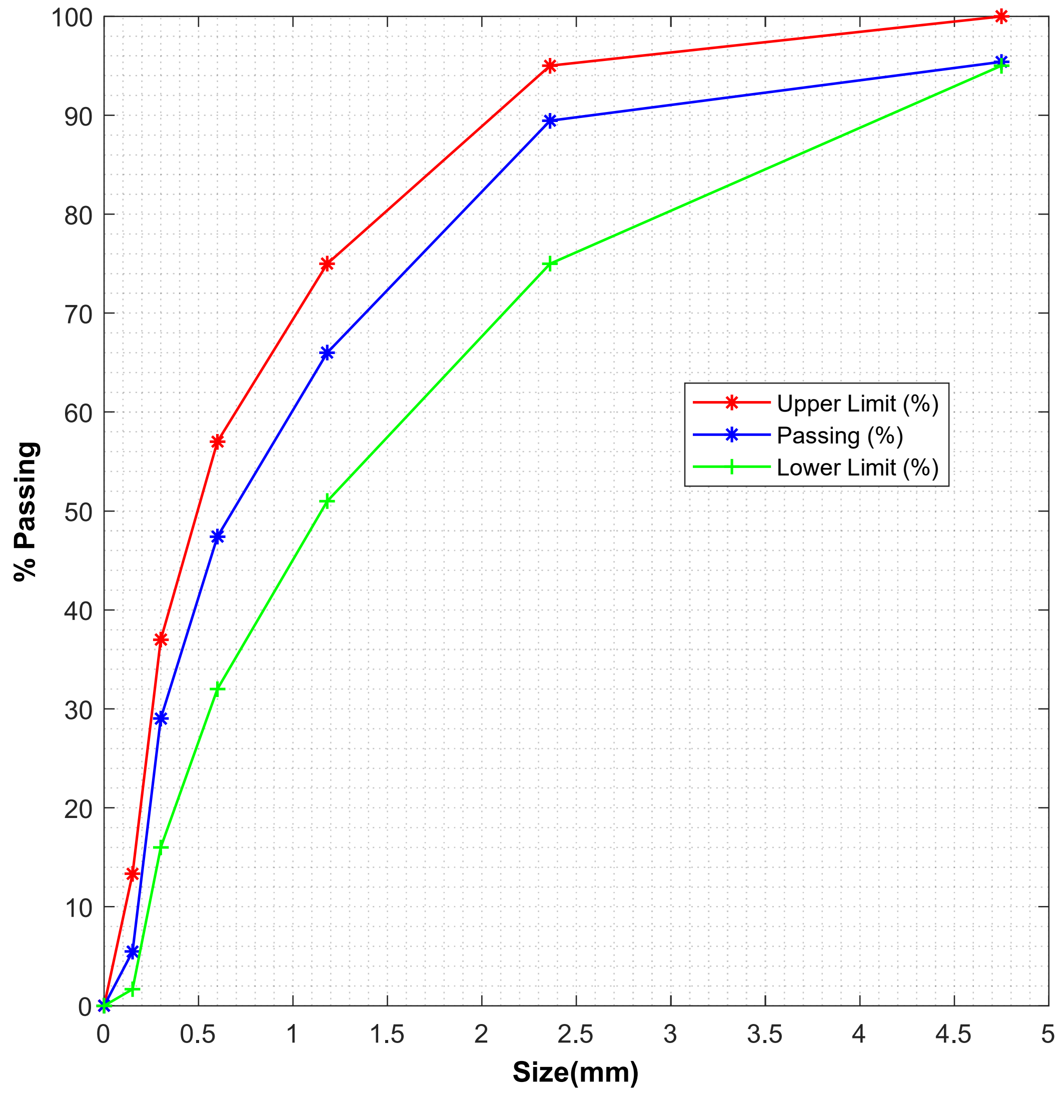

Figure 4. 2 Fine Aggregates Sieve Analysis

The 2.71 Fineness Modulus (FM) was determined to be within the specified range of 2.5-3.2, thus considered medium sand. However, because the material was more on the finer end of the grading curve, there was an increased water demand, which decreased workability because of the high specific surface. A high dosage of SP is also necessary to improve the cohesion and fluidity of concrete. However, finer aggregate enhances the packing of the concrete's pore structure, which lowers permeability.

4.2.3 Sugarcane Bagasse Ash

The SCBA was sieved through 150 μm, to remove larger and unwanted materials. The oxide content of the SCBA was examined using X-ray fluorescence (XRF); data from the XRF test is shown in Appendix A1; the results are tabulated in Table 4.2. The specific gravity of the SCBA was determined according to (*ASTM C128-22*) and recorded as 2.08.

The Loss on Ignition (LOI) test was used to determine the amount of unburned carbon. The LOI was determined by weighing the sample and later calcinating it in a muffle furnace. The temperature in the furnace was raised gradually, reaching 500°C at the end of one hour. Then, it was gradually raised to 750°C at the end of the second hour. The samples were allowed to cool in a crucible and then weighed. The laboratory data is as shown in Appendix A2. The difference in the two weights is the LOI in percentage, an average value recorded as 7.70% less than the limit set by (*ASTM C618*, 2008) of 10%. This qualifies the SCBA as Class N fly ash that can be used in concretes with average strengths. This means that the combustion process at the factory was complete.

Table 4. 2 Chemical Composition of SCBA

Element	**SiO_2**	**Al_2O_3**	**MgO**	**CaO**	**K_2O**	**Fe_2O_3**	**Ti**	**P_2O_5**	**Mn**	**Others**	**LOI**
Composition (%)	76.19	8.83	3.96	2.95	3.33	3.01	0.39	0.65	0.22	0.48	7.70

The SCBA contains more than 70% SiO_2, and the summation of the acidic oxides (SiO_2+Al_2O_3+Fe_2O_3), responsible for pozzolanic properties in the SCBA, is 88.03%. Therefore, based on (*ASTM C618*, 2008) specifications, the SCBA satisfies the chemical composition of a good pozzolanic material.

The rheological and water demand characteristics of concrete and mortar depend heavily on LOI levels. SCBA with substantial LOI values in cement composites are undesirable as they reduce fluidity during mixing. A study by (Chen et al., 2019) found that a lower value of LOI translates to superior concrete in fresh and hardened states. Another study by (Sagawa et al., 2015) discovered that source material with a high LOI produced geopolymer mortar with lower compressive strength. The SCBA had less than 10% LOI, yet the source material was rich in alumina and silica.

The (*ASTM C618*, 2008) specifies the limit for the alkalis (K_2O+Na_2O) to 1.5%; however, from the chemical composition, it was found to be at 3.328%. This poses no risk to the durability and mechanical properties of the GPC since an alkaline solution was used as the activator. In characterizing the SCBA, (P. Zhang et al., 2020) noted that low CaO content (2.95%) indicates that the hydraulic activity of the SCBA could be negligible.

4.3 Workability

The workability of fresh concrete mix is the ease with which the concrete can be handled, placed, compacted and finished (Pradhan et al., 2023; Waqas et al., 2021). The workability of the GPC mix was tested using the standard slump cone test just after mixing. The concrete was cohesive and sticky and exhibited no bleeding or segregation as shown in Figure 4.3, and low slump values were recorded, as shown in Figure 4.4.

Figure 4. 3 Fresh SCBA-Based GPC

Figure 4. 4 Slump Cone Test

Adequate compaction was achieved, even with the viscous nature of the mix. The slump test data as shown in Appendix B1. The data were graphed as shown in Figure 4.5 the results of the workability test on the SCBA-based GPC with varying micro lime content from 0-7%. The slump value ranged from 55 mm at 0% micro lime to 34 mm at 7% micro lime.

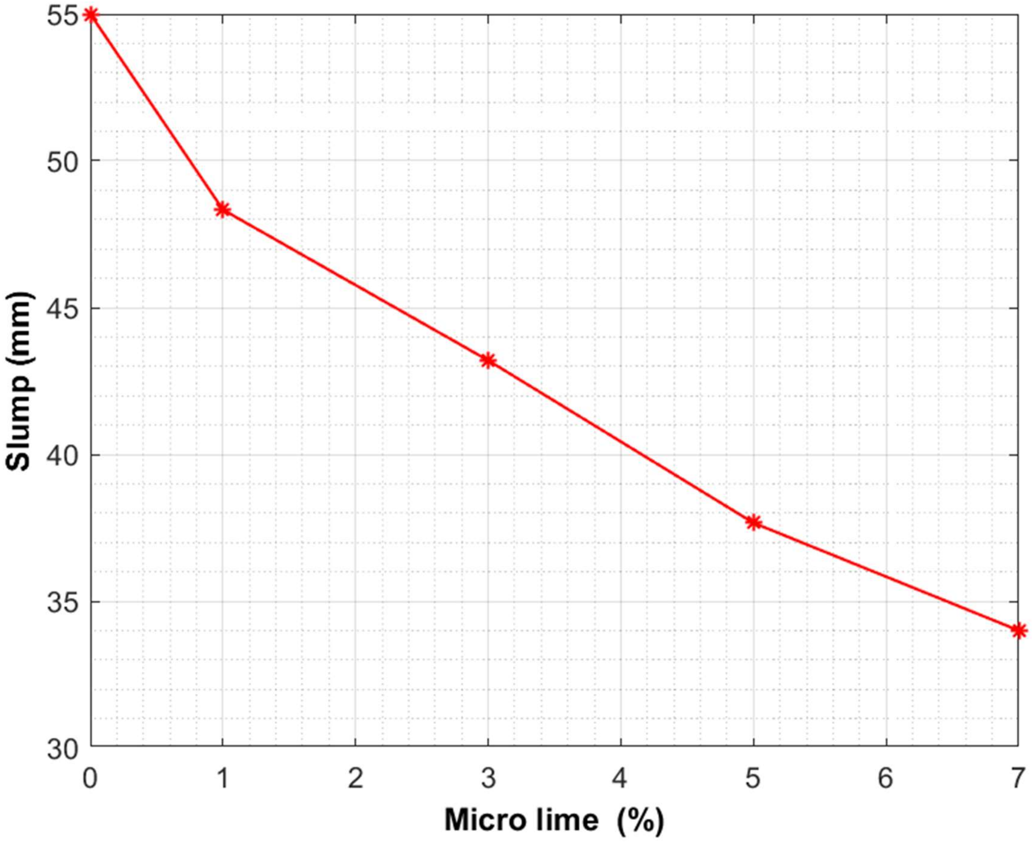

Figure 4. 5 Workability

The workability record was low despite using a superplasticizer because of the highly viscous nature of sodium silicate and sodium hydroxide, which were used as activator solutions that are alkaline in nature. Compared to traditional concrete, the GPC's alkaline activator is more viscous than water, giving it greater stickiness and cohesiveness, with similar results to (Fang et al., 2018). In this investigation, the raw components were dissolved at a high concentration of sodium hydroxide (16 M) as performed by (Srinivasa Reddy et al., 2021). Therefore, the high concentration of sodium hydroxide reduced the SCBA-based GPC workability. The low workability was also linked to the spongy and flaky-shaped particle of SCBA, which reduced the lubricating action of the freshly mixed GPC. The particle size and nature of the source material affect the workability (Waqas et al., 2021). A study by (Srinivas et al., 2021) found that the spongy nature of the SCBA absorbs the water, thus reducing the workability, despite the liquid content kept constant over time. A study by (P. Zhang et al., 2020) discovered that SCBA has many porous grains instead of spherical glass grains, which impairs fresh concrete workability. They added that the absence of a ball-bearing action may prevent the SCBA from enhancing the rheological characteristics of fresh-state concrete.

Workability declined as micro lime application increased, as shown in Figure 4.5. This could be explained by reducing the water content in the mix by increasing the powder content. The increase in the powder content reduced the alkaline activator content, reducing the mix consistency. It can be concluded that the SCBA-based GPC workability in the research was affected by the powder admixture, the micro lime. In their research (Hutagi & Khadiranaikar, 2018) observed the increase of the powder admixture and the slump value decreases, as obtained in the present research.

The declined workability can also be attributed to the high content of the calcium ions due to the increase of the micro lime. A study by (Khater, 2012) found that calcium obstructs the spread flow, resulting in low workability, similar results as observed by (Adam et al., 2019). This could be explained by the quick precipitation of calcium silicate hydroxide that results from the reaction of the calcium ions with the alkaline activator (Hu et al., 2019).

In the study by (Adam et al., 2019), the proportion of the lime content was set at 6%, as the further increase of the lime would result in flash setting. However, in this study, where micro lime was used instead of lime, the flash setting was not observed even at a 7% addition of micro lime.

Mixing, compacting, and finishing the concrete did not cause any form of segregation or bleeding in the mixtures. It was determined that the geopolymer concrete mixes' range of workability was suitable for casting different types of concrete members, such as slabs, beams, columns, and footings.

4.4 Compressive Strength

Compressive strength is one of the crucial mechanical qualities of concrete connected to other material aspects. According to BS EN 12390-3:2009, compressive strength tests on 100 mm cubes were performed in this research using universal testing equipment. Three identical samples from each blend were tested at 3, 7, 14, 28 and 56 days. The average compressive strength for the various mixes was recorded and plotted, as shown in Figure 4.6. It shows the test samples' compressive strength for different periods of ambient curing and the 0% micro lime.

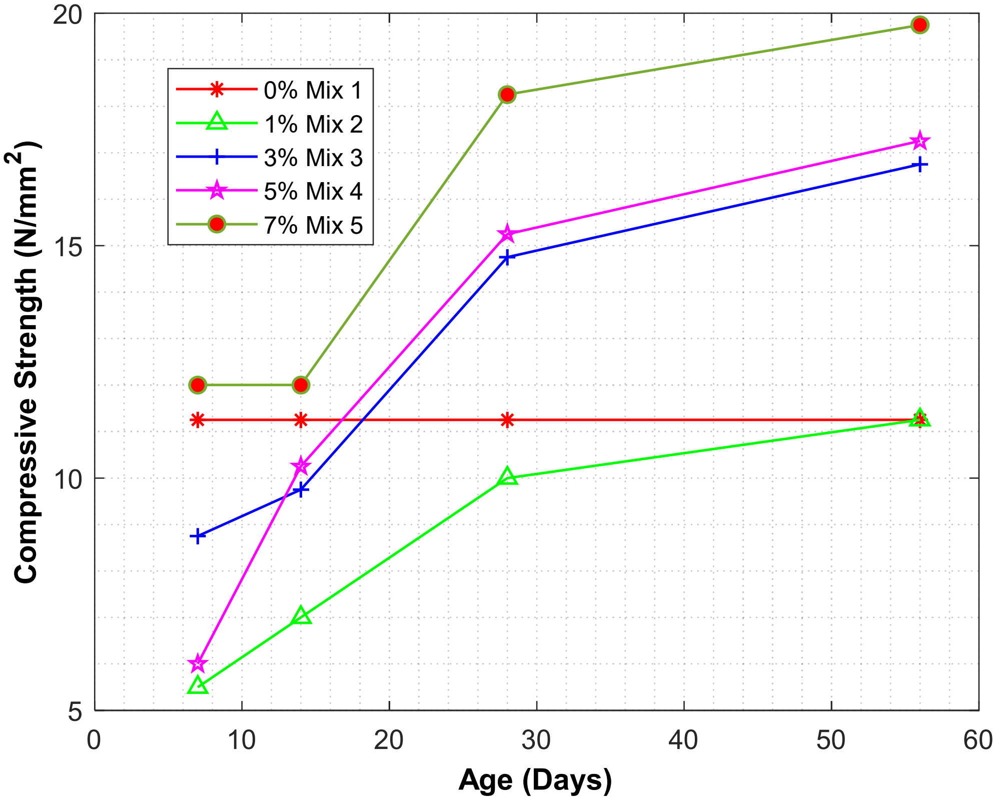

Figure 4. 6 Compressive Strength Trend

The 0% geopolymer concrete was cured under high temperatures and achieved a constant compressive strength of 11.25N/mm^2 over time; no strength developed. The heat treatment forms the complex GPC structures more quickly during their dissolution and subsequent polymerization (Hu et al., 2019). The high-temperature curing led to early high strength gain compared to mixes 2,3& 4.

To accomplish ambient curing, 1%-7% of the micro lime is used as an admixture to the SCBA-based GPC. It is observed that the compressive strength increased with time for Mix 2, 3, 4, and 5. Comparable to water-cured OPC concrete, the compressive strength increased as the number of days for curing increased. There was slow strength development over the early days (7 days) but significant strength development over the 14 and 28 days, after which the rate of strength gain decelerated after 28 days of curing to 56 days. This could be explained by the type of gel that forms and its relative distribution within the geopolymer network, which are related to the variations in the rates at which strength develops. The calcium aluminosilicate silicate hydrate (CASH) gel predominates in the initial curing stages. On the other hand, at the later stages of curing, the sodium aluminosilicate silicate hydrate (NASH) gel predominates (Wong et al., 2021).

It can also be observed that the strength development rate significantly depends on the micro lime content. The proportion of micro lime at 5% gave a higher compressive strength than the 3%. However, there was no significant difference. The optimum compressive strength at day 28 was achieved at the 7% addition of micro lime, which aligned with the findings of (Adam et al., 2019).

Compared to the controlled sample cured at high temperatures, the compressive strength at 28 days for 3, 5, and 7% was more significant. The compressive strength achieved at 3, 5, and 7% was more significant than the ones found by (Adam et al., 2016) with fly ash as the source material, 12N/mm^2 at day 28. Figure 4.6 shows that the 28-day compressive strength increased from 10 N/mm^2 to 18.25 N/mm^2, indicating an 82.5%

increase from the 1% mix to the 7% mix. The 56-day compressive strength showed an increase from day 28, but the increase from the graph, Figure 4.6, is moderate from the graph gradient.

This is due to the increased quantities of reactive calcium ions in the alkaline solution, converting the N-A-S-H to C-A-S-H and C-S-H, thus increasing the compressive strength. The C-A-S-H and C-S-H gel helps the GPC matrix to harden at ambient temperature. According to a study (Temuujin et al., 2009), calcium will enhance the geopolymerization reaction by improving the source material's ability to dissolve in the alkaline medium and precipitate calcium silicate hydrate or aluminate hydrate. The fresh GPC matrix's C-A-S-H and C-S-H gel also provide more nucleation sites, activating the geopolymer gel formation at ambient temperature and causing a quick solidification and hardening process. Therefore, the more remarkable synthesis of C-A-S-H and C-S-H gel through the hardening process could account for the higher strength caused by increased micro lime content. As a result, the quantity of C-A-S-H and C-S-H gel accessible in the matrix would increase in proportion to the amount of micro lime present in the mixture, increasing the specimens' compressive strength. Similar findings were reported by (Rajasekar et al., 2018); they noted that cement composites with a high silica concentration kept reacting with lime to create more C-S-H gel, increasing their strength. The study by (Hu et al., 2019) noted that the high calcium ions present, which would create the gel phase (C-A-S-H) and improve the compactness of the microstructure, could be attributed for the gain in compressive strength. In addition, this study (Puligilla, 2017) found that the free calcium ions might accelerate the dissolving of the source material and promote the development of geopolymer gels. The GPC mix 2, 3, 4, and 5's 56-day strength were acquired at room temperature, and could be attributed to hydration and polymerization contributed to the increment in strength, as found in similar studies by (Parveen et al., 2018).

Comparing the effect of micro lime against slaked lime and quick lime on geopolymer concrete is illustrated in Table 4.3.

Table 4. 3 Comparison on the effect of Micro, Slaked and Quick Lime

Micro lime	Quick lime and slaked lime
1% of micro lime, ambient temperature curing was achieved.	For ambient temperature curing was achieved at 5% of slaked lime (Kalaivani et al., 2020) For ambient temperature curing was achieved at 4-7% of slaked lime (Adam et al., 2019) For ambient temperature curing was achieved at 5% of lime (Temuujin et al., 2009)
The compressive strength achieved was 10-18.25N/mm^2 with 28 days of ambient curing, with Sugarcane bagasse ash as the source material.	The compressive strength achieved was 8-12N/mm^2 at 28 days of ambient curing, with fly ash as the source material and quick lime as the admixture (Adam et al., 2016).

4.5 Water Absorption

The water absorption test facilitates the assessment of the influence of incorporating micro lime on the ambient cured SCBA-based geopolymer concrete. The impact of micro lime content on the water absorption rate on SCBA-based geopolymer concrete samples after 28 days of curing, as recommended by (*BS 1881-122:2011*). The water absorption test data are shown in Appendix B3.4. The rate at which the SCBA-based GPC absorbs water is represented in a graph as shown in Figure 4.7.

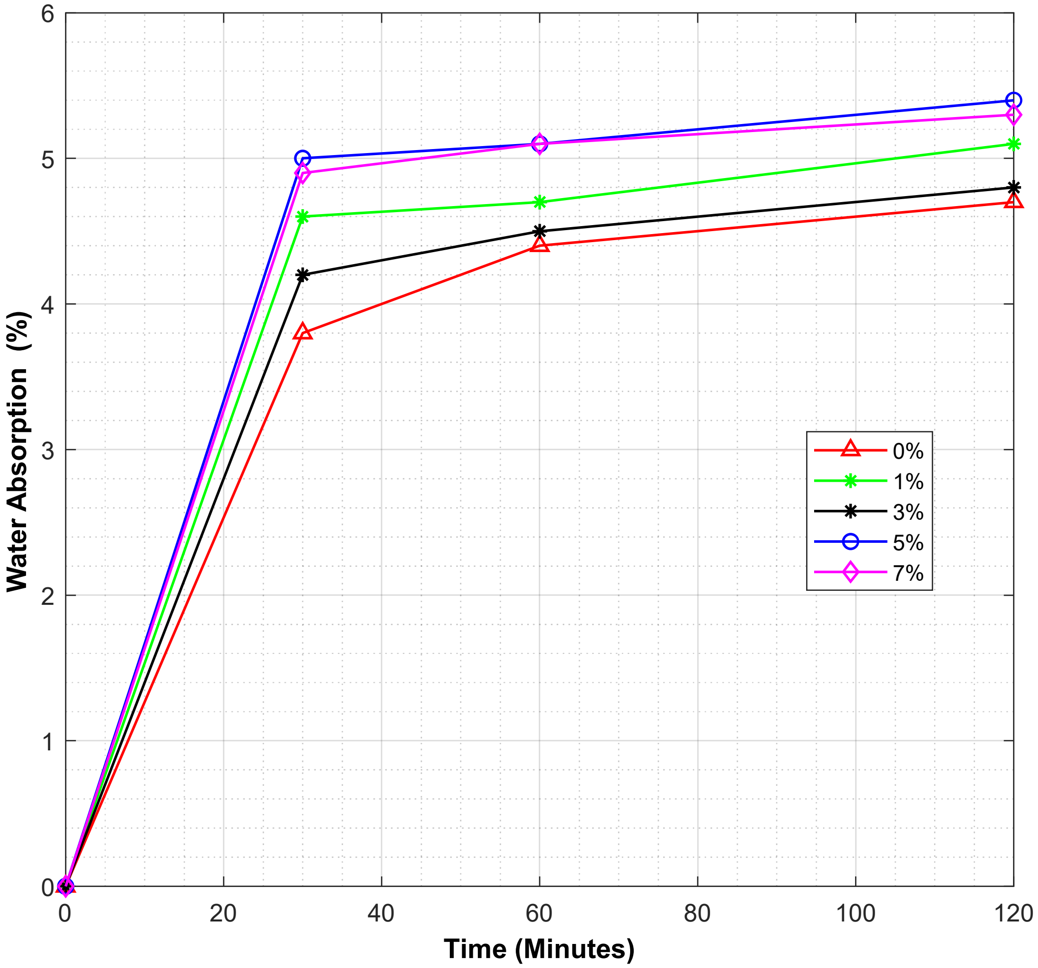

Figure 4. 7 Water Absorption Rate

In general, the water absorption rate for the 0, 1, 3, and 7 % mixes was relatively lower than the 5% for the first 60 minutes, after which the rate reduced apart from the 1% mix. The best performance for the absorption rate among the ambient and elevated temperature cured concrete was achieved by the 0% cured geopolymer concrete, which had a water absorption rate of 3.8% for the first 30 minutes and 4.7% for 120 minutes.

The ambient cured geopolymer concrete with the lowest water absorption rate achieved at 3% addition of micro lime.

A study by (Abdullah et al., 2017) asserts that geopolymer concrete's water absorption properties substantially impact the structure's endurance. The structure’s concrete will spall off if water penetrates the geopolymer concrete. When it comes to steel-reinforced concrete, the water corrodes the embedded steel bars, shortening the lifespan of the concrete construction.

The water absorption rate is at least 3% when micro lime is added to allow ambient curing. As the amount of micro lime increases, the rate of absorption rises. As a result of the C-S-H and C-A-S-H gel created when the reactive calcium was added with the micro lime, densification of the concrete is at its best at 3%. The least water absorption rate at 3% indicates that the concrete matrix holds a homogenous dense microstructure with fewer voids.

The associated pores account for 1, 5, and 7% of high permeability. Concrete is a porous substance that interacts with its surroundings and permits water to travel through concrete structures, which affects how long SCBA-based geopolymer concrete will last.

Because sodium is soluble in water, the 1% micro lime mix contained insufficient calcium ions to prevent N-A-S-H conversion to C-A-S-H. As a result, inadequate hydration and polymerization occurred, leading to pores (Garcia-Lodeiro et al., 2011). The more calcium ions there are, the more stable and soluble C-A-S-H is created. The extra calcium ions cause the pores in the concrete to hydrate by absorbing water from the matrix.

Sorptivity is a technical indicator of the microstructure and properties of a material that is essential for endurance. It refers to a substance's ability to draw water into itself by capillary action and absorb it. A more popular method of measuring concrete resistance to exposure to hazardous environments is sorptivity. A study by (S. P. Zhang & Zong, 2014) describes the water absorption process regarding internal and surface sorptivity. When a specimen is immersed in water, surface sorptivity happens right away, whereas inner sorptivity takes time to develop. They were unable to find any connection between sorptivity and the strength of compression, though. This explains why the 5 and 7% mix exhibits significant compressive strength and absorbs water at a rate that is higher than the 3% mix. The scientists concluded that sorptivity is not affected by the strength of concrete but rather by the capillary suction of water via the pore spaces within solid concrete particles.

The values for the water absorption rates were within the limits set. In order to provide appropriate durability, (T Tracz & J Śliwińsk, 2012) stated that the water absorption rate should be between 4 and 6%; if it is less than 5%, the material is deemed to be of good quality (Wilson & Tennis, 2021).

4.6 Chemical Resistance

The 100mm x 100mm x 100 mm cubes were fully immersed in 2.5% sulfuric acid-water solution. The acid solution was replaced weekly after the cubes were thoroughly washed with a brush, dried, and the weight recorded. The weight loss of the cubes was recorded over seven weeks according to (*ASTM C1898*).

4.6.1 Weight Loss

The rate of weight loss data, due to the chemical resistance acid attack is as shown in Appendix B3.2 and the data was represented by the graph as shown in Figure. 4.8; On descriptive analysis, the 1 and 3% were the lowest compared to the rest of the ambient cured SCBA-based GPC, and the 0% was superior, as it was cured under elevated temperature, which acted as the control.

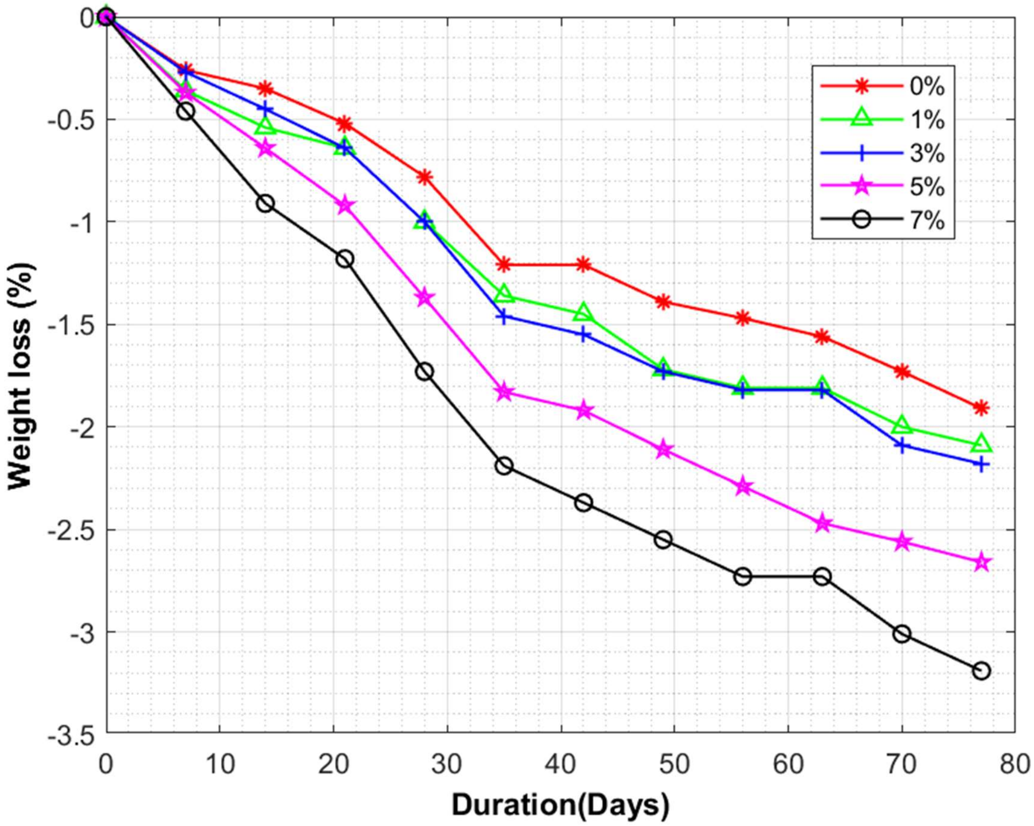

Figure 4. 8 Weight Loss Trend after Acid Attack

According to (Bassuoni & Nehdi, 2007), sulfuric acid intrusion from underground and acid rain is a risk for concrete components like foundations. Acid assault has a negative effect on concrete because of the dissolving effect caused by hydrogen ions. Sulfate ions interact chemically with the constituents of hardened concrete in a series of reactions known as sulfate attack. A study by (Sinkhonde et al., 2022) found that sulfuric acid was preferred over seawater, indicating a sulfate attack. They noted that the exposure to sulfuric acid was disastrous compared to sulfate attack from seawater. Considering these reactions could result in the cracking, spalling, or loss of strength of concrete structures, appropriate test methodologies are needed to determine the resilience of concrete after sulfate exposure. The chemical reaction between the calcium ions and sulfuric acid generates less dense calcium sulfate. This reaction could cause the geopolymer material to be displaced and lose weight. The calcium sulfate is also soluble, leading to leaching, which causes disintegration and can also lead to weight loss (Sinkhonde et al., 2022).

On analysis of variance (ANOVA) with 5% (α) significance level, meaning that only 5% of tests conducted on groups without any noticeable distinction had a value of 0.05. The MatLab code used to analyze variance is shown in Appendix C. The SCBA-based GPC, cured under elevated and ambient temperatures, showed no significant weight loss when immersed in 2.5% sulfuric acid. The stable nature of the chemical matrix of the geopolymer concrete could explain this. Because a dense and durable network of calcium and sodium aluminosilicate is generated in the gel matrix of geopolymers during the geopolymerization process, these materials are known for their exceptional chemical resistance (Davidovits, 2013; Sukontasukkul et al., 2023). Owing to its low porosity and strong cross-linking, this network is impervious to chemical degradation and assault. Sulphate ions in sulfuric acid may not be able to interact with the aluminosilicate structures due to the dense geopolymer matrix. This may help to explain why, when exposed to 2.5% sulfuric acid over extended periods of time, the geopolymer matrix's overall weight essentially stays constant.

This can be explained by the study (Bassuoni & Nehdi, 2007), which noted that a high absorption rate translates to high capillary suction, causing deep infiltration of the acid solution into the concrete, increasing the exposed surface area in contact with acid. This can also be explained by the low calcium content in the ambient cured GPC, leading to low amounts of calcium sulfate formed when it reacts with the sulfuric acid.

4.6.2 Appearance of the Exposed Specimen.

The images of the concrete cubes before and after exposure to the 2.5% sulfuric acid-water solution for 84 days are shown in Figure 4.9 and Appendix B3.1.

(a) **(b)**

Figure 4. 9 Appearance of Concrete Cube Before (a) and After Immersion (b)

After immersion, the cube exhibited a porous appearance and signs of cracking along the edges, with no deposits on the surface. These findings point to a reaction between chemicals and matrix deterioration in the geopolymer.

The reaction between the calcium ions present in the ambient cured geopolymer concrete and the sulfuric acid leads to the formulation of calcium sulfate. The calcium sulfate leaches out. This calcium sulfate leaching weakens the matrix, causing the pores to develop and giving them a visible porous look. With the exposure to sulfuric acid, the samples eventually degrade to the point that the aggregates are exposed.

(Sinkhonde et al., 2022) found that the leaching of calcium sulfate consequently leads to concrete disintegration. The most likely cause of the breaking around the margins is the sodium and calcium that leached during the acid attack, which resulted in crystal formation and deposition inside the pores and air gaps. Gypsum crystals are formed and deposited within the deteriorating layer due to the reaction between calcium ions and sulfate anions in the solution (Sukontasukkul et al., 2023). The geopolymer matrix may get stressed as a result of these gypsum crystals, which could eventually cause expansion, corrosion layer cracking, and strength loss, as discussed in 4.2.4.3.

4.6.3 Compressive Strength Loss

The cubes were placed in 2.5 sulfuric acid-water solution for 84 days as recommended by (*ASTM C1898*). After 84 days the cubes were surfaced-dried using a cloth. Then the compressive strength of the cubes, were determined by the compressive strength testing machines. The data were tabulated as shown in appendix B3.3. The data included the initial compressive strength (Before immersion) and residual compressive strength (After immersion). The percentage compressive strength loss was graphed as shown in Figure 4.10.

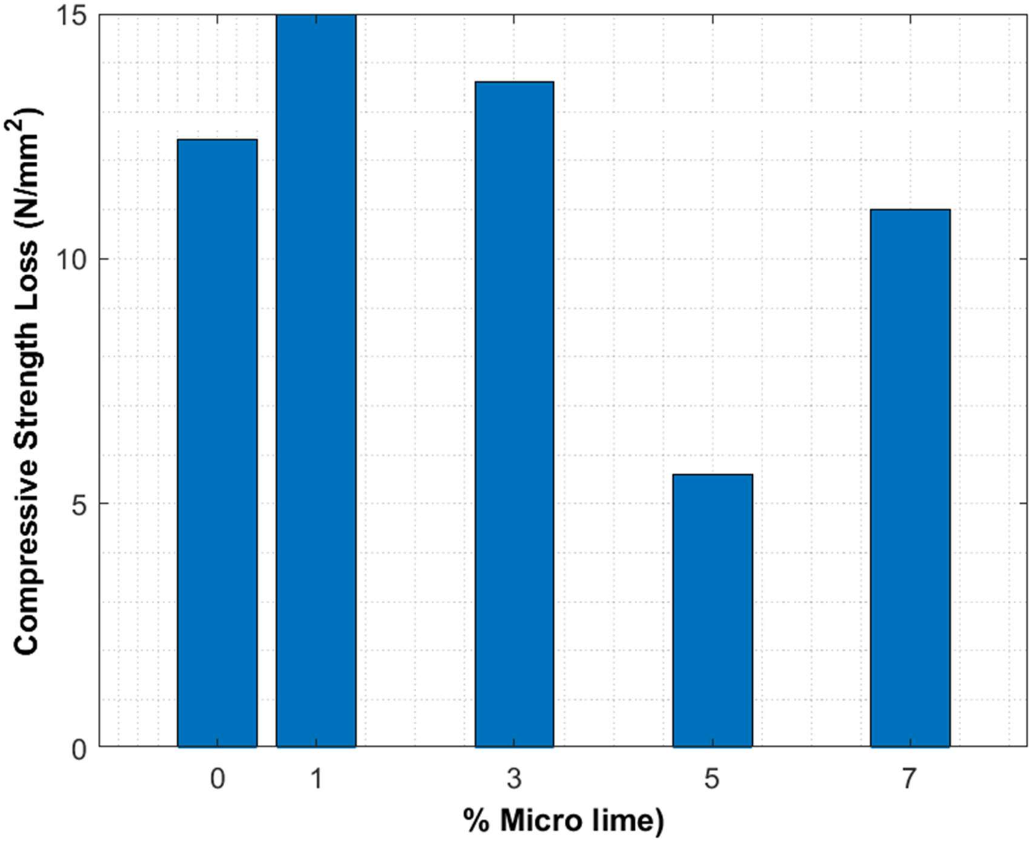

Figure 4. 10 Compressive Strength Loss after Acid Attack

Based on descriptive analysis, the compressive strength of the SCBA-based GPC was reduced after immersion in the sulfuric acid for 84 days. The compressive strength loss percentage ranges from 5.6% at 5% micro lime mix and 15.0% at 1% micro lime mix, which was significant compared to what was found by (Sata et al., 2012).

On analysis of variance (ANOVA) with a 5% (α) level of significance, 0, 1 and 3% micro lime mixes had significant loss in compressive strength. This could be explained by the initial low compressive strength for the 0 and 1% mixes. This can also be explained by the alumina-silicate linkages being broken down by excessive sulfuric acid exposure, which may result in a loss of strength upon exposure to acid solutions. Similar results were found by (Sukontasukkul et al., 2023), who discovered that geopolymer specimens subjected to 2.5 % sulfuric acid saw a drop in compressive strength. In acidic environments, (Bakharev, 2005)found that aluminosilicate polymers' depolymerization and zeolite formation caused strength to decrease significantly.

The 5 and 7% mixes had insignificant losses. The initial high compressive strength could explain this compared to the other mixes. The sample's compact nature reduces the quantity of sulfuric acid exposure to the geopolymer matrix, which lessens the geopolymer matrix's overall strength loss over time, as explained in 4.2.4.1.

4.7 Summary of the Findings.

The following is the summary of the findings from the research;

1) The workability of the fresh SCBA-based GPC, based on the slump value, was 34-55mm.
2) With an increase in the micro lime content, the compressive strength rose, 10N/mm^2 at 1%, to 18.25N/mm^2 at 7% micro lime, indicating an 82.5% strength increase. The strength increased with curing time, even at 19.75 N/mm^2 at 56 days of curing for the 7% micro lime.

3) The geopolymer concrete with ambient curing at 3% micro lime had the lowest water absorption rate of 4.8% compared to the other percentage of micro lime, in the range of 5.1-5.4%.
4) The elevated and ambient cured SCBA-based geopolymer concrete had no significant weight loss on exposure to sulfuric acid, indicating better sulfate attack resistance. The 0, 1 and 3% micro lime ambient temperature cured GPC significantly changed compressive strength when exposed to the 2.5% sulfuric acid. In contrast, 5% and 7% had no significant loss of compressive strength.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the study's conclusions and recommendations based on the results.

5.1 Conclusions

This study presents the results of the investigations of the effect of micro lime on the ambient temperature-cured SCBA-based geopolymer concrete. The results allow for the following inferences to be made;

1) The SCBA-based geopolymer concrete had low workability of 34-55mm, with neither bleeding nor segregation.
2) The compressive strength increased with the increase of the micro lime, 10N/mm^2 at 1%, to 18.25N/mm^2 at 7% micro lime, indicating an 82.5% strength increase. The strength also increased with curing time.
3) The geopolymer concrete with ambient curing at 3% micro lime had the least water absorption rate compared to the other percentage of micro lime.
4) The ambient temperature cured geopolymer concrete had insignificant weight loss on exposure to sulfuric acid, 1-3% had significant and 5-7% had insignificant change in compressive strength when exposed to the 2.5% sulfuric acid.

5.2 Recommendations

The recommendations from this study are as follows:

5.2.1 Recommendations Resulting from This Study

1. SCBA is used for GPC as a viable and sustainable alternative to traditional concrete for structural and non-structural applications.

2. The use of micro lime to achieve ambient temperature-cured SCBA-based geopolymer concrete.
3. The use of 7% micro lime as an admixture for ambient temperature cured SCBA for higher compressive strength and chemical resistance-acid attack.

5.2.2 Recommendations for Future Studies

1. Further research should be performed to determine the effect of the fineness of the SCBA.
2. The study recommends further analysis of SCBA, using X-ray diffraction analysis (XRD), to determine the state of the silica and alumina in the SCBA, either crystalline or amorphous.
3. Investigate long-term durability and performance under various environmental conditions.
4. The effect of micro lime as a partial replacement of the source material for ambient cured SCBA-based GPC should be studied instead of an admixture.
5. Optimize mix design for cost-effectiveness and broader practical applications.

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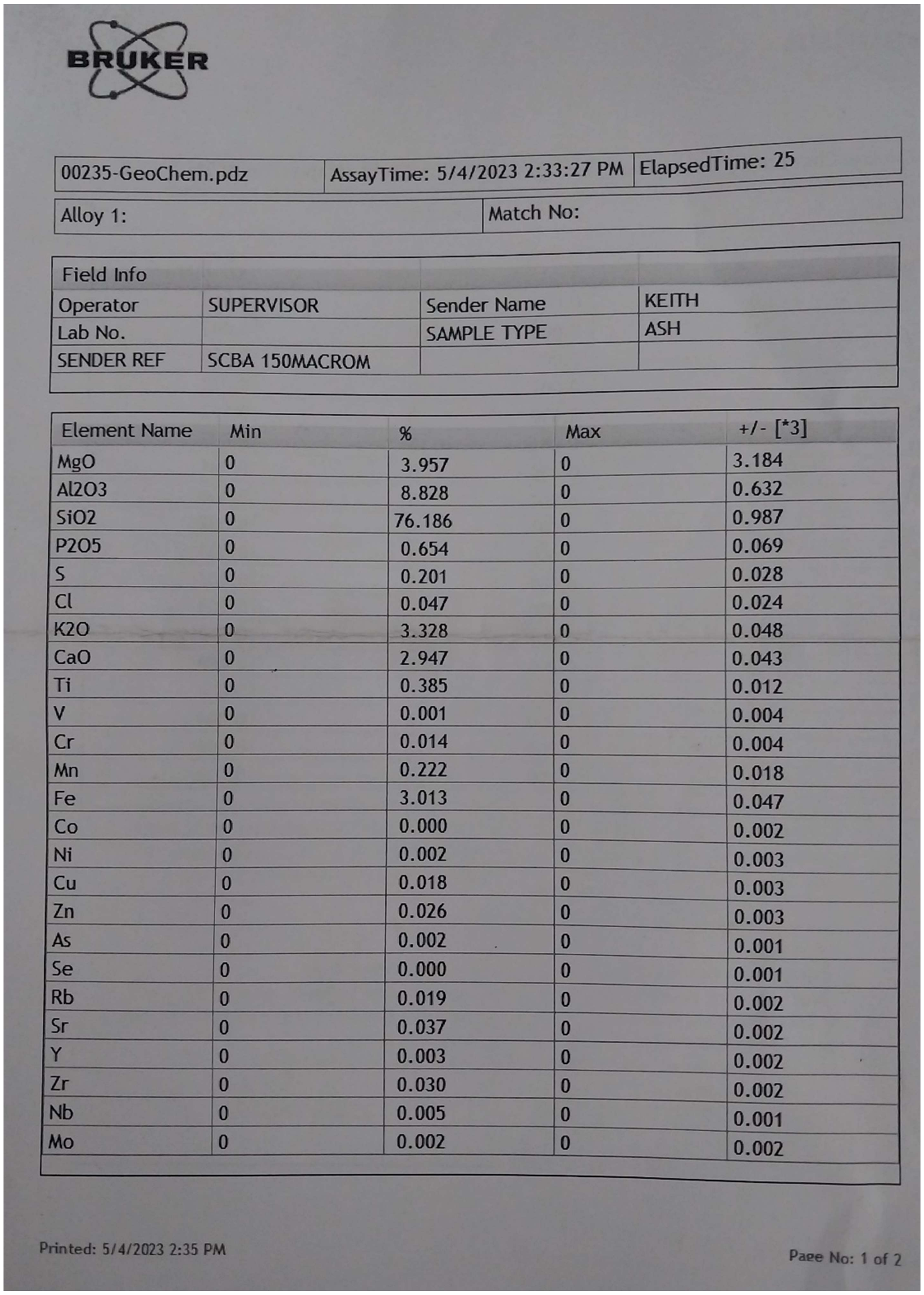
APPENDICES

APPENDIX A: PRELIMINARY TEST ON MATERIALS

A1: Chemical Composition of the SCBA Laboratory report



BRUKER

00235-GeoChem.pdz	AssayTime: 5/4/2023 2:33:27 PM	ElapsedTime: 25
Alloy 1:	Match No:	

Field Info			
Operator	SUPERVISOR	Sender Name	KEITH
Lab No.		SAMPLE TYPE	ASH
SENDER REF	SCBA 150MACROM		

Element Name	Min	%	Max	+/- [*3]
MgO	0	3.957	0	3.184
Al2O3	0	8.828	0	0.632
SiO2	0	76.186	0	0.987
P2O5	0	0.654	0	0.069
S	0	0.201	0	0.028
Cl	0	0.047	0	0.024
K2O	0	3.328	0	0.048
CaO	0	2.947	0	0.043
Ti	0	0.385	0	0.012
V	0	0.001	0	0.004
Cr	0	0.014	0	0.004
Mn	0	0.222	0	0.018
Fe	0	3.013	0	0.047
Co	0	0.000	0	0.002
Ni	0	0.002	0	0.003
Cu	0	0.018	0	0.003
Zn	0	0.026	0	0.003
As	0	0.002	0	0.001
Se	0	0.000	0	0.001
Rb	0	0.019	0	0.002
Sr	0	0.037	0	0.002
Y	0	0.003	0	0.002
Zr	0	0.030	0	0.002
Nb	0	0.005	0	0.001
Mo	0	0.002	0	0.002

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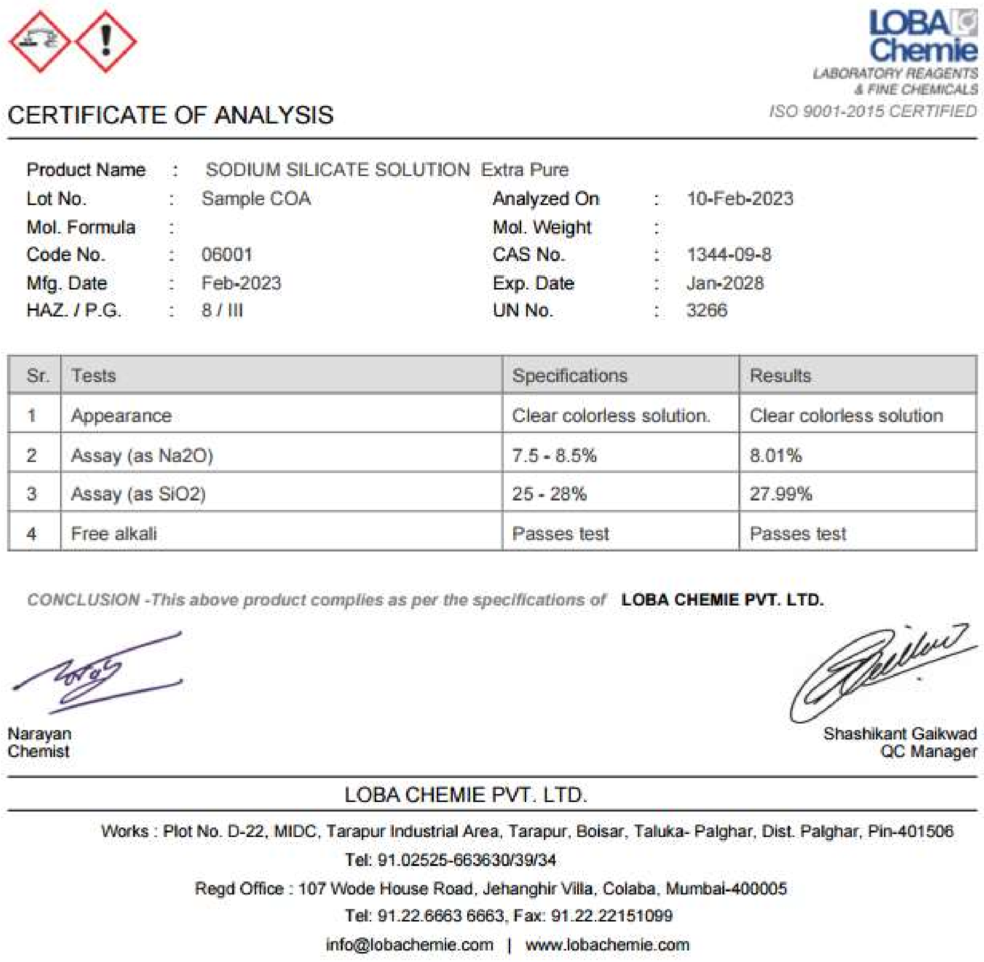
Page No: 1 of 2

A2: Laboratory Report on LOI

Crucible mass	Crucible + sample mass before heating	Crucible + sample mass after heating
 	 	

A3: Certificate of Analysis: Sodium Silicate Solution



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ISO 9001-2015 CERTIFIED

CERTIFICATE OF ANALYSIS

Product Name	: SODIUM SILICATE SOLUTION Extra Pure		
Lot No.	: Sample COA	Analyzed On	: 10-Feb-2023
Mol. Formula	:	Mol. Weight	:
Code No.	: 06001	CAS No.	: 1344-09-8
Mfg. Date	: Feb-2023	Exp. Date	: Jan-2028
HAZ. / P.G.	: 8 / III	UN No.	: 3266

Sr.	Tests	Specifications	Results
1	Appearance	Clear colorless solution.	Clear colorless solution
2	Assay (as Na2O)	7.5 - 8.5%	8.01%
3	Assay (as SiO2)	25 - 28%	27.99%
4	Free alkali	Passes test	Passes test

CONCLUSION -This above product complies as per the specifications of **LOBA CHEMIE PVT. LTD.**

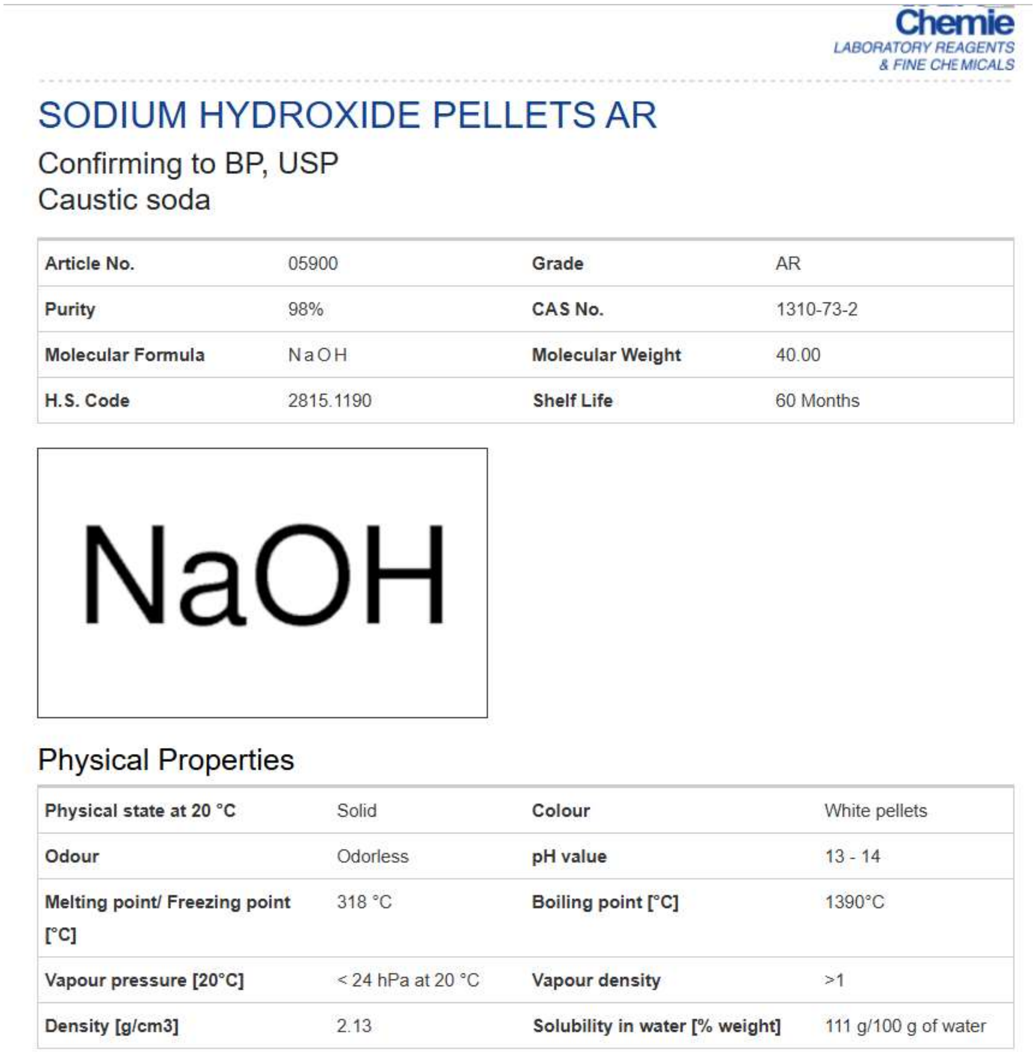
Narayan
Chemist

Shashikant Gaikwad
QC Manager

LOBA CHEMIE PVT. LTD.

Works : Plot No. D-22, MIDC, Tarapur Industrial Area, Tarapur, Boisar, Taluka- Palghar, Dist. Palghar, Pin-401506
Tel: 91.02525-663630/39/34
Regd Office : 107 Wode House Road, Jehanghir Villa, Colaba, Mumbai-400005
Tel: 91.22.6663 6663, Fax: 91.22.22151099
info@lobachemie.com | www.lobachemie.com

A4: Certificate of Analysis: Sodium Hydroxide



Chemie
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SODIUM HYDROXIDE PELLETS AR

Confirming to BP, USP
Caustic soda

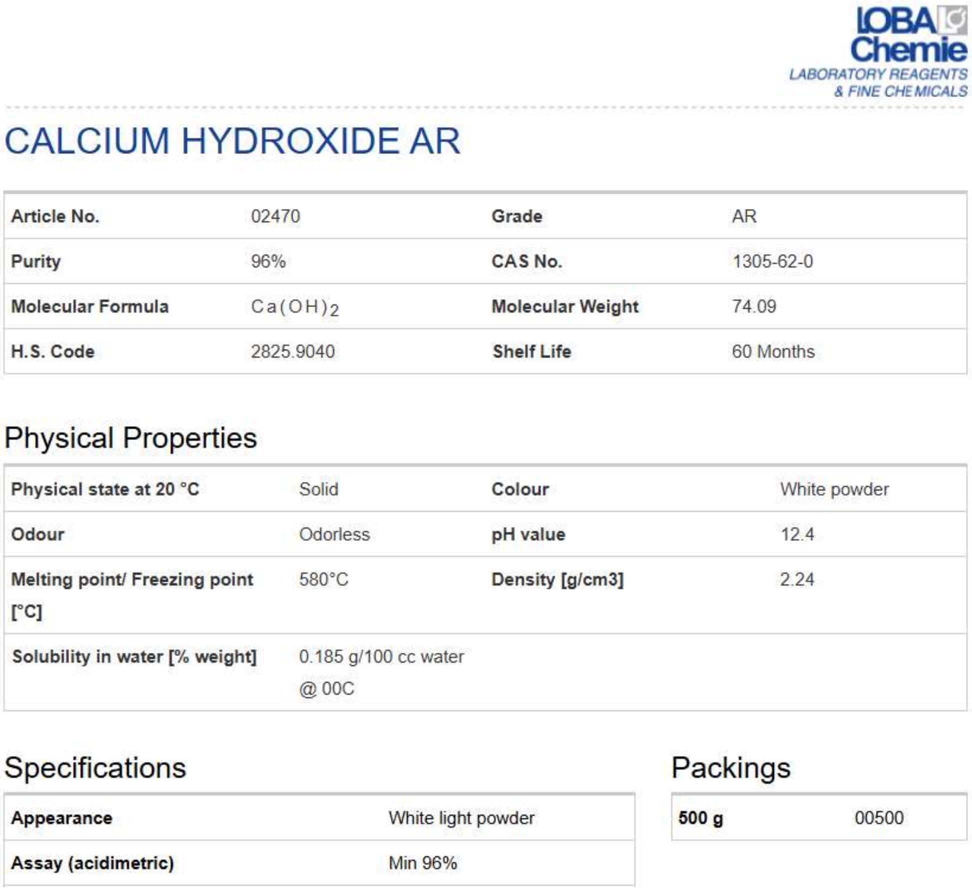
Article No.	05900	**Grade**	AR
Purity	98%	**CAS No.**	1310-73-2
Molecular Formula	NaOH	**Molecular Weight**	40.00
H.S. Code	2815.1190	**Shelf Life**	60 Months

NaOH

Physical Properties

Physical state at 20 °C	Solid	**Colour**	White pellets
Odour	Odorless	**pH value**	13 - 14
Melting point/ Freezing point [°C]	318 °C	**Boiling point [°C]**	1390°C
Vapour pressure [20°C]	< 24 hPa at 20 °C	**Vapour density**	>1
Density [g/cm3]	2.13	**Solubility in water [% weight]**	111 g/100 g of water

A5: Certificate of Analysis: Calcium Hydroxide



LOBA Chemie
LABORATORY REAGENTS
& FINE CHEMICALS

CALCIUM HYDROXIDE AR

Article No.	02470	**Grade**	AR
Purity	96%	**CAS No.**	1305-62-0
Molecular Formula	$Ca(OH)_2$	**Molecular Weight**	74.09
H.S. Code	2825.9040	**Shelf Life**	60 Months

Physical Properties

Physical state at 20 °C	Solid	**Colour**	White powder
Odour	Odorless	**pH value**	12.4
Melting point/ Freezing point [°C]	580°C	**Density [g/cm3]**	2.24
Solubility in water [% weight]	0.185 g/100 cc water @ 00C		

Specifications

Appearance	White light powder
Assay (acidimetric)	Min 96%

Packings

500 g	00500

APPENDIX B: TESTS ON CONCRETE

B1: Results of Slump Test on Fresh Concrete

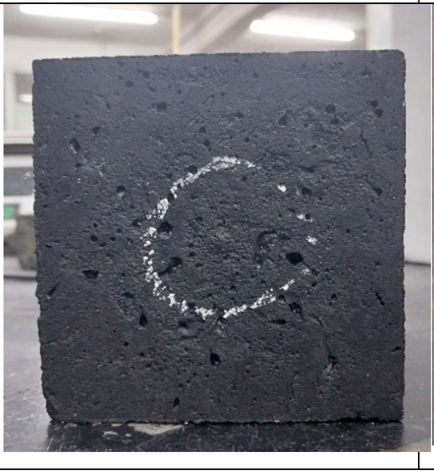
Concrete mix	% Micro lime	Slump (mm)
Mix 1	0	55
Mix 2	1	48
Mix 3	3	42
Mix 4	5	37
Mix 5	7	34

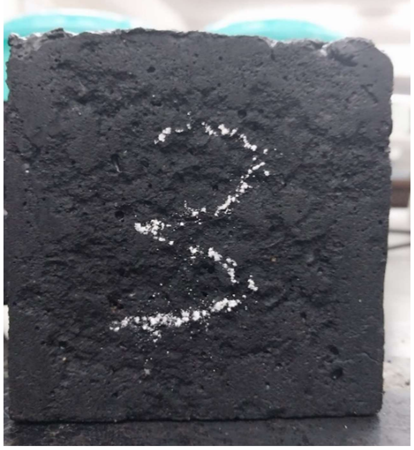
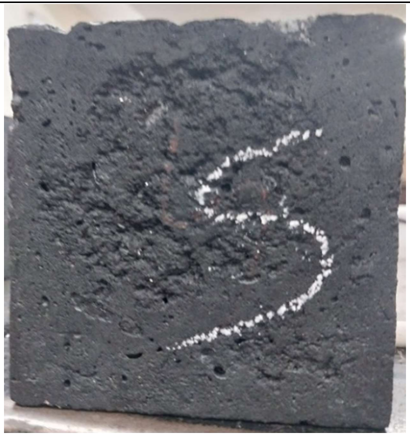
B2: Results of Compressive Strength Test on Hardened Concrete

Concrete mix	% Micro lime	Compressive strength (N/mm^2) in age, Days			
		7	14	28	56
Mix 1	0	11.25	11.25	11.25	11.25
Mix 2	1	5.5	7	10	11.25
Mix 3	3	8.75	9.75	14.75	16.75
Mix 4	5	6	10.25	15.25	17.25
Mix 5	7	12	12	18.25	19.75

B3: Chemical Resistance - Acid Attack

B3.1: Image of the cubes before and after immersion in the 2.5 sulfuric acid

% Micro lime	Before	After
0		

1		
3		
5		

7		

B3.2: Weight Loss

Concrete mix	Weight in grams											
	7	**14**	**21**	**28**	**35**	**42**	**49**	**56**	**63**	**70**	**77**	**84**
Mix 1	2.306	2.300	2.298	2.294	2.288	2.278	2.278	2.274	2.272	2.270	2.266	2.262
Mix 2	2.204	2.196	2.192	2.190	2.182	2.174	2.172	2.166	2.164	2.164	2.160	2.158
Mix 3	2.198	2.192	2.188	2.184	2.176	2.166	2.164	2.160	2.158	2.158	2.152	2.150
Mix 4	2.184	2.176	2.170	2.164	2.154	2.144	2.142	2.138	2.134	2.134	2.130	2.128
Mix 5	2.196	2.186	2.176	2.170	2.158	2.148	2.144	2.140	2.136	2.136	2.130	2.126

B3.3: Compressive Strength Loss

Concrete mix	Compressive Strength Before immersion (N/mm^2)	Compressive Strength after Immersion (N/mm^2)	Strength loss (%)
Mix 1	11.25	9.85	12.4
Mix 2	10.00	8.50	15.0
Mix 3	14.75	12.75	13.6
Mix 4	15.25	14.40	5.6
Mix 5	18.25	16.25	11.0

B3.4: Water Absorption Results

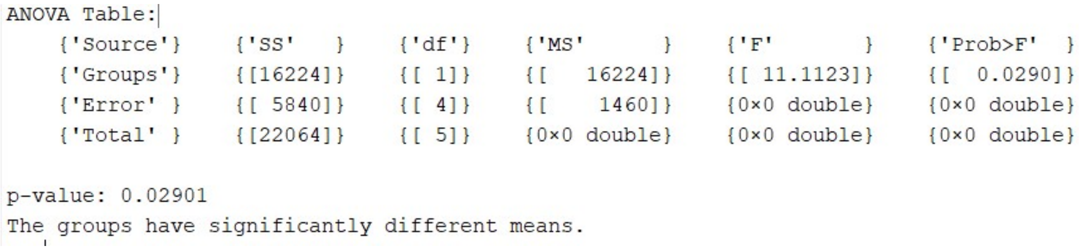
Time in Minutes	**0**	**30**	**60**	**120**
Concrete Mix	%	%	%	%
Mix 1	0	3.81	4.37	4.74
Mix 2	0	4.58	4.73	5.06
Mix 3	0	4.21	4.54	4.83
Mix 4	0	4.97	5.12	5.41
Mix 5	0	4.95	5.10	5.34

APPENDIX C: ANALYSIS OF VARIANCE (ANOVA)

C1: Matlab Code

```matlab
% Example Data (Group A and B)
A = [2046, 2080, 2012];
B = [2150, 2192, 2108];

% Combine data into a single array
data = [A, B];

% Create a grouping variable (1 for A, 2 for B)
groups = [ones(1, length(A)), 2*ones(1, length(B))];

% Perform One-Way ANOVA
[p, tbl, stats] = anova1(data, groups, 'off');

% Display ANOVA table
disp('ANOVA Table:')
disp(tbl)

% Display p-value
disp(['p-value: ', num2str(p)])

% Check for significance
if p < 0.05
    disp('The groups have significantly different means.')
else
    disp('The groups do not have significantly different means.')
end
```

C1: Matlab Code Result



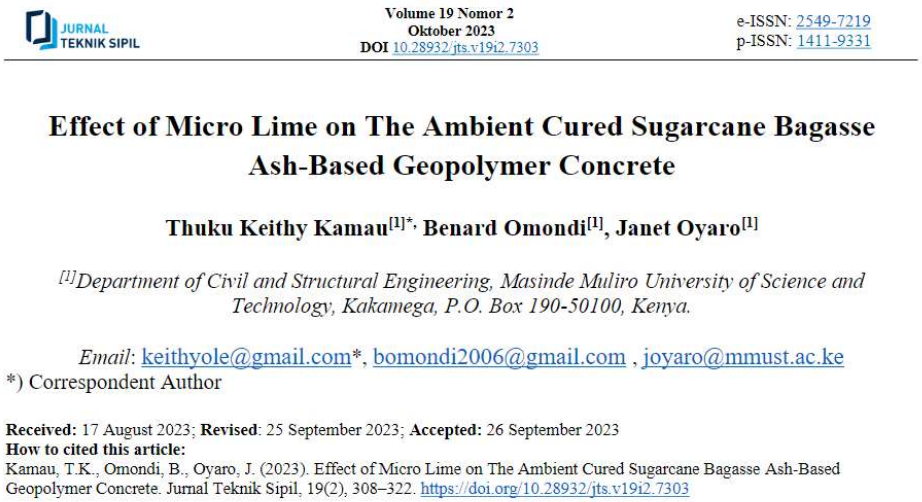
```
ANOVA Table:
    {'Source'}    {'SS'   }    {'df'}    {'MS'      }    {'F'       }    {'Prob>F'  }
    {'Groups'}    {[16224]}    {[ 1]}    {[   16224]}    {[ 11.1123]}    {[  0.0290]}
    {'Error' }    {[ 5840]}    {[ 4]}    {[    1460]}    {0×0 double}    {0×0 double}
    {'Total' }    {[22064]}    {[ 5]}    {0×0 double}    {0×0 double}    {0×0 double}

p-value: 0.02901
The groups have significantly different means.
```

APPENDIX D: JOURNAL PAPER

D1: Jurnal Teknik Sipil

Please click the link below to access the paper:

https://journal.maranatha.edu/index.php/jts/article/view/7303/2600



JURNAL TEKNIK SIPIL
Volume 19 Nomor 2
Oktober 2023
DOI 10.28932/jts.v19i2.7303
e-ISSN: 2549-7219
p-ISSN: 1411-9331

Effect of Micro Lime on The Ambient Cured Sugarcane Bagasse Ash-Based Geopolymer Concrete

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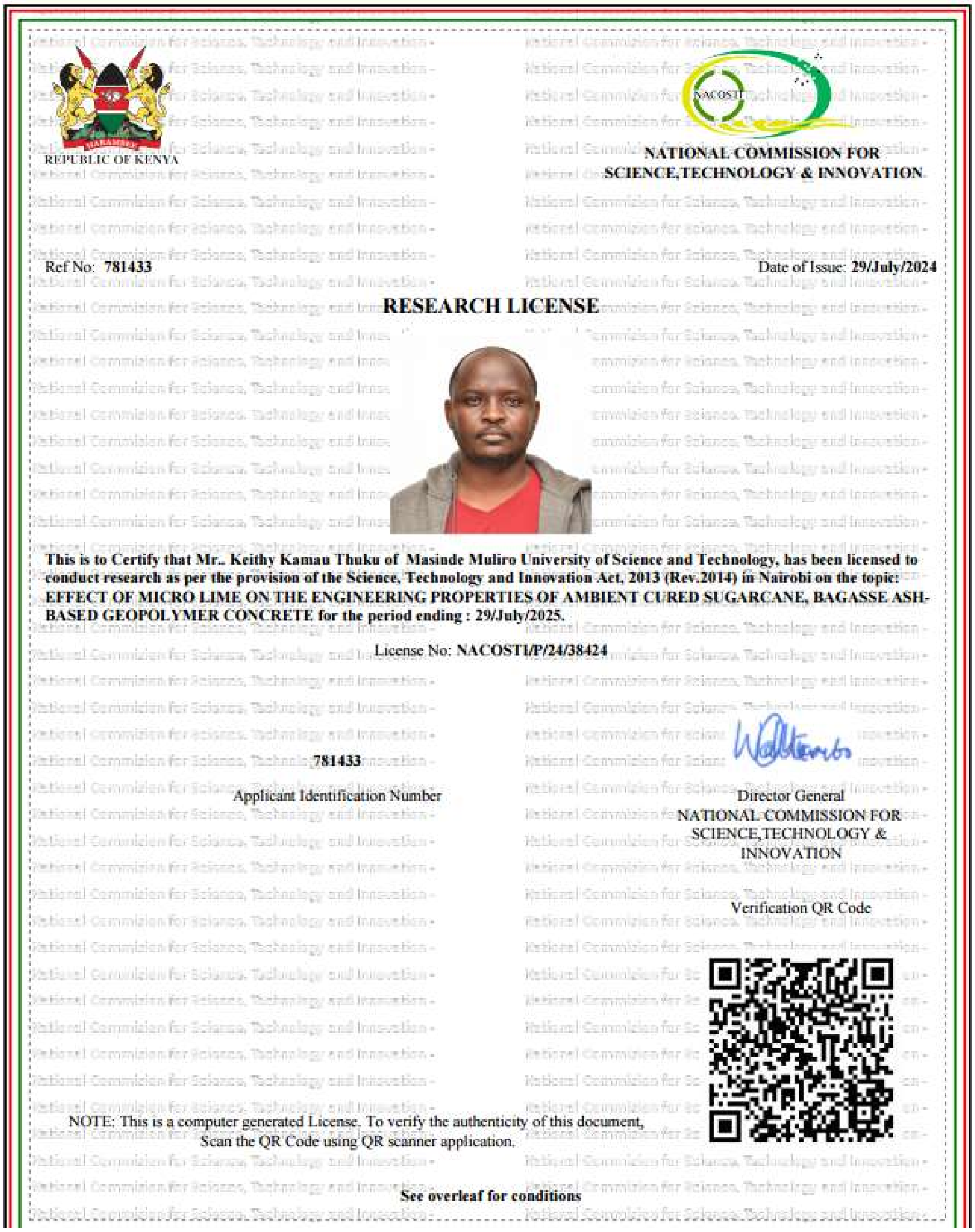
Received: 17 August 2023; **Revised**: 25 September 2023; **Accepted:** 26 September 2023
How to cited this article:
Kamau, T.K., Omondi, B., Oyaro, J. (2023). Effect of Micro Lime on The Ambient Cured Sugarcane Bagasse Ash-Based Geopolymer Concrete. Jurnal Teknik Sipil, 19(2), 308–322. https://doi.org/10.28932/jts.v19i2.7303

APPENDIX E: NACOSTI PERMIT



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