SYNTHESIS OF GEOPOLYMERS FROM INDUSTRIAL WASTES FOR SUSTAINABLE CONSTRUCTION

KELVIN LEE KAI WEN

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Bachelor of Civil Engineering (Environmental) with Honours

Faculty of Engineering and Green Technology
Universiti Tunku Abdul Rahman

May 2024

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature :

Name : KELVIN LEE KAI WEN

ID No. : 19AGB04717

Date : 23/04/2024

APPROVAL FOR SUBMISSION

I certify that this project report entitled **“SYNTHESIS OF GEOPOLYMERS FROM INDUSTRIAL WASTES FOR SUSTAINABLE CONSTRUCTION”** was prepared by **KELVIN LEE KAI WEN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Environmental) Civil Engineering with Honours at Universiti Tunku Abdul Rahman.

Approved by,

Signature :

Supervisor : Ir. Ts. Dr. Leong Kah Hon

Date : 23/04/2024

Specially dedicated to
my beloved father, mother and friends.

ACKNOWLEDGEMENTS

I am sincerely grateful to Universiti Tunku Abdul Rahman (UTAR) for providing me with an invaluable platform and ample equipment and facilities to conduct my final year research. Additionally, I extend my heartfelt appreciation to Kitaran Recovery Sdn. Bhd for generously supplying the materials necessary for my research project. I am deeply indebted to my esteemed supervisor, Ir. Ts. Dr. Leong Kah Hon, for his invaluable guidance, unwavering support, and patience throughout my final year project. His dedication and willingness to invest his time and expertise have been instrumental in shaping the trajectory of my research.

Special thanks are due to Dr. Muhammad Hasnolhadi bin Samsudin for his invaluable assistance in resolving my questionnaire and providing crucial materials. I am also grateful to the laboratory officers, including Ms. Ng Suk Ting, Mr. Tamilvanan, Mr. Yong Tzyy Jeng, and Pn. Ropidah, for their technical support and assistance during laboratory work. I would like to express my gratitude to Wong Ai Wei, a postgraduate senior, for her informative advice and guidance, which greatly facilitated my progress in the laboratory.

Heartfelt appreciation goes to my beloved parents for their unwavering support, encouragement, and sacrifices throughout my academic journey. Their belief in me has been a constant source of motivation and strength. Finally, I extend my sincere thanks to my friends and coursemates for their camaraderie, support, and solidarity during the challenges of our final year project. Their collaboration and encouragement have been invaluable in navigating this academic endeavour.

SYNTHESIS OF GEOPOLYMERS FROM INDUSTRIAL WASTES FOR SUSTAINABLE CONSTRUCTION

ABSTRACT

In the current era of rapid development, the construction sector is thriving due to the increasing global population. Cement, a fundamental construction material, is extensively utilized in large quantities. However, the high demand for cement leads to heightened production rates, resulting in significant energy consumption and environmental harm due to elevated carbon emissions. Concurrently, the escalating human population has led to a surge in waste generation from various activities, exacerbated by events such as the Covid-19 pandemic, which bolstered production in medical-related industries like glove manufacturing. Recycling glass poses challenges due to its intricate sorting and cleaning processes, rendering it impractical. In pursuit of a more sustainable future aligned with Sustainable Development Goals (SDGs) and circular economy principles, the invention of green substitute cement has emerged. To address waste generation challenges and harness the potential of geopolymers, this research study was undertaken. Geopolymer paste was synthesized by replacing traditional binders with glove former waste (GFW) and colored glass waste bottles (GW), alongside pulverized fly ash. Various mix designs, including 100FA, 10GW, 20GFW, 30GFW, 40GFW, 10GW, 20GW, 30GW, and 40GW, were synthesized into 50mm cubes and cylinders and subjected to ambient curing at room temperature for testing at 7th, 14th, and 28th day intervals. Laboratory tests, including compressive strength, water absorption, porosity, FESEM, FTIR, XRD, and sieve analysis, were conducted throughout the study. Results indicated that all mix designs met the standards' requirements. Despite potential impacts on strength and performance due to increased substitution of GFW and GW, results exceeded mandated standards. Optimum replacements for GFW and GW were determined to be 30%. Specifically, 30GFW yielded 68.513MPa compressive strength, 3.199% water absorption, and 9.70% porosity, while 30GW exhibited 73.971MPa compressive strength, 2.811% water absorption, and 8.78% porosity, as validated by FESEM images. Carbon estimation for OPC paste was 0.35kg per unit compared to zero carbon emissions for geopolymer paste, affirming geopolymer paste as a green substitute for OPC across various construction sector facets. In conclusion, the synthesized waste geopolymer represents a significant step towards sustainability within the construction industry. By utilizing waste materials, it aligns with numerous Sustainable Development Goals (SDGs) and embraces the principles of the circular economy. This innovative approach not only addresses environmental concerns but also contributes to social and economic development, highlighting its potential as a green substitute for traditional construction materials.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

$^{\circ}C$	Degree Celsius
%	Percentage
ρ	Density, kg/m^3
$<$	Lesser than
$=$	Equal
$>$	Greater than
$\times$	Times
$\leq$	Lesser or equal to
$\geq$	Greater or equal to
μ	Micron
μm	Micrometer
cm	Centimeter
cm	Centimeter
cm^{-1}	Reciprocal centimetre or inverse centimetre
g	Gram
g/ml	Gram per mililitre
kg	Kilogram
MJ/ton	Megajoule per ton
mm	Milimeter
mm^2	Milimeter square
mm^3	Millimetre cubic
MPa	Megapascal
N	Newton
N/mm^2	Newton per milimeter square
ppm	Parts per millon

$(Al(OH)_4^-)$	Aluminium hydroxide
$(Si(OH)_4)$	Orthosilicic acid
Al	Aluminium
Al_2O_3	Aluminium oxide
Al-O	Aluminium oxygen bond
Al-O-Si	Silicon- oxygen- aluminium
ASTM	American Society for Testing Materials
ATR	Attenuated Total Reflectance
BaO	Barium oxide
BC	Biochar
BS EN	British Standard European Norm
C_2S	Dicalcium silicate
C_3A	Tricalcium aluminate
C_3S	Tricalcium silicate
C_4AF	Tetracalcium aluminoferrite
CaO	Calcium oxide
CCA	Corncob Ash
CKC	Calcined Kaolinic Clay
Cl	Chlorine
CO_2	Carbon dioxide
Cr_2O_3	Chromium (III) oxide or chromia
C-S-H	Calcium Silicate Hydrate
CuO	Copper (II) oxide
FA	Pulverized Fuel Ash
Fe	Iron
Fe_2O_3	Iron (III) oxide or ferric oxide
FESEM	Field Emission Scanning Electron Microscopy
FTIR	Fourier- Transform Infrared Spectroscopy
Ga_2O_3	Gallium oxide
GFW	Glove Former Waste
GGBS	Ground Granular Blast- furnace Slag
GW	Glass Waste
H_2O	Dihydrogen monoxide or water

IC	Illite Clay
K_2O	Potassium oxide
KOH	Potassium hydroxide
LOI	Loss Of Ignition
MARGMA	Malaysian Rubber Glove Manufacturers Association
MgO	Magnesium oxide
MgO	Magnesium oxide
MK	Metakaolin
MMT	Million metric ton
MnO_2	Manganese dioxide
MSW	Municipal Solid Waste
MT	Metric Ton
Na_2O	Sodium oxide
Na_2SiO_3	Sodium silicate
NaOH	Sodium hydroxide
Nb_2O_5	Niobium oxide
-NH	Amine group
NiO	Nickel Oxide
NP	Natural Perlite
OH^-	Hydroxide ions
-OH	Hydroxyl group
OPC	Ordinary Portland Cement
P_2O_5	Phosphorus pentoxide
PbO	Lead (II) oxide or lead monoxide
PPE	Personal Protective Equipment
Rb_2O	Rubidium oxide
RM	Ringgit Malaysia
SDGs	Sustainable Development Goals
SEM	Scanning Electron Microscopy Test
Si	Silicon
Si-O	Silicon oxygen bond
SiO_2	Silicon dioxide
Si-O-Si	Siloxanes or silicon- oxygen- silicon

SnO_2	Tin (IV) oxide
SO_3	Sulphur trioxide
SrO	Strontium oxide
TeO_2	Tellurium dioxide
ThO_2	Thorium oxide
TiO_2	Titanium dioxide
US$	United Stated Dollar
V_2O_5	Vanadium(V) oxide or vanadia
WGP	Waste Glass Powder
XRD	X- Ray Diffraction
Y_2O_3	Yttrium oxide OR yttria
Yb_2O_3	Ytterbium (III) oxide
ZrO_2	Zirconium dioxide or zirconia

`

CHAPTER 1

INTRODUCTION

1.1 Research Background

Cement is essential in construction as it binds materials together to form durable structures and provides strength and stability. It is produced using a precise manufacturing process from various minerals, chiefly limestone, clay, and gypsum. Cement creates a paste when combined with water that eventually solidifies to produce a sturdy and long-lasting binder. Cement serves as the building block for construction projects all over the world, enabling the development of solid foundations, strong walls, and durable structures that form our cities and sustain our everyday lives. Cement is widely used in buildings, bridges, highways, and countless other constructions. Cement is a crucial part of the building industry because of its strength, adaptability, and capacity to attach to various materials.

While cement aids in the building of modern infrastructure, it is critical to recognize its detrimental impacts on the environment and human health. The substantial carbon footprint of cement manufacturing is one of the main issues. Currently, the concrete industry relies on fossil fuels to heat furnaces to extremely high temperatures, emitting about 7-8% of carbon. Significant CO2 emissions are also caused by the calcining process and the use of carbon-emitting by-products like coal in the manufacturing of clinker. (Amran et al., 2022) Large volumes of carbon dioxide (CO2) are released into the atmosphere during the cement manufacturing process, increasing greenhouse gas emissions, and accelerating climate change. Manufacturing cement is a very energy-intensive process that accounts for 2-5% of global energy consumption. Cement production mainly relies on fossil fuels, further depleting limited resources, and maintaining reliance on non-renewable energy sources. (Amran et al., 2022) Additionally, the destruction of natural habitats and ecosystems during the mining of raw materials for cement manufacture contributes to the decline in biodiversity. Therefore, utilisation of waste will be one of the practical solutions in reducing the high amount of CO2.

Waste refers to items or substances that have been dumped and are no longer useful. Due to reasons such as population increase, urbanization, industrialization, and changes in consumer patterns, Malaysia's waste generation is gradually rising. Furthermore, during the period from 2015 to 2020, Malaysia experienced a rise in its daily average waste generation by approximately 5.19%, with the output escalating from 38,563 tonnes to 49,670 tonnes. (Ghani, 2021) General waste includes both industrial and non-industrial waste, which includes components from homes, workplaces, and commercial facilities. This increase in waste creates significant environmental issues, especially when it comes to the proper management and disposal of different waste kinds, such as glass debris, and former gloves.

Glass waste is defined as wasted or shattered glass products that come from a variety of sources, including the glass-producing sector. Glass waste in the glass industry can come from post-consumer glass goods, surplus or rejected glass products, and production faults. Malaysia, as a major player in the glass sector, confronts the difficulty of handling a growing volume of glass debris. Due to issues with weight, transportation, and a smaller market, glass recycling is more difficult and less common than plastic recycling. Glass waste is relatively insignificant in comparison to plastic waste since not all forms of glass can be recycled. The above factors contribute to the fact that glass is frequently thrown into landfills rather than recycled. (Guo et al., 2020) Glass waste should be disposed of properly to avoid damaging the environment by contaminating the land, water, and air.

The surge in glove demand during the pandemic has led to the emergence of glove former waste as an additional environmental concern. Malaysia has emerged as one of the key providers in the worldwide glove manufacturing business, continuously supplying expanding global demand for gloves. In 2020, rubber glove exports from Malaysia reached 52.7 billion ringgit (US$12.7 billion), and about 65 % of the global market (300 billion pieces). (ASEAN Business News, 2021) Worn-out glove molds or formers that were used to make gloves are referred to as "glove former waste." Typically composed of ceramic or aluminum, these glove molds serve as temporary molds throughout the production process. Glove formers may become defective or obsolete during production, resulting in waste. Unfortunately, the waste glove forms are frequently dumped in landfills by the glove manufacturer. The main justification for this method of disposal is the non-biodegradability of the materials utilized, which makes it difficult to identify substitute disposal methods. The ecology suffers because of the disposal of used gloves former in landfills. It increases the amount of non-biodegradable waste that is generated, takes up valuable landfill space, and has the potential to release hazardous compounds into the soil and groundwater.

These gloves former and glass are typically disposed of in landfills, raising issues with the environment and wasting resources. However, there is a rising interest in investigating other alternatives, such as reusing glove formers waste and glass waste. Their use in modifying cement manufacture is one possible method of repurposing. We may be able to address the environmental effects of both sectors simultaneously by using these wastes as a component in cement manufacture. This strategy offers a potential chance to lessen the carbon footprint of the cement industry in addition to offering a sustainable option for controlling these wastes. Considering this, this study suggests examining the viability and advantages of reusing glove formers' waste and glass waste in the manufacture of cement, stressing the possible environmental and financial benefits it may provide. Glass typically contains approximately 70 to 75 percent silica content (https://newatlas.com/author/ben-coxworth, 2019). Fe An environmentally friendly alternative to traditional cement, geopolymer is produced by blending these components with sodium hydroxide and sodium silicate. The inclusion of silica waste is especially advantageous due to its significant silica content, which plays a crucial role in the creation and effectiveness of geopolymers. Given their valuable properties as crucial process components, glove former waste and glass waste containing silica and pure alumina present ideal resources to produce geopolymer.

Geopolymer is an inorganic polymer that is created by a chemical reaction involving silicon (Si) and aluminium (Al) rich source materials and alkaline activators. A three-dimensional network structure like that of conventional cementitious materials is produced by this process, known as geopolymerization. Geopolymerization, an innovative and ecologically beneficial method, provides an alternative to regular Portland cement by using waste materials from the glass and glove industries. Geopolymer binder has qualities comparable to Portland cement but with significant benefits. In comparison to conventional Portland cement, geopolymer cement and concrete provide improved durability, chemical resistance, and mechanical properties making them great options for radiation shielding in a variety of environmental settings. The carbon footprint of geopolymer concrete was around 9% lower than Ordinary Portland cement-made concrete. (Singh and Middendorf, 2020) Furthermore, because geopolymerization makes use of industrial by-products that would otherwise be thrown away as trash, it greatly lowers carbon emissions when compared to the manufacturing of Portland cement.

Incorporating both pure alumina and silica waste in fabrication of new geopolymer not only acts as a more environmentally friendly substitute for conventional Portland cement, but it also adheres to the basic principles of a circular economy. In the circular economy, waste material from the glass and glove industry is utilized and modified into geopolymers. Originally, these wastes are disposed of through landfilling activities which will bring adverse impacts to the environment. The total process's energy consumption for geopolymer has an embodied energy of 645 MJ/ton which is roughly one-sixth of the OPC. (La Scalia et al., 2021) This points out that the production of geopolymers requires lower energy, which lessens its impact on the environment. Geopolymers with higher quality and better performance than conventional cement, also add value for customers in the building sector. The glove and glass industries can also make money and reinvest it back into their own companies by trading the waste materials for the geopolymer manufacturing process. This mutually beneficial relationship promotes a circular economy where waste is transformed into a useful resource that benefits the economy and the environment. Geopolymer invention by replacing this glass waste and glove waste also in another way achieving several sustainable development goals (SDGs). Through the carbon footprint reduction, waste elimination and durability properties by the geopolymer, it achieves 9 sustainable development goals (SDGs) which shown in the below diagram.

Figure 1.1: Sustainable Development Goals

1.2 Problem Statement

Ordinary Portland Cement (OPC) is used extensively in buildings, which raises serious environmental issues, particularly about climate change and resource depletion. At least 8% of human-caused global emissions on a per-person basis originate from the cement sector alone. (Concrete needs to lose its colossal carbon footprint, 2021) OPC production is a substantial contributor to the world's greenhouse gas emissions and a major source of carbon dioxide emissions. These emissions exacerbate climate change and the greenhouse effect, resulting in negative consequences like rising temperatures, changing weather patterns, and a rise in the frequency of extreme weather occurrences. Furthermore, the manufacture of OPC is highly reliant on limited resources including clay, limestone, and fossil fuels. The extraction of these materials for the manufacture of cement causes habitat loss, land degradation, and biodiversity loss. Cement manufacturing is a high-energy-intensive process. About 2% of the world's primary energy, or nearly 5% of overall industrial energy consumption, is thought to be used by the cement sector. (Worrell et al., 2001) As a result of the energy-intensive procedures used to make cement, such as burning fossil fuels, non-renewable energy sources are increasingly depleted, and overall energy consumption rises.

Another significant problem emerges from the inappropriate disposal of silica-rich glass debris and glove moulding waste. Such waste frequently ends up in landfills, worsening its effects on wildlife, vegetation, and the ecosystem. This will result in the release of greenhouse gases, such as methane, which will greatly contribute to climate change. Additionally, the build-up of these wastes in landfills causes leachate to form as well as take up valuable land space. Around 3 million litres of leachate are produced from landfills every day in Malaysia, according to estimations. (Banch et al., 2019) Heavy rainfall in the whole country is somewhat to blame for this large amount of leachate. By polluting the soil, groundwater, and surrounding bodies of water, this hazardous liquid, which is created when rainfall flows through the waste, poses major hazards to both human health and ecological systems.

Concerns about human exposure to hazardous substances are also raised by improper disposal. Glass debris causes safety concerns for waste management employees during processing and transportation due to its sharp pieces. Furthermore, the accumulation of glass waste and glove former waste in landfills disrupts the natural decomposition process, creating anaerobic conditions that hinder organic matter breakdown and contribute to greenhouse gas emissions, exacerbating climate change and upsetting ecological balance.

To reduce environmental dangers, protect human health, and advance sustainable waste management practices, the issue of glass waste and glove former disposal must be addressed. We can lessen the burden on landfills, cut down on greenhouse gas emissions, and lessen the negative effects on the environment, vegetation, and human health by using these wastes to produce geopolymers instead of OPC.

1.3 Aim and Objectives

The objective of this report is to evaluate the efficiency of utilizing glass and glove former waste, which are abundant in silica and aluminium content, for the synthesis of geopolymers as a greener substitute for cement paste. This report aims to obtain the optimum percentage of both silicate waste to replace fly ash content through assessing the characteristics and performance of the geopolymer paste.

i. To characterize the industrial waste material
ii. To optimize the geopolymerization process using industrial waste material
iii. To evaluate the engineering properties of the synthesized geopolymer

1.4 Outline of Study

The goal of this study is to undertake a viable study on the utilization of glove former waste and glass waste, both of which include a high percentage of silica and alumina content. The study's main objective is to obtain the optimum percentage of replacement binder (purified fly ash) for 10, 20, 30 and 40% from both GFW and GW. The two different types of binder are used to replace the fly ash to from a geopolymer paste respectively. Binder- alkaline activator ratio in this study is fix to the 0.48. The alkaline activator used is the sodium hydroxide and sodium silicate which is fixed in the ratio of 1: 1. The synthesised geopolymer paste will be used to replace the OPC. The geopolymer paste will be mould in 5× 5× 5 cm cubic moulds and cured at ambient temperature. Various laboratory experiments will next be carried out to assess the mechanical performance, material characteristic and physical property of the geopolymers after ambient curing for 7, 14 and 28 days of testing age. The goal of the final year project is to assess the viability to use the waste materials which is glove former waste and coloured glass waste to produce geopolymers paste as a sustainable substitute for OPC.

1.5 Overall Thesis Framework

Table 1.1: Research Thesis Framework

Chapter	Title of Chapter	Scope of Chapter
1	Introduction	• Overall background of OPC and its negative impacts towards the environment • Introduction of GW and GFW as one of the ingredients to replace cement. • Introduction of geopolymer paste and its benefits. • Overall background of circular economy and SDGs • Overview of the research study's goal, purpose, and scope
2	Literature Review	• Overall background of the OPC • History of the OPC • Mechanism and Process for OPC manufacturing • Application of OPC • Properties and Drawbacks of OPC • General background of GW • Properties and chemical composition of GW • Drawbacks of GW • Research-related works that use GW in eco-friendly material. • General background of GFW • Properties and Drawbacks of GFW • General background of Geopolymer • Mechanism and Process of geopolymerisation

		• Properties and Drawbacks of geopolymer • Relevant past research on geopolymer fabrication • Circular economy and SDGs
3	Research Methodology	• Introduction to the research methodology • Material preparation procedure • Mix design for the geopolymer fabrication. • Moulding and demoulding process • Curing process and various laboratory testing
4	Result and Discussion	• Data Analysis on several laboratory test • Report and discuss the result from the laboratory testing. • Compare data between the different percentage substitution of silica waste. • Compare data between various age of specimens. • Economic Appraisal for synthesized geopolymer paste. • Carbon Evaluation of the OPC and geopolymer paste
5	Conclusion and Recommendation	• Summary to conclude the research work. • Recommendation to enhance the geopolymer properties.

CHAPTER 2

LITERATURE REVIEW

2.1 Ordinary Portland cement

Rapid urbanization and unprecedented city expansion have resulted in an exponential increase in cement production and application, positioning cement as a key factor defining the modern construction landscape.

The invention of Ordinary Portland cement (OPC) is commonly attributed to Joseph Aspdin which issued in 1824, contribute to a milestone in the development of a binding agent achieved through the roasting of clay and limestone by the term of "Portland cement." This technique involved moderate-temperature firing, which led to the partial decomposition of calcium carbonate within the stone. However, it was Isaac Johnson's contributions in 1845 that truly revolutionized the field. Johnson painstakingly refined the proportions of clay and limestone, propelling the advancement of Portland cement. He achieved the efficient production of binding compounds of exceptional quality by implementing higher-temperature roasting. The latter part of the 19th century witnessed a rapid expansion of the cement industry in both Europe and the USA, largely attributed to this transformative approach. Following World War II, cement production experienced rapid acceleration. Global output surged remarkably, reaching its peak at 134 million metric tons in 1950, further soaring impressively to 832 million metric tons in 1980, and currently exceeding 1600 million metric tons. (Igliński and Buczkowski, 2017)

When OPC is mixed with water, a chemical process known as hydration occurs, which leads to the formation of cementitious compounds that provide binding strength to the concrete. The cement hydration process involves partial hydration even in humid air, but complete hydration requires substantial water mixing. The water-cement ratio or water-solid ratio influences the rheology, hydration progress, and ultimate characteristics of the hydrated material in this process. As a result, fresh cement paste exhibits a paste-like consistency when formulated with water-cement ratios of 0.3 to 0.6. This consistency gradually transforms into hardened cement paste during hydration, signifying a shift from a plastic to a solid form to achieving measurable strength. (Odler, 1998)

Cement manufacturing involves a series of intricate processes, commencing with the grinding and milling of raw materials to create raw meals. This raw meal then undergoes precise blending, pre-calcination, clinker generation through burning, and ultimately, cement grinding. Essentially, limestone and other source materials abundant in calcium, silicon, aluminium, and iron oxides are meticulously crushed and milled to produce raw meals. Before pre-heating, this raw mixture is thoughtfully blended, often within blending silos, to induce the dissociation of carbonate into calcium oxide and carbon dioxide. To maintain optimal temperatures, an additional fuel source is introduced into the pre-heating system. Following this, the treated mixture is conveyed to the kiln, where elevated temperatures foster the reaction between calcium oxide and various elements. This reaction leads to the creation of calcium silicates and aluminates, all transpiring at temperatures of up to 1450°C. Primary fuel is judiciously utilized to uphold the appropriate temperature within the kiln's combustion zone, a crucial factor for the completion of chemical reactions. These reactions culminate in the emergence of nodular clinker material from the kiln. Ultimately, the careful combination of this clinker with additives like gypsum, limestone, and ashes produces a finely ground product known as cement. Figure 2.1 shows the intricate process from the manipulation of raw components to the realization of the final product, is illuminated through this comprehensive technique. (Kääntee et al., 2004)

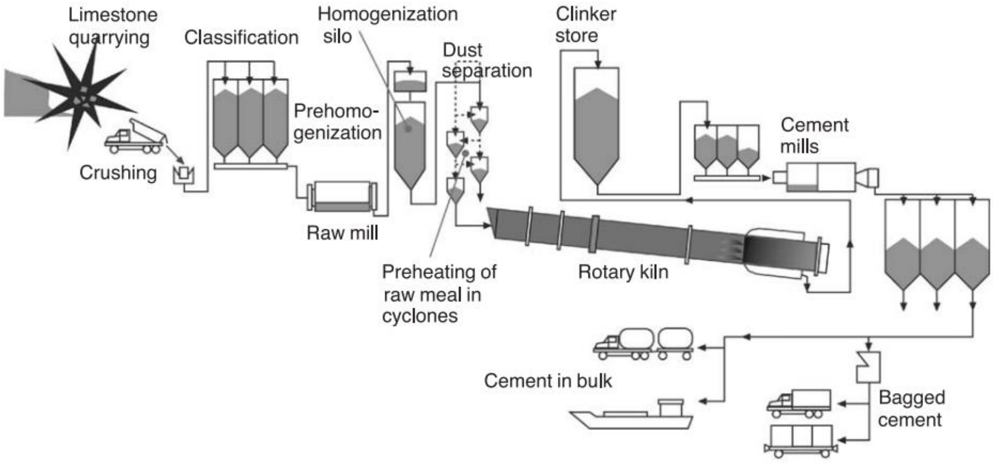


Figure 2.1: Process flow diagram for manufacture of cement

In another words, cement which is a crucial building ingredient, functions as a binding agent that sets and hardens to cling to stones, bricks, tiles, and other materials. It comprises fine, powdery materials made of clay, sand, limestone, and other minerals. It becomes a rock-hard substance after being heated and processed, and when combined with water, it turns into a paste that is used to bond building components. By anchoring and waterproofing structures, cement, which is used to make concrete and mortar, is an essential component of urban infrastructure. (civiltoday.com, n.d.) According to the International Cement Directory, there are now approximately 2273 functioning cement-producing units globally. (V. Saraswathy et al., 2017)

2.1.1 Properties of cement

The mechanism of cement involves hydration, which is a chemical reaction of cement mixed with water. The four major phases of cement are tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF). These phases are critical in determining the properties and characteristics of the finished cement product. Calcium silicate hydrate gel and other substances are produced when water is added to cement, which includes substances like tricalcium silicate and dicalcium silicate. Hydration is an exothermic process which heat is released while binding strength is created. Dissolution, nucleation, formation of hydration products, and setting are the stages involved. Hydration components solidify and interlock, which causes cement to harden. The material is transformed from a plastic to a solid state throughout the beginning to final stages of the setting process. This process creates a sturdy, solid cement structure that is essential for construction and other uses. (Marchon and Flatt, 2016)

The introduction of water into cement initiates a series of complicated chemical processes. Silicate and calcium ions are released during the dissolution in fundamental compounds such C_3S and C_2S. After their interaction, these ions form nuclei that eventually develop into the vital C-S-H gel. As this gel continues to be created, it permeates the spaces between the cement and aggregate particles, leading to the creation of a strong binding structure. Beyond this hydration stage, cement's chemical characteristics affect how different additives interact with it. (Bullard et al., 2011) The most significant properties of cement in concrete are its setting strength, and assessing and regulating cement quality involves measuring its strength under regulated conditions. It is well known that cement's compressive strength improves as its fineness or specific surface area increases. In addition, cements with a smaller range of particle sizes perform stronger than those with a wider range of particle sizes when subjected to an identical surface area. Chemical composition also contributes to a substantial impact on cement's setting strength. (Sajedi and Razak, 2011)

2.1.2 Drawbacks of cement

The need for cement and concrete has increased significantly during the past few decades as cement is in scarcity. Global per capita consumption of cement has increased from 1 metric ton to 3 metric tonnes over the past 50 years. The rapid industrial development of developing nations like China and India is one reason for the increase in cement use worldwide. Meanwhile, in developed regions, demand is driven by the need to replace, repair, and enhance existing structures. But there are concerns about the potential negative effects of this escalating cement usage.(Kumar Mehta et al., n.d.)

However, the cement industry presents significant environmental challenges, with the substantial consumption of non-fuel raw materials emerging as a prominent concern among its drawbacks. In the process of producing cement, non-fuel raw materials like limestone, clay, shale, and aggregates play crucial roles in manufacturing but do not serve as sources of energy or undergo combustion. According to Oss and Padovani (2003), about one MT of cement is made from about 1.7 MT of non-combustible raw materials. The amount of non-combustible raw materials needed to produce cement globally today is close to 3 billion MT; the corresponding fuel consumption is about 200 million metric tons in straight mass terms annually. This cement requires a total of roughly 15 billion MT in raw materials, primarily aggregates, to make 13-14 billion MT of concrete and mortars. The production of cement consumes vast quantities of non-fuel raw materials, raising concerns about potential shortages in the future. Water also contributes significantly to the manufacturing of cement. The correct setting of the cement requires about 1 billion tons of water every year. While some cement manufacturers need water for their processes, which causes it to evaporate, others do not. It is critical for maintaining an uninterrupted supply of clean water. (Oss and Padovani, 2003)

When the industrial revolution began in the mid-18th century, atmospheric CO_2 levels were around 280ppm. CO_2 levels increased to 310 ppm in the two centuries prior to World War II, increasing by 0.15 ppm annually. Alarmingly, from 1960 to 2000, there was an astonishing rise from 315 ppm to 365 ppm, which translates to an accelerated rate of 1.25 ppm each year. (Figure 2.2)

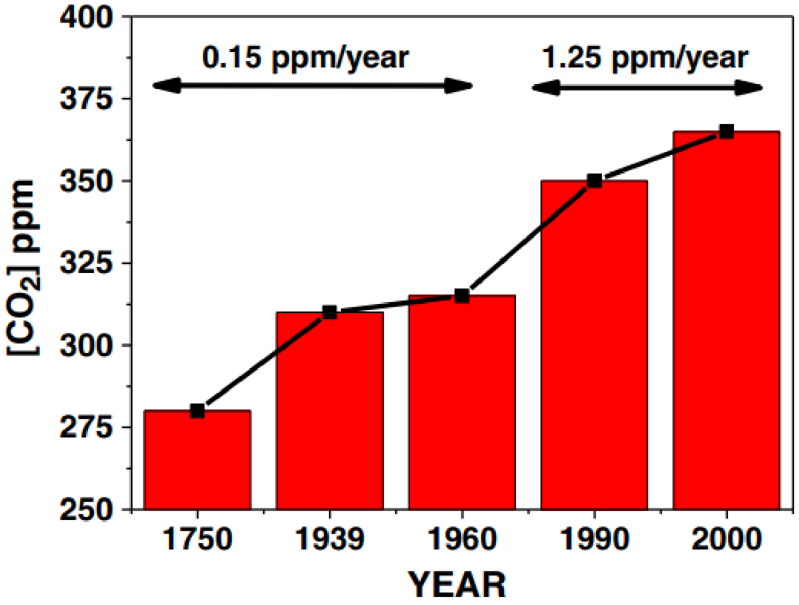


Figure 2.2: Global carbon dioxide emission.

Currently, the world's cement sector produces around two billion tonnes of cement each year while also producing almost two billion tonnes of CO2 which already contribute roughly 6 to 7% of all global CO2 emissions. (Shi, Jiménez and Palomo, 2011) The production of concrete and cement is revealed to be a significant source of carbon emissions. It is the most significant volumetrically manufactured product in the world, with an annual use close to 20,000 MMT. The manufacture of cement is principally responsible for the carbon emissions associated to the use of concrete. The global concrete industry used around 2,300 MMT of cement in 2005. The manufacturing of modern cements, which contain 84% Portland clinker, results in the emission of 0.9 metric tonnes of CO2 for every metric tonne of clinker. As a result, the direct yearly CO2 emissions from kilns used to produce clinker are estimated to be 1,740 MMT. The use of cement increased between 1990 and 2005, which caused the carbon footprint of the cement sector to almost double.(Kumar Mehta, Meryman and Ap, no date) Therefore, climate change is becoming more severe due to the huge amount of carbon dioxide produced in the cement industry.

Cement manufacturing contributes greatly to climate change through massive carbon emissions. Cement is produced by heating raw materials in energy-intensive kilns, which results in large CO2 emissions. Urbanization and infrastructure construction expansion are increasing cement consumption, which increases emissions, especially from clinker-producing kilns. From Figure 2.3, many procedures are required in the cement production process, including the calcination process, which involves heating the calcium carbonate or limestone to 1400 ° C. When calcium carbonate is heated, quicklime and carbon dioxide gas are produced as shown in equation 2.1. (Hason et al., 2020)

$$CaCO_3 + heat \rightarrow CaO + CO_2 \tag{2.1}$$

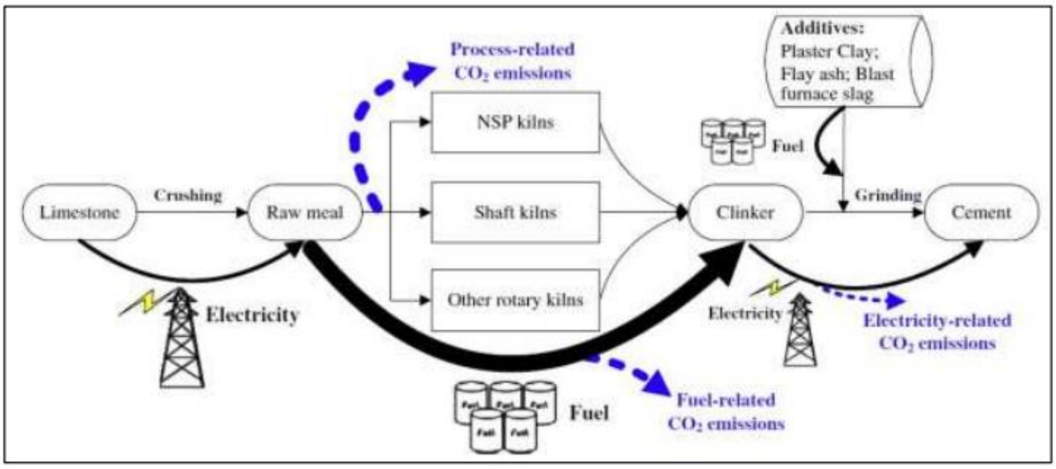


Figure 2.3: Flowchart illustrating the manufacture of cement and associated greenhouse gas emissions.

The impact is amplified by concrete, which is made of cement and releases CO2 during curing. The movement of commodities across the supply chain, which releases emissions at different stages, significantly increases the industry's carbon footprint. The increase in carbon dioxide emissions will alter the climate by to rising the average earth temperature of 1.1° C compared to the late 1800s. The impacts of climate change are becoming more noticeable in a variety of ways. The most recent ten years, from 2011 to 2020, have been classified as the warmest on record, showing a pattern of steadily rising temperatures that have exceeded those of any decade since the 1980s. Due to the excessive moisture evaporation caused by these rising temperatures, rainfall is intensifying, and destructive storms are occurring more frequently. Droughts brought on by climate change worsen water scarcity in areas already at risk, lowering crop output and harming animals. Due to the melting of ice sheets, the warming of the oceans has noticeably accelerated in the last 20 years, affecting all ocean depths to be risen. (United Nations, 2020)

2.2 Glass waste

Glass waste, a resource that usually gets overlooked as insignificant, has an inherent worth that is often underestimated. Despite being usually considered useless; glass waste is now recognized as an important material. Transparency, high inbuilt strength, low permeability, and chemical resistance are just a few of its outstanding properties. The ability of glass waste to survive the ravages of time while proving its impermeability and durability against chemical responses makes it a valuable resource. Glass waste can be categories to a variety of glass, including borosilicate glass, aluminosilicate glass, barium glass, and lead glass.

Malaysia generated around 3.3% of its Municipal Solid Waste (MSW) in the form of glass in 2018. This equates to a daily production of about 1140 tons. Therefore, the issue of excessive MSW created by glass is a major concern that must be addressed immediately. (Mallum et al., 2021) The general perception of waste materials has altered dramatically, with landfilled goods now being considered as valuable commodities. Glass waste is one prominent illustration of this change. Glass waste, which was formerly discarded and dumped in landfills, is now recognized for its immense utility and worth. (Federico and Chidiac, 2009) Diverse and fractured glasses with different colors and sources lead to unpredictable features and discolouration in new glass goods, preventing effective recycling and causing landfill disposal. As a result, the overall recycling rate for waste glass remains low, as seen in the Figure 2.4.

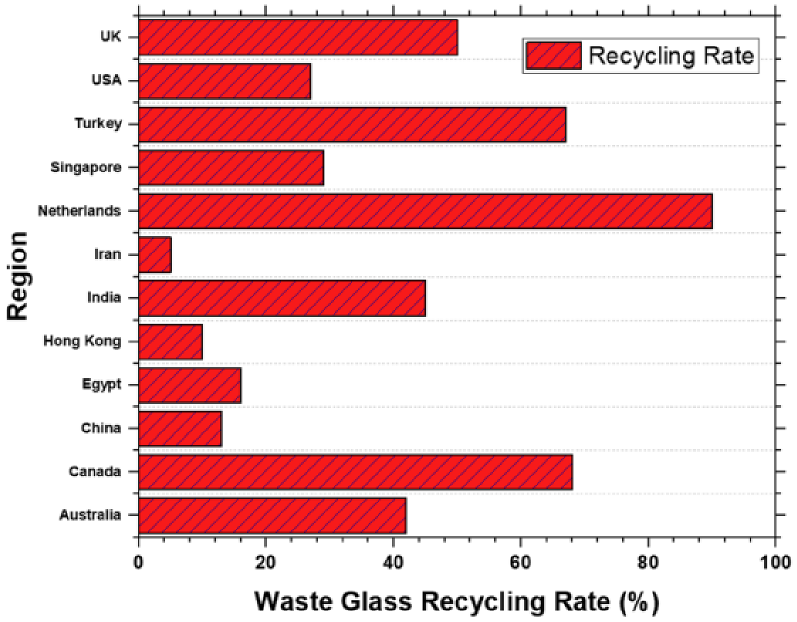


Figure 2.4: Rate of Recycling in Different Location

2.2.1 Properties of glass waste

Under normal conditions of nature, glass is an inert substance that may be recycled in a variety of ways without changing its chemical properties. (Torres-Carrasco and Puertas, 2015) Glass is categorized as an amorphous material and commonly consists of SiO_2, CaO, Na_2O, Al_2O_3, and Fe_2O_3 for its chemical composition. Glass has a wide range of physical and chemical characteristics that set it apart from other materials. Except from its widely known transparent property, which permits light to travel through it, another property is its high resistance to chemical deterioration, particularly in the presence of acids and alkalis. For some specific cases, glass may result in vulnerabilities to strong acids and bases. Furthermore, glass is also high resistance to corrosion and waste, which increases its endurance in a variety of applications. (Torres-Carrasco and Puertas, 2015) Table 2.1 shows the chemical composition of a general glass waste.

Table 2.1: Chemical Composition of Glass Waste

Waste Glass	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	Na_2O	K_2O	Loss of Ignition
Weight Percentage (%)	11.75	70.71	2.05	1.17	0.52	11.71	1.08	0.83

2.2.2 Drawbacks of glass waste

Waste recycling has become a popular and common method of cutting down on waste, and glass waste is no exception. But sorting, melting, and cleaning are the list of the complex procedures involved in recycling glass debris. Considering different types and colors of glass have different chemical properties, proper sorting is essential to guarantee higher quality. However, recycling glass requires a lot of effort and energy consuming. (Guo et al., 2020) The qualities of the newly generated glass can be altered by impurities and pollutants that may exist in the waste glass with the composite color. (Ruth and Dell'Anno, 1997) Glass that is fractured and mixed-colored glass makes recycling complicated since it is impracticable. (Federico and Chidiac, 2009) Therefore, glass is still seldom recycled at the present day, which frequently leads to its disposal in landfills. In 2018, an astonishing 130 million tons of glass were produced worldwide. Surprisingly, only 21% of this considerable quantity was recycled. (Guo et al., 2020) Globally, low recycling rates for the glass waste are expected to lead to an insufficient of landfill capacity. (Zhang et al., 2013)

Due to glass waste contains a high silica content, it is a valuable resource. Glass waste is partially dissolved throughout the process using chemicals like NaOH in a highly acidic solution. Because of its silicon-rich composition, glass has been indicated to be an appropriate replacement for typical sodium silicate activators in the manufacture of geopolymers. (Torres-Carrasco and Puertas, 2017)

2.2.3 Some research-related works that use glass waste in eco-friendly material.

Table 2.2: Past Research Works on Glass Waste for building materials

Title	Glass Type	Product	Percentage of Substitution (%)	Optimum Substitution	Compressive Strength (MPa)	References
Effect of composition on characteristics of thin film transistor liquid crystal display (TFT-LCD) waste glass-metakaolin-based geopolymers	Liquid-crystal display glass powder	Metakaolin-based geopolymer	0 – 40%	10% waste glass and 90% metakaolin	62	(Lin et al., 2012)
The Reuse of Waste Glass as Aggregate Replacement for Producing Concrete Bricks as an Alternative for Waste Glass Management on Sichang Island	Waste glass	Concrete Bricks with waste glass substitution	0, 10, 20, 30, and 100	<20% waste glass	48.49	(Warnphen, Supakata and Kanokkantapong, 2019)

Strength, microstructure, efflorescence behaviour and environmental impacts of waste glass geopolymers cured at ambient temperature.	Crushing soda lime glass bottles	Fly ash -based geopolymer paste	0, 25, 50, 75, and 100	25% waste glass and 75% fly ash	34.5	(Xiao et al., 2020)

2.3 Glove former waste

In recent times, the glove manufacturing sector has experienced remarkable expansion, largely propelled by the global impact of the COVID-19 pandemic. The persistent scarcity of disposable medical gloves has underscored an immediate and pressing requirement to augment manufacturing output. (Tan, 2022) The exportation of the glove from Malaysia glove manufacturing sector is up to 182 billion gloves in 2019. However, due to the out-break of the COVID-19 epidemic, the Malaysian Rubber Glove Manufacturers Association (MARGMA) predicts that the glove demand outbreak will jump to a huge number of 240 billion pieces. (Ab Rahman et al., 2020) This situation has necessitated rapid and adept adoption of cutting-edge methodologies, aligning with the principles of Industry 4.0. By embracing these advanced practices, glove manufacturers aim to streamline and enhance diverse facets of the industry, ensuring its resilience and efficiency in the face of unprecedented demand. (Tan, 2022) As a result, there has been an exponential increase in glove production to meet the extraordinarily high demand during the pandemic scenario.

The glove manufacturing sector operates in a setting that is impacted by a variety of factors. These reasons include raw material price fluctuations, labour issues, local and international legislation, and an increasing awareness of environmental concerns. (Tan, 2022)

2.3.1 Properties of glove former waste

Glove former waste is a subset of ceramic waste that can be recognized by its chemical composition, which is abundant in alumina and silica content. Because of its composition, it is a great resource to produce ceramic supports. (Ibrahim, Amira Nadzirah Suhaidi and Shah, 2018)

Several processes are involved in the glove production process, beginning with preliminary cleaning to provide a clean mould for the gloves. To construct the rubberized glove structure, coagulant and latex dipping are used. Chemicals are applied during the beading process to improve durability and vulcanization. After that, the gloves are leached to eliminate any remaining residues. Drying and vulcanization are critical processes in which ovens are used to cross-link polymer chains, resulting in elasticity and strength. To prevent stickiness, some gloves are dusted with corn starch, however many medical gloves avoid this owing to allergy concerns. Finally, the gloves are removed from the formers, examined, and packaged.

Multiple washing, drying, and stripping cycles lead to glove former waste, which includes items such as utilized formers, leftover chemicals, and latex fragments. These residue and chemical will contaminate the glove mould itself and cause the increasing of the glove former waste produced due to the high demand in the production line of the glove. Due to these glove moulds involved complex and costly process for recycling, the glove mould is usually end up into landfills.

2.3.2 Drawbacks of glove former waste

Glove production, particularly in high-demand industries, is encountering an increasing issue due to glove former waste. Glove formers, which are required in the glove manufacture process, are unavoidably contaminated with colour and contaminants such as latex decomposition. Cleaning these hand moulds has traditionally been a necessary procedure, but it has a substantial disadvantage. The traditional technique of washing uses a large amount of water, which not only poses environmental problems but also proves to be cost-inefficient, especially when demand for glove production is high. As a result, the beneficial effect of cleaning hand moulds for high-demand glove production has become more doubtful. This issue prompts to look into alternative solutions to address the issue of glove former waste more effectively. (Yik Teeng Leong and Mei, 2020)

There are several difficulties and disadvantages associated with disposing of glove former waste. A considerable amount of this waste often ends up in landfills due to the impracticality and lack of cost efficiency in the process of recycling. While sanitary landfills appear to be a more ecologically beneficial option than non-sanitary alternatives, they are not exempt to possible failures. This raise worries regarding leachate pollution and the release of hazardous biogases to the environment. These leachates, which are impacted by Malaysia's high rainfall, include heavy metals and hazardous chemicals that might threaten human health. (Vaverková, 2019) Furthermore, as these leachates enter water bodies and soil, they cause a chain reaction of environmental contamination, thereby posing health concerns to communities and ecosystem.

2.4 Geopolymer

Due to the large amounts of glass waste and glove former waste produced, which pose severe landfill-related difficulties, there is a pressing demand for sustainable and environmentally friendly solutions. Geopolymer, which is developing as one such alternative, stands out as an environmentally friendly binder that uses these waste elements to generate construction materials, outperforming traditional binders such as Ordinary Portland Cement (OPC). Notably, geopolymer not only respond to environmental issues but also outperforms in terms of durability and strength. This geopolymer which is known as the greener cement not only addresses waste management issues, but also improves the quality and sustainability of construction materials, making it an appealing alternative for the future of environmentally responsible construction.

Geopolymerization is a series of polycondensation reactions that convert aluminosilicate, which is high in silicon (Si) and aluminium (Al) content, into a solid and long-lasting binder known as a geopolymer. This is achieved by the application of alkaline activators, which generally consist of a solution of sodium hydroxide (NaOH), or potassium hydroxide (KOH) mixed with an alkaline silicate solution, such as sodium silicate (Na_2SiO_3) forming an amorphous phase and three-dimensional aluminosilicate network structure. (Cong and Cheng, 2021)

2.4.1 Properties of Geopolymer

Geopolymer materials have several of physical and chemical properties that make it to become an innovative and greener building option. One of the notable characteristics is their mechanical strength and durability. The compressive strength of geopolymer can be influenced by curing time, raw materials, type of alkaline activators used, curing conditions, and particle size. (Cong and Cheng, 2021) Alkali solutions are typically made up either sodium or potassium molecules. Whether generated from geological sources or waste products, the source materials for geopolymer should have a high silicon and aluminium content. Because of its high silica and alumina concentration, fly ash is an excellent source material for geopolymer synthesis. Mortars and concretes made with fly ash geopolymer binders have comparable strength and physical appearance to those made with traditional Portland cement. Geopolymer binders have showed outstanding mechanical characteristics, fire resistance, and acidity tolerance. (Tho-In et al., 2018)

The formation of geopolymer involves several unique steps. At the beginning, dissolution of the aluminosilicate solid material will take place due to the alkaline activator. Alkaline activator provides the highly alkaline conditions This breakdown sets up the conditions for the formation of oligomers, which are the precursors of geopolymers, in the following stage. Oligomers is formed by sharing the oxygen atom through bonds which is Si – O – Si and Si – O – Al bonds. Then, the formation of a three-dimensional aluminosilicate framework results from the reorganization of polysilicates and partial precursors as the process moves forward. The undissolved solid particles then combine with one another, solidifying and creating the geopolymer structure as a result. (Lin et al., 2012) Below Figure 2.5 shows the chemical reaction for the geopolymer precursor which and geopolymer backbone. The initial aluminosilicate-rich materials that provide silicon and aluminium ions for the reaction is known as the geopolymer precursor. The three-dimensional network structure created by polycondensation processes connecting silicon and aluminium ions is the final product of the reaction which is the geopolymer backbone.

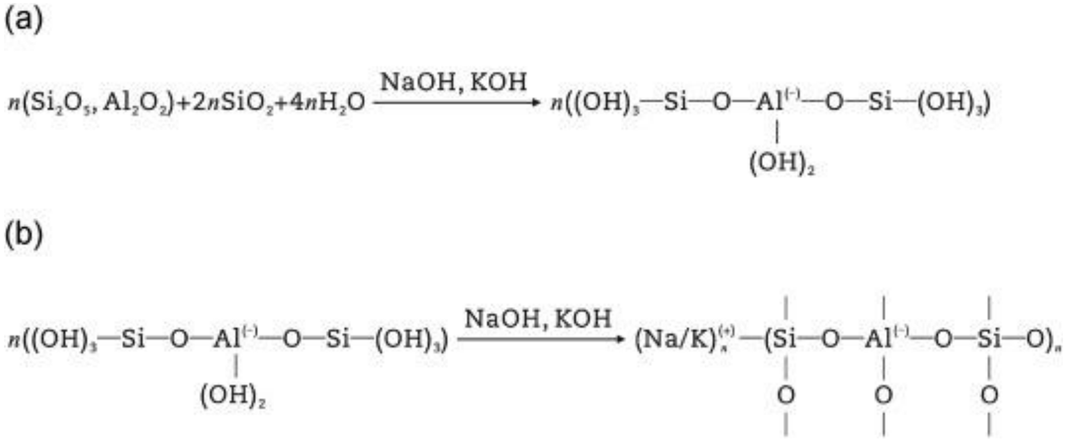


Figure 2.5: (a) Geopolymer precursor. (b) Backbone of Geopolymer.

2.4.2 Advantages of geopolymer

Geopolymer materials have emerged as a significant innovation in the construction sector, offering a plenty of benefits that have the potential to revolutionize traditional building practices. The concrete industry which involved cement production, now relies extensively on fossil fuels to generate the high temperatures necessary in its furnaces, resulting in around 7-8% of carbon emissions. Furthermore, significant CO2 emissions result from the calcination process and the use of carbon-intensive by-products, such as coal, in clinker production. (Amran et al., 2022) The cement industry consumes around 2% of the world's primary energy, accounting for almost 5% of overall industrial energy consumption. This energy consumption is mostly caused by the burning of fossil fuels during the cement manufacturing process. (Worrell et al., 2001)

The benefits of geopolymer over OPC are significant, indicating a more sustainable and ecologically conscientious option. To begin, geopolymer is a greener and more ecologically friendly option to OPC, especially in terms of sustainability and durability. A unique gel nuclei particle is used in the design of geopolymer, ensuring stability and resistance to depolymerization. This stability aids in the formation of a new gel phase, hence increasing the strength and endurance of geopolymer. In comparison, geopolymer has major environmental benefits. When compared to OPC, it has the potential to cut industrial waste by 12.2 MMT per year. Furthermore, the environmental effect is significantly decreased, with geopolymer releasing 5 to 6 times less carbon dioxide (CO_2) during manufacture. In contrast, the decarbonation of limestone in kilns emits a similar amount of CO_2 into the environment during the manufacture of one ton of OPC. (Amran et al., 2020) Additionally, geopolymer is better than OPC in chemical resistance and strength. (Figure 2.6) These characteristics not only make it a more durable option, but they also add to its overall structural integrity and lifespan.

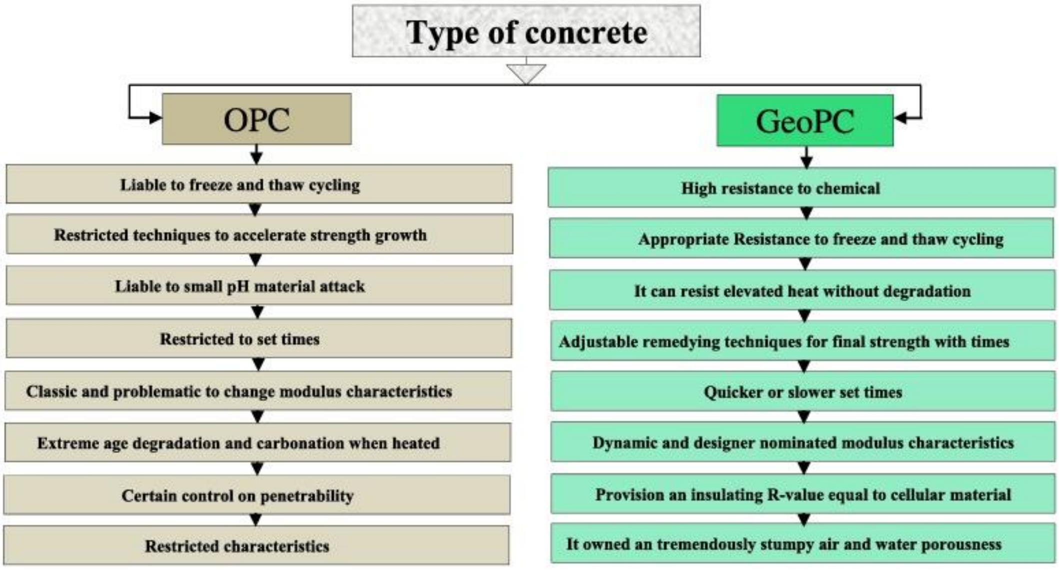


Figure 2.6: Comparisation between the OPC and Geopolymer synthesis concrete

2.5 Relevant Past Research

Currently, the circular economy principle and the sustainable development goals (SDGs) concept is aligned with industries for a good practice. As the conventional OPC brings many adverse impacts to the environment, a greener and environmentally friendly substitute which is the geopolymer is invented to replace cement. Most of the research conduct the fabrication of the geopolymer using different type primary and main source of the aluminosilicate which include fly ash, metakaolin, natural perlite, ground granular blast slag and others. The waste substitution used include the glass waste, calcined kaolinic clay, illite clay, biochar, corncob ash and others. However, there is no research use the glass waste and glove former waste from the glass and glove industry as the main source substitution of fly ash. Below Table

2.3 shows the relevant past research that utilizing different type of main source of the aluminosilicate and its substitution as a geopolymer binder to enhance the strength with different percentage of the substitution.

Table 2.3: Past Relevant Research on Different Types of Binder for Geopolymer Fabrication

Binder Type	Percentage of Substitution (%)	Optimum Substitution (%)	Particle size used for the binder	Compressive Strength (MPa)	References
FA + WGP	WGP: 10 – 40	20	80 µm	34 – 48	(Tho-In et al., 2018)
MK + WGP	WGP: 0 – 30	30	45.3 µm	17 – 55	(Burciaga-Díaz et al., 2020)
FA+ WGP	WGP: 20 – 40	20	44 µm	55.59	(Topark-Ngarm et al., 2019)
FA+GGBS+ WGP	WGP: 0 – 30	30	11.5 µm	-	(Samarakoon, Ranjith and De Silva, 2020)
FA+GGBS+ WGP	WGP: 0 – 40	10–20	Smaller than 75 µm	Improve 5% - 11%	(Khan, Kuri and Sarker, 2021)

Natural Perlite (NP) + Calcined Kaolinic Clay (CKC)	CKC: 0 – 50	10	< 63 µm	36.36	(Aziz et al., 2021)
MK + Illite Clay (IC)	IC: 25, 50, 75, and 100	50	< 150 µm	28	(D. Eliche-Quesada et al., 2021)
MK + Biochar (BC)	BC: 20, 30, 40, 50 and 70	70	< 80 µm	-	(Piccolo et al., 2021)
Ground Granulated Blast Slag (GGBS) + Corncob Ash (CCA)	CCA: 0–100	CS: 20–40 EE: 40	< 45 µm	> 40	(Oyebisi et al., 2022)

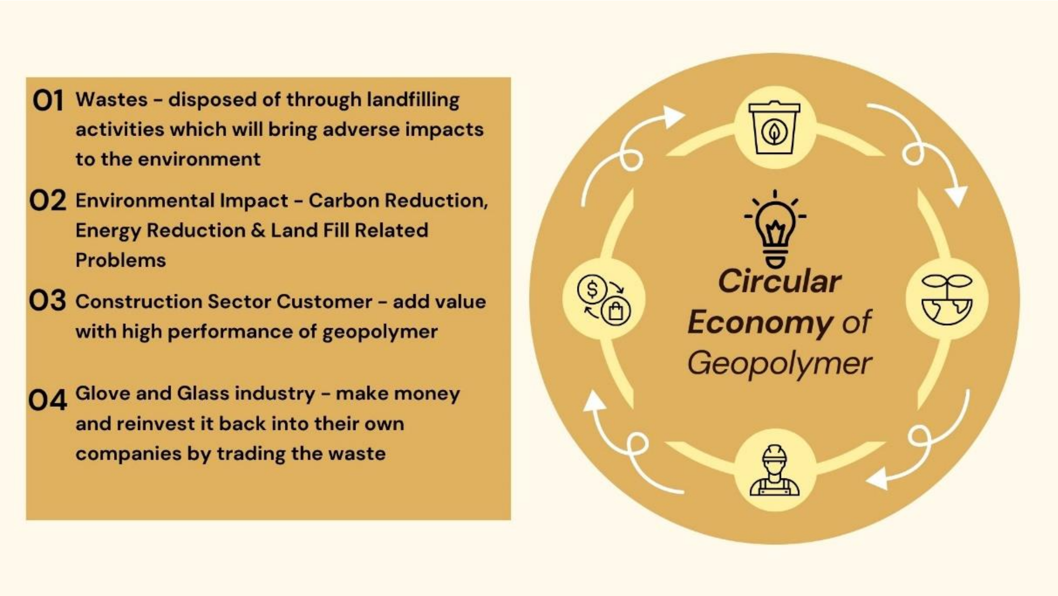
2.6 Circular Economy and SGDs

The circular economy concept is gaining acceptance, particularly in industries where waste generation poses significant environmental issues. Fabrication of geopolymer is one of the ways where the principles of a circular economy are being applied innovatively. The approach specifically targets glove former waste and glass waste produced by the glove and glass industry. Due to their complex and costly processing needs, recycling these materials was once considered impractical, leading to the practice of landfill disposal. However, as life cycle design becomes a primary mover toward greener and more ecologically friendly construction methods, there is a rising awareness of the need for cheaper and environmentally friendly building materials. (Nodehi and Taghvaee, 2021)

The limited supply of raw materials, such as limestone and fossil fuels, typically used for the manufacturing of cement, highlights the importance of finding alternative solutions. This is where the utilization of glove formers and glass waste materials comes in. These waste materials can be recycled in the geopolymer sector, providing a more environmentally friendly alternative for conventional Portland cement (OPC). By implementing circular economy practices, we not only reduce the burden on landfills, but we also reduce the extraction of scarce resources, thereby connecting our construction industry with the ideals of sustainability and a greener future. (Nodehi and Taghvaee, 2021)

The utilization of geopolymers made from waste materials, which not only reduces environmental effect but also addresses many of the crucial issues. Unlike Ordinary Portland Cement (OPC), whose manufacturing process produces high levels of carbon emissions due to calcination and clinker formation, geopolymers provide a more environmentally friendly alternative. Because it runs at lower temperatures, geopolymer synthesis consumes significantly less energy. Furthermore, waste materials that were previously destined for landfills find a new purpose in geopolymer synthesis, addressing landfill-related issues as well as associated environmental and health risks. Geopolymers are used in the construction sector, acting as binding materials for bricks and as a paste in geopolymer concrete, giving improved durability and mechanical strength while being cost-effective.

In addition, the circular economy concept broadens its application to industries such as glass and gloves, which can trade their waste to the constructing sector, making extra cash and reinvesting in their own operations. This dynamic utilization of waste materials and their economic reinvestment represents a fully operational circular economy, eliminating waste, lowering environmental impact, and supporting sustainable behaviours across multiple industries. (Figure 2.7)



01 Wastes - disposed of through landfilling activities which will bring adverse impacts to the environment

02 Environmental Impact - Carbon Reduction, Energy Reduction & Land Fill Related Problems

03 Construction Sector Customer - add value with high performance of geopolymer

04 Glove and Glass industry - make money and reinvest it back into their own companies by trading the waste

Figure 2.7: Circular Economy of Geopolymer Paste

Geopolymer having an excellent performance in terms of the durability and compressive strength. When compared to OPC, carbon produced during the manufacture of geopolymer concrete is 9% lower. (Singh and Middendorf, 2020). Manufacturing process of geopolymer requires lower energy compared to cement. The glove and glass waste which is originally dump into landfill can be reduce through the geopolymer fabrication process. Therefore, geopolymer is also a green invention that achieve several sustainable development goals (SDGs) which is shown in Table 2.4 and Figure 2.8.

Table 2.4: Sustainable Development Goals

Sustainable Development Goals (SDGs)	Application
Goal 1: No Poverty	By embracing the principles of a circular economy, the utilization of geopolymers derived from glove and glass waste, which would otherwise be destined for landfills, can foster job creation, and generate potential income across multiple industries.
Goal 3: Good Health and Well- Being	The utilization of geopolymers derived from glove and glass waste minimizes health risks, fosters a cleaner environment, reduces exposure to hazardous substances, and contributes to the overall improvement of health and well-being for individuals and communities.
Goal 4: Quality Education	The adoption of alternative environmentally friendly building materials, such as geopolymer, contributes to enhancing inclusive and equitable quality education by creating a more sustainable educational environment.
Goal 7: Affordable and Clean Energy	The utilization of waste materials in geopolymer production reduces the reliance on energy-intensive cement manufacturing, fostering the use of cleaner energy sources and enabling access to affordable and sustainable energy for all.
Goal 9: Industry, Innovation, and Infrastructure	It serves as a competitive alternative to OPC, providing superior mechanical performance, workability, durability, and fire resistance.
Goal 11: Sustainable Cities and Communities	Carbon footprint is reduced, as geopolymer fabrication emits less carbon dioxide and enhances building durability, contributing to the creation of sustainable and resilient cities.

Goal 12: Responsible Consumption and Production	The valorisation and reuse of glove and glass waste in geopolymer manufacture reduces waste formation and reduces the reliance on virgin resources, hence encouraging circular economy principles.
Goal 13: Climate Action	Geopolymers significantly decrease energy consumption and carbon footprint compared to OPC, resulting in lower greenhouse gas emissions, and actively contributing to climate change mitigation and the achievement of climate action goals.
Goal 17: Partnerships for the Goals	The collaborative efforts between industry, government, and communities play a critical role in the widespread adoption and scaling up of geopolymer technologies, thereby driving sustainable development in the construction industry.

Figure 2.8: Sustainable Development Goals (SDGs) that related to the study.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter provides a comprehensive overview of the methodology used in this research investigation. It covers the materials and equipment used, the step-by-step process to generate geopolymer from glass waste and glove forming waste, and the laboratory tests used to determine the geopolymer's properties and durability. The investigation involves varying proportions of glass waste and glove former waste as preliminary reactants for the geopolymerization process. The optimization of the substitution ratio using these waste materials is determined through multiples laboratory tests. The subsequent Figure 3.1 presents a comprehensive flow diagram of the research methodology.

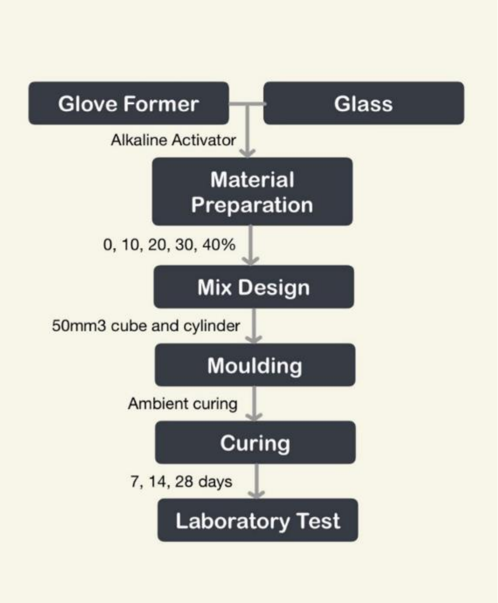


Figure 3.1: The Research Methodology

3.2 Material Preparation

3.2.1 Pulverized Fuel Ash (PFA)

The pulverized fuel ash used is categories as the Class F fly ash which fulfilled the BS EN 450 standard, with a calcium oxide level of less than 10%. The sources of PFA, which provided by Micro Dimension Concrete Sdn. Bhd. It was whitish grey in colour and had a specific surface area of 341 square meters per kilogram. It measured 2.288 grams per cubic centimeter for specific gravity. It is largely constituted of 21.00% aluminum oxide and 59.00% silicon dioxide, which is significant information regarding its composition for the study under consideration. (Khairul Nizar Ismail, Kamarudin Hussin and Mohd Sobri Idris, 2007)

Figure 3.2: Pulverized Fuel Ash

3.2.2 Glass Waste

In this research, glass waste serves as a fundamental component, contributing to the aluminosilicate composition essential for its aluminium and silicon content. The glass waste used in the study is collected from mainly green colour glass bottles, predominantly from soft drink bottles, wine bottles, and liquor bottles. To prepare the glass waste for utilization, a multi-step process is undertaken. Initially the glass bottle was collected mainly from beer bottle which the internal and external of the bottle to free from stain and containments. (Figure 3.3) As shown as Figure 3.4, the collected glass is subjected to crushing by using a hammer, aided by the presence of a cloth to contain fragments. Next, the fragmented glass as shown in Figure 3.5 undergoes further refinement through grinding using a grinder to form fine glass powder. To ensure a consistent particle size, the glass powder is subsequently subjected to sieving through a No. 128 sieve using a sieve shaker. This meticulous preparation procedure ensures that the glass waste is appropriately processed and refined before the geopolymer fabrication.

Figure 3.3: Green Bottle Glass

Figure 3.4: Hammering process for glass waste bottle.

Figure 3.5: Fragments of the glass waste bottle

3.2.3 Glove Former Waste

In this research, glove former waste is also a significant ingredient that contributes to the aluminosilicate composition, essential for its aluminium and silicon content. The glove former waste plays a crucial role in our experiment, much like the glass waste. The glove former waste as shown in Figure 3.6 we're using is obtained from a reliable source, Kitaran Recovery Sdn. Bhd. From this company, the glove former waste received is already processed and ground into a fine powder form. This finely ground glove former waste is then subjected to a refining process for regrinding process as shown in Figure 3.7 before it becomes a part of the geopolymer mix. To ensure uniformity in particle size, the glove former waste powder is sieved by using a No. 128 sieve with a sieve shaker. This step ensure that the particles are of consistent size, making them suitable for integration into the geopolymer formulation.

Figure 3.6: Glove Former waste from Kitaran Recovery Sdn. Bhd.

Figure 3.7: Refining Process by the Grinder

3.2.4 Sodium Hydroxide

Sodium Hydroxide act as one of the alkaline activators in the fabrication of the geopolymer. It plays an important role in the chemical reaction that results in the formation of the geopolymer structure. For safety purposes, personal protective equipment (PPE) such as glove, goggles and lab coat due to sodium hydroxide is high corrosive and caustic. In this research, sodium hydroxide pellet used is Merck brand (Figure 3.8). Sodium hydroxide in pellet form dissolved in water to form a sodium hydroxide solution. Sodium hydroxide is stirred using a stirring rod with a beaker with the help of the electromagnetic stirring. Below Table 3.1 shows the chemical composition of the sodium hydroxide.

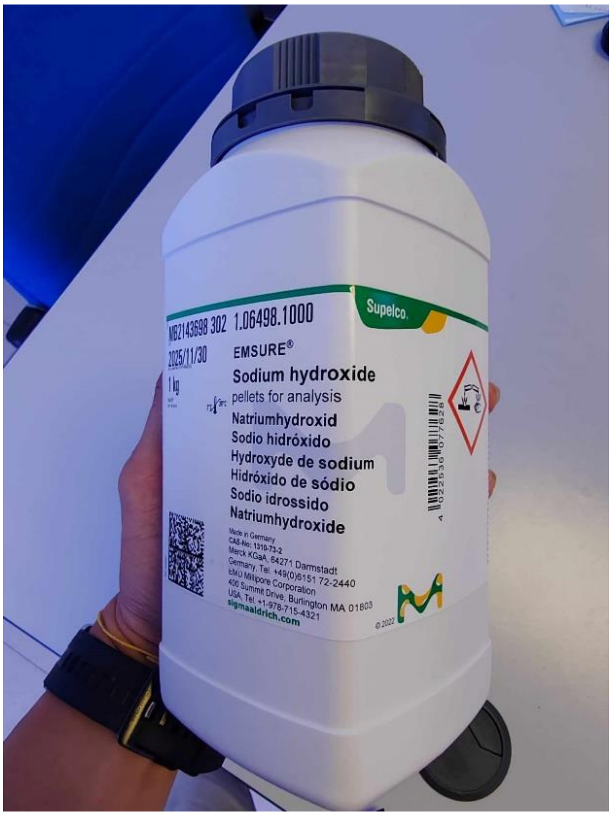


Figure 3.8: Sodium Hydroxide from Merck Brand

Table 3.1: Chemical Composition of Sodium Hydroxide

Specification	**Contains**
NaOH (g/kg)	⩾ 990
Na_2CO33 (g/kg)	⩽4
SO4	⩽0.01
Fe	⩽0.002
Cl	⩽0.01
Al	⩽0.002

3.2.5 Sodium Silicate Solution

Sodium silicate solution is commonly known as the glass water which is a key component in the fabrication of the geopolymer. Sodium silicate solution act as one of the alkaline activators and providing silicate ions which is needed in geopolymerization. To ensure better performance in the geopolymerization process, sodium silicate solution must be prepared with precise measurements. Due to sodium silicate solution is an alkaline solution, proper protective equipment (PPE) such as glove is required when handling it. In this research study, the brand of the sodium silicate used is R&M Chemical Brand. (Figure 3.9) Below Table 3.2 is the chemical composition of sodium silicate solution used.

Figure 3.9: Sodium Silicate used from R&M Chemical

Table 3.2: Chemical Composition of Sodium Silicate Solution

Specification	**Contains**
Assay (acidimetric, Na2O)	7.5 – 8.5 %
Assay (acidimetric, SiO2)	25.5 – 28.5 %
Density (20°C)	1.296 – 1.396 g/ml
Fe (Iron)	<= 0.005%
Heavy Metals (as Pb)	<= 0.005%

3.1 Mix Design

Based on the past relevant result, which is related with my research study, several trial mixes were design to carry out with different mixture portion ratio for the fabrication of the geopolymer. The geopolymer mortar mix design was produced for two types of binder material which is glove former waste and glass waste, and it was then compared with standard cement mortar controls. The amount of aluminosilicate and alkaline activators used is shown in below Table 3.3. From Table 3.3, different fly ash is replaced with different percentage of the glass waste or glove former waste and the binder-to-alkaline ratio is set to 0.38 and the sodium hydroxide to sodium silicate ratio is set to be 1:1 with the sodium hydroxide is fixed at 12 moles. The sodium silicate solution and sodium hydroxide solution are mixed by using a stirrer to form alkaline activator mixture. Glass waste or the glove former waste powder is then mixed with the fly ash powder for constant premixing. Then, gradually add the remaining alkaline activator mixture with constant mixing (Figure 3.10).

Figure 3.10: Mixture of binders and alkaline activators

Table 3.3: Mix design of the geopolymer.

Mix Design Code	Mass (g)				
	Binder			Alkaline Activator	
	Pulverized Fly Ash	Glass Waste	Glove Former Waste	Sodium Hydroxide	Sodium Silicate
100F	842	0	0	160	160
10GFW	758	0	84	160	160
20GFW	674	0	168	160	160
30GFW	589	0	253	160	160
40GFW	505	0	337	160	160
10GW	758	84	0	160	160
20GW	674	168	0	160	160
30GW	589	253	0	160	160
40GW	505	337	0	160	160

3.2 Moulding & Demoulding

The mould size using is cube mould (50mm × 50mm × 50mm) and cylinder (50mm height × 50mm diameter). Firstly, for the moulding process, the geopolymer mould is ensured to be clean and free from debris and impurities. The geopolymer is poured carefully into the mould and filled completely to prevent overflow. Figure 3.11 shows the geopolymer is then compacted to achieve a better uniform density and to prevent air voids. A flat surface board is used to smooth the surface of the geopolymer. For the demoulding process, the sample is ensured to be fully gained strength. The mould is inverted gently to let the sample slide out easily by using demould air gun.

Figure 3.11: Moulding Process for Geopolymer

3.3 Curing Process

In this laboratory test carried out, the curing process used is the ambient curing method which the geopolymer is wrapped with the plastic sheet and leave it in the ambient environment. The ambient curing process for geopolymer involves providing regulated conditions that foster the chemical reactions that result in the material gaining strength and desirable properties. The geopolymer was allowed to undergo the curing process under the ambient environment to stay overnight to gain strength. The samples are left in a 28 ° C of a controlled environment for 7, 14, and 28 days until the specimen testing age. The geopolymer will be labelled accordingly by name to differentiate them.

3.4 Laboratory Tests

In the laboratory test carried out, there are two different important properties is required to be determined by the geopolymer which is engineering properties and durability properties. One of the objectives of my laboratory test is to evaluate the engineering properties of the fabricated geopolymer by obtaining the optimum ratio for the geopolymer composition. Below Figure 3.12 is the laboratory test which will be conducted. From the Figure 3.12, Sieve Analysis, Scanning Electron Microscopy Test (SEM) and X-ray Diffraction (XRD) are performed to determine the material characteristic properties. Under the mechanical performance tests, compressive strength test will be carried on. While water absorption test and porosity test are being conducted to determine the physical property properties. Below Table 3.4 shows the overall requires geopolymer sample for the whole research works.

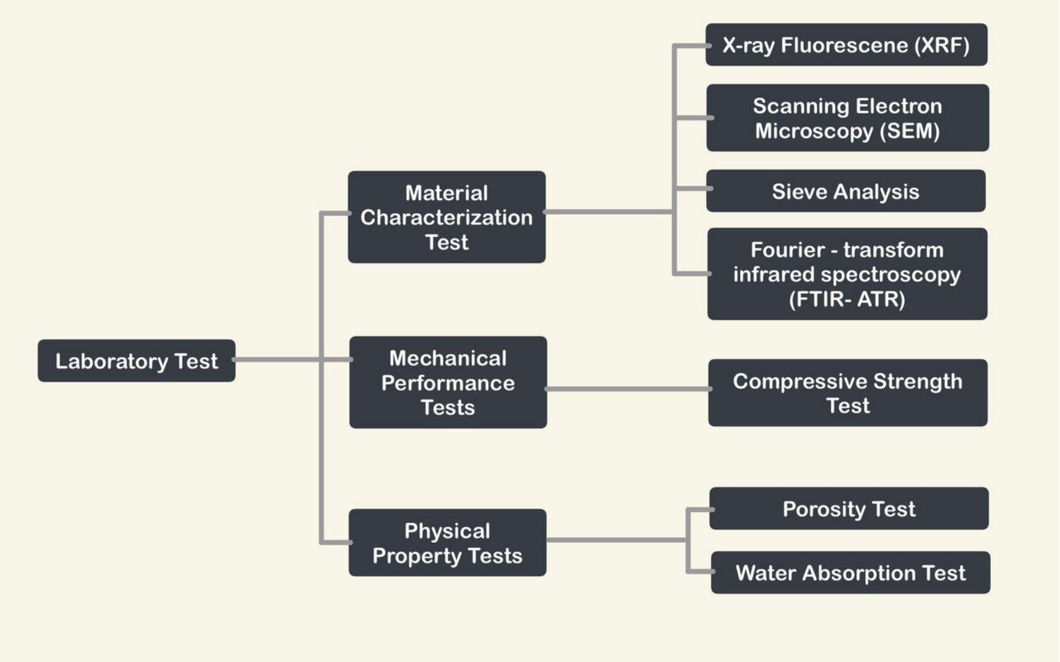


Figure 3.12: Laboratory Test

Table 3.4: Quantity of Geopolymer Sample Requires

Test	Specimen Age (Day)	Number of Specimen
Compressive Strength	7	3 (× 9 mix design)
	14	
	28	
Water Absorption	7	3 (× 9 mix design)
	14	
	28	
Porosity	7	3 (× 9 mix design)
	14	
	28	
SEM and FTIR	7	3 (× 9 mix design)
	14	
	28	
Total:		108

3.4.1 Material Characterization Test

3.4.1.1 Sieve Analysis

Sieve Analysis is conducted in this study to evaluate the particle size distribution of the binder powder, which is the PFA, GW and GFW after grinding. In this sieve analysis, the sieve size used is the 0.3, 0.25, 0.18, 0.125, 0.106, 0.09, 0.063, 0.045, 0.01ηm. The sieve is stack from the largest sieve to the smallest sieve from the top to the bottom. The sieve is then installed into the sieve shaker for 20 minutes as illustrated in Figure 3.13. After sieving, the weight of the retained powder is weight using the electronic balance.

Figure 3.13: Sieve Analysis

3.4.1.2 X-ray Fluorescence (XRF)

X-ray Fluorescence is the process that used to determine the chemical composition of the geopolymer. By knowing the composition of the geopolymer, it helps in quality control, research, and optimization of geopolymer formulations. The geopolymer is sent to external laboratory for the XRF testing. The energy spectra of the generated fluorescence X-rays are studied to identify the chemical composition of the geopolymer substance.

3.4.1.3 Scanning Electron Microscopy Test (SEM)

The geopolymer Scanning Electron Microscopy (SEM) test involves examining the material's surface morphology and microstructure. The geopolymer sample is prepared, placed on a specimen holder, and coated with a thin coating of conductive material. The coated sample is then put in the scanning electron microscope chamber, where an electron beam scans the surface. The signals created by the electron beam's interactions with the sample are gathered to form high-resolution pictures that show specific information about the material's surface characteristics, particle sizes, and distribution. SEM examination helps to comprehend the texture, porosity, and microstructure of the material, offering vital insights into its overall composition and prospective performance capabilities.

3.4.1.4 Fourier-transform infrared spectroscopy (FTIR) analysis

FTIR analysis is an analytical technique used for the characterization of geopolymers through capturing the high-resolution spectral data across a wide spectral range to display the infrared spectrum of absorption or emission of a substance. FTIR provides information on the molecular structure of geopolymers by identifying functional groups like Si-O, Al-O, -OH (hydroxyl group), and -NH (amine group) by measuring the absorption of infrared light at various wavelengths. In this research work, Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) spectroscopy is used as ATR- FTIR is a type of FTIR spectroscopy that is widely used to examine both liquid and solid samples (Figure 3.14). Each different mix design in the research is used to undergo ATR- FTIR analysis to compare with the control design which is the pure fly ash design.

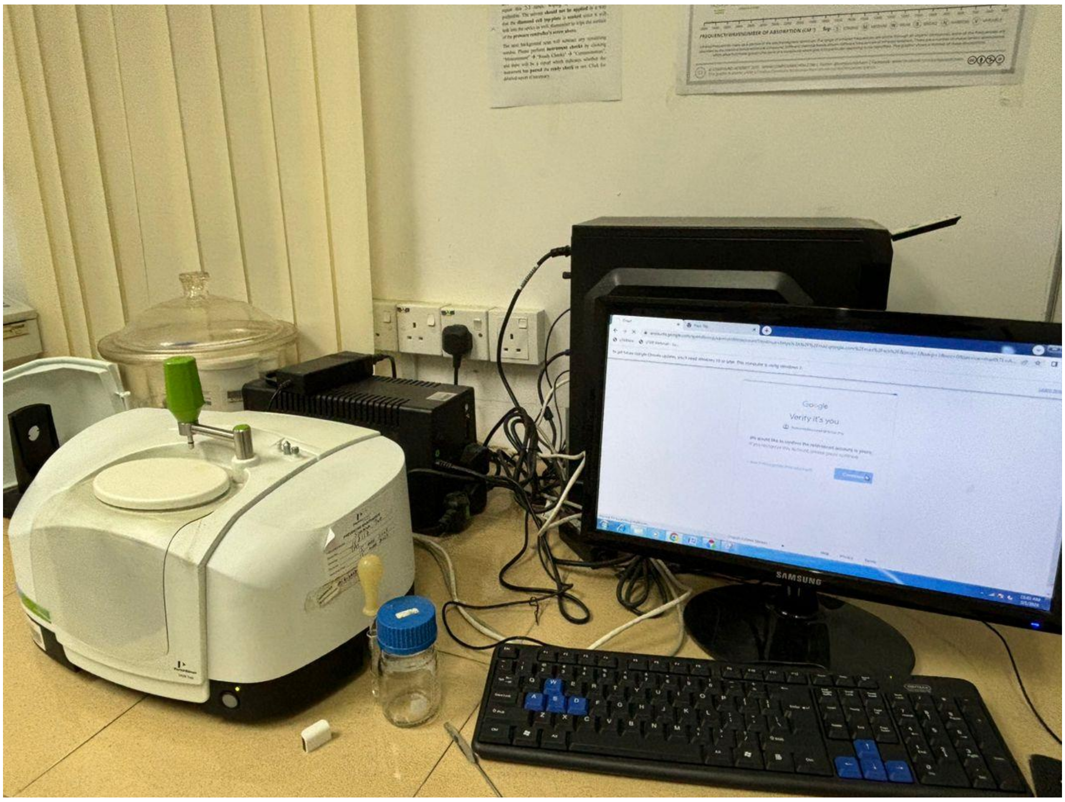


Figure 3.14: Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) spectroscopy.

3.4.2 Mechanical Performance Test

3.4.2.1 Compressive Strength

Geopolymer compressive strength testing involves determining the capacity of the geopolymer specimen to withstand axial loads. In this compressive strength test, it involved three geopolymer specimen with the age of 7 days, 14 days, 28 days, respectively. These specimens are exposed to a regulated compressive stress on a compressive strength machine (Figure 3.15). Few pieces of the metal plate are placed on the bottom of the geopolymer for a uniform and better compression (Figure 3.16). The compressive strength is calculated by dividing the greatest force at which the specimen fails by the cross-sectional area of the specimen. Therefore, the dimension of the geopolymer must be measured before the compression test. This test offers information on the material's load-bearing capability and structural integrity. Below equation 3.1 compressive strength formula is used to calculate the strength.

$$P = \frac{F}{A} \tag{3.1}$$

where

P = Compressive Strength, N/mm^2

F = Maximum load applied on specimen, N

A = Specimen surface area, mm^2

Figure 3.15: Compressive Test Machine

Figure 3.16: Compressive Test for Geopolymer

3.4.3 Physical Property Test

3.4.3.1 Porosity Test

To determine the number of empty voids within the geopolymer, a porosity test is carried out. These voids have a direct influence on the durability and strength of the geopolymer. A higher amount of porosity has a detrimental impact on the geopolymer's lifetime. A total of three samples aged at 7, 14, and 28 days are required to determine porosity. To remove extra moisture, these specimens are dried in an oven (Figure 3.17). Samples are put in a vacuum-saturated desiccator after 24 hours. Water is added to a level one centimetre above the specimen's height (Figure 3.18). The evacuation process takes 15 minutes. After that, the specimens soak in water for 3 hours before being evacuated for another 15 minutes. The specimens are then submerged in water for 24 hours. The specimens are wiped and weighed while immersed and submerged after being removed from the water. Equation 3.2 is used to calculate porosity.

$$n = \frac{w_w - w_d}{w_w - w_s} \times 1000 \qquad (3.2)$$

where

n = Porosity, %

W_d = Weight of dry specimen, g

W_w= Weight of the submerged specimen, g

W_s = Weight of immersed specimen, g

Figure 3.17: Drying Process for geopolymer

Figure 3.18: Vacuuming Process for Geopolymer

3.4.3.2 Water Absorption Test

The water absorption test determines the quantity of water of the geopolymer can absorb when submerged or subjected to water. It describes the porosity and water retention capacity of the material. The geopolymer specimens are fully cured and ready for testing. Each geopolymer specimen should be weighed using a digital scale and its starting mass (w_0) recorded. A container filled with distilled water that is deep enough to completely immerse the geopolymer specimen should be prepared. The geopolymer specimen should be carefully placed in the water and fully submerged (Figure 3.19). Allow the specimen to soak in water for 24 hours. To remove any excess water, gently wipe the surface with absorbent paper or cloth. After removing any extra surface water, the specimen should be weighed again, and its mass (w_1) recorded.

$$M = \frac{w_1 - w_0}{w_0} \times 100 \tag{3.3}$$

M = Percentage of water absorption, %

w_0 = Weight of dry specimen, g

w_1 = Weight of saturated specimen, g

Figure 3.19: Soaking Process in the desiccator

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The chapter will analyse and discuss several laboratories testing in the term of mechanical performance properties test, material characterisation properties test and physical property test. This test can be achieved through sieve analysis, FESEM, XRD, FTIR, compressive strength test, porosity test and water absorption test. The percentage of replacement of fly ash in synthesis of geopolymer specimens are 0, 10, 20, 30, 40% for both glove former waste and glass waste respectively.

4.2 Material Characterization Test

4.2.1 X-ray Fluorescence (XRF)

Table 4.1: The Composition Present in Glove Former Waste and Glass Waste

Compound Name	Concentration Unit (wt%)		
	Purified Fly Ash (Khairul Nizar Ismail, Kamarudin Hussin and Mohd Sobri Idris, 2007)	Glove Former Waste	Glass Waste (Wang et al., 2020)
SiO_2	59.00	63.750	65.97
Al_2O_2	21.00	29.892	3.33
Na_2O	0	0	11.08

K_2O	0.9	3.171	0.35
Fe_2O_3	3.70	1.401	0.62
CaO	6.90	0.469	11.85
P_2O_5	0	0.459	0
TiO_2	0	0.292	0
Cr_2O_3	0	0.155	0
ZrO_2	0	0.041	0
MnO_2	0	0.040	0
Rb_2O	0	0.037	0
BaO	0	0.025	0
MgO	1.40	0.017	1.11
V_2O_5	0	0.006	0
SrO	0	0.006	0
Y_2O_3	0	0.006	0
SnO_2	0	0.006	0
TeO_2	0	0.006	0
PbO	0	0.006	0
Ga_2O_3	0	0.005	0
Nb_2O_5	0	0.005	0
ThO_2	0	0.005	0
NiO	0	0.003	0
CuO	0	0.003	0
Yb_2O_3	0	0.002	0
SO_3	1.00	0	0

As from above Table 4.1, major chemical composition for glove former waste is SiO_2 (63.750%), Al_2O_2 (29.892%), K_2O (3.171%) and Fe_2O_3 (1.401%). The major chemical composition for glass waste is SiO_2 (65.97%), Al_2O_2 (3.33%), Na_2O (11.08%) and CaO (11.85%). When compared between both different type of the wastes, SiO_2 which is the silica content for glove former waste is slightly lower than glass waste but the Al_2O_2 which is the alumina content is relatively higher than glass waste. Both waste precursor contains abundant of the silica and alumina content which is the aluminosilicate species for geopolymerisation which the formation Si – O – Al bond in a geopolymer paste will affect a geopolymer paste in terms of its microstructure and mechanical properties.

4.2.2 Sieve Analysis

Particle distribution of the binder power might be one of the factors which will greatly affect the effectiveness and efficiency of geopolymer formation by its mechanical and microstructure properties. Therefore, sieve analysis is done in Table 4.2 to determine the overall particle size distribution of the binder.

Table 4.2: Percentage Finer for the glove former, glass waste and fly ash in different sieve size.

Sieve Size (mm)	%Mass Passing/ Percentage Finer %		
	Glove Former	Fly Ash	Glass Waste
0.3	100.00	100.00	100.00
0.25	99.18	99.18	99.45
0.18	76.92	97.81	84.89
0.125	54.40	89.04	65.66
0.106	46.15	83.56	56.87
0.09	39.01	79.18	49.45
0.063	26.10	56.16	35.44
0.045	17.58	33.42	24.45
Pan	0.00	0.00	0.00

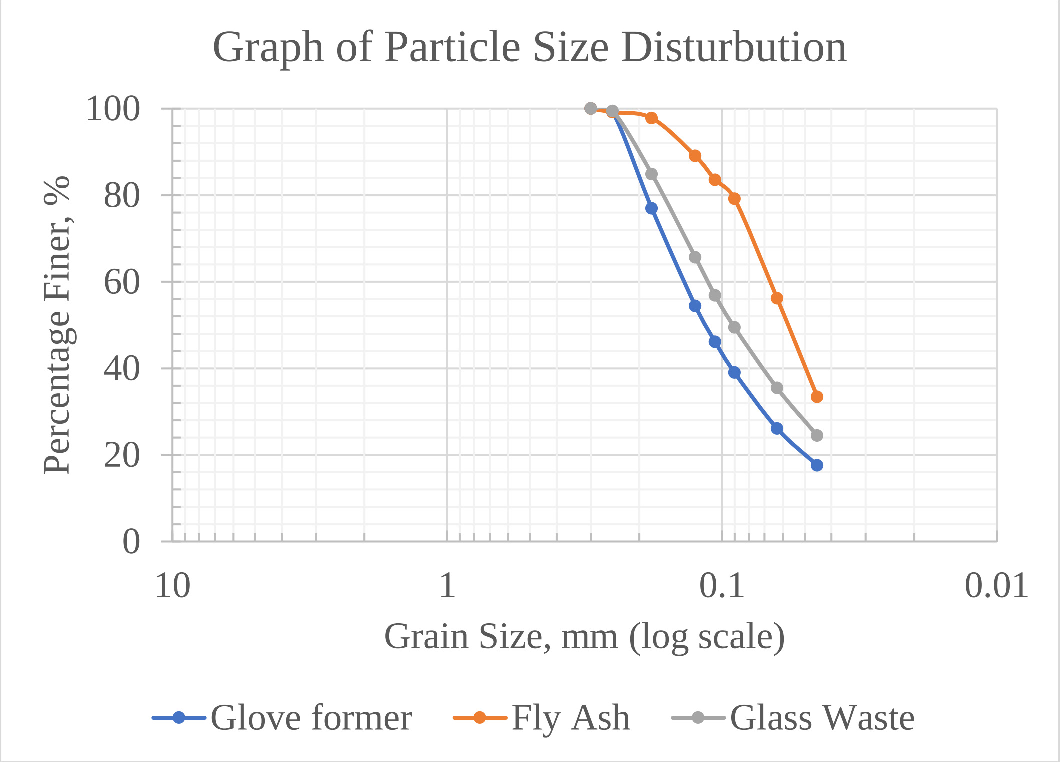


Figure 4.1: Particle Size Distribution for Fly Ash, Glove Former Waste and Glass Waste

Based on Figure 4.1 and Table 4.2, the overall particle sizes of the fly ash, glove former waste, and glass waste vary between 300um and 45um. Particle retaining at the 0.25mm mesh size is below 1% for all three kinds of binders. The dominant particle sizes for glove former waste, fly ash, and glass waste are observed within the ranges of 0.125mm - 0.25mm, 0.045mm - 0.09mm, and 0.125mm - 0.18mm, respectively.

The percentage of mass passing through the smallest sieve, which is 0.045mm, for glove former waste, fly ash, and glass waste is 17.58%, 33.42%, and 24.45%, respectively. As the fly ash having highest mass passing (%) through the finest sieve in the sieve analysis, it proves that the overall particle fineness of fly ash is finer compared to glass waste, followed by glove former waste. This observation is supported by the graph's less steep slope for fly ash compared to the steeper slopes observed for glass waste and glove former waste.

4.2.3 Scanning Electron Microscopy (SEM)

The microstructure of geopolymer paste with different percentages of GFW and GW substitution was observed and studied using Field Emission Scanning Electron Microscopy (FESEM) analysis, which was carried out in this work. This method produces high-resolution images, allowing for extensive analysis of microstructural characteristics. In this research works, SEM is conducted on different mix design which is on GFW and GW at ×10000 magnification.

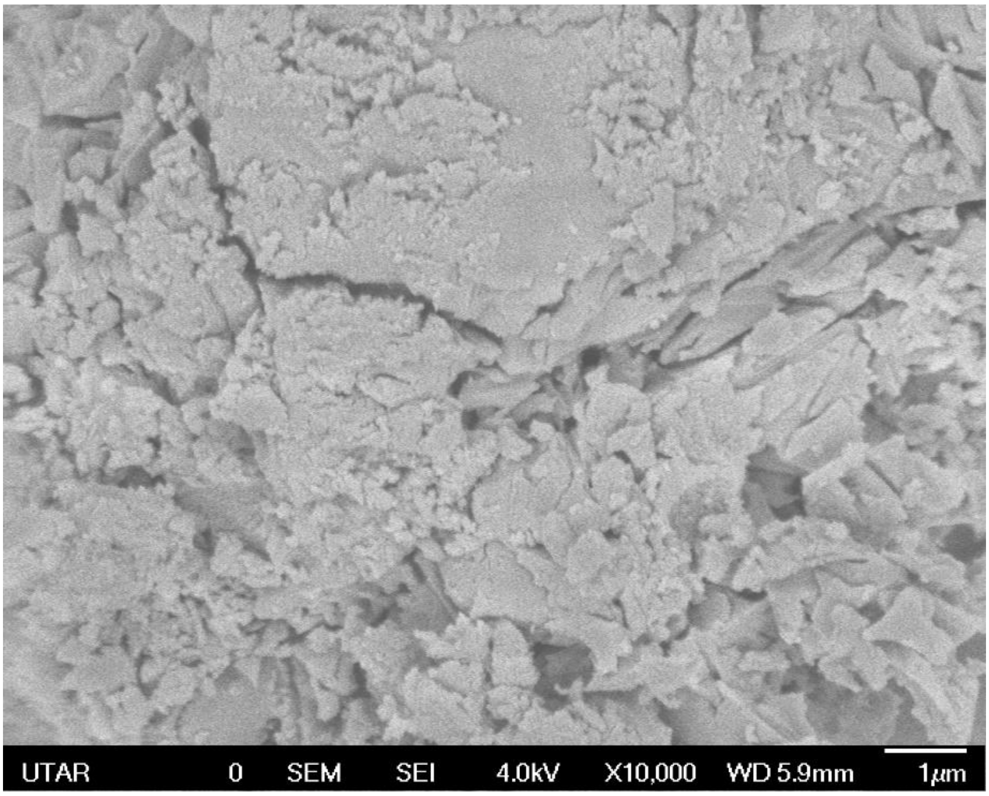


Figure 4.2: FESEM Image of Specimen 100FA at x10000 magnification

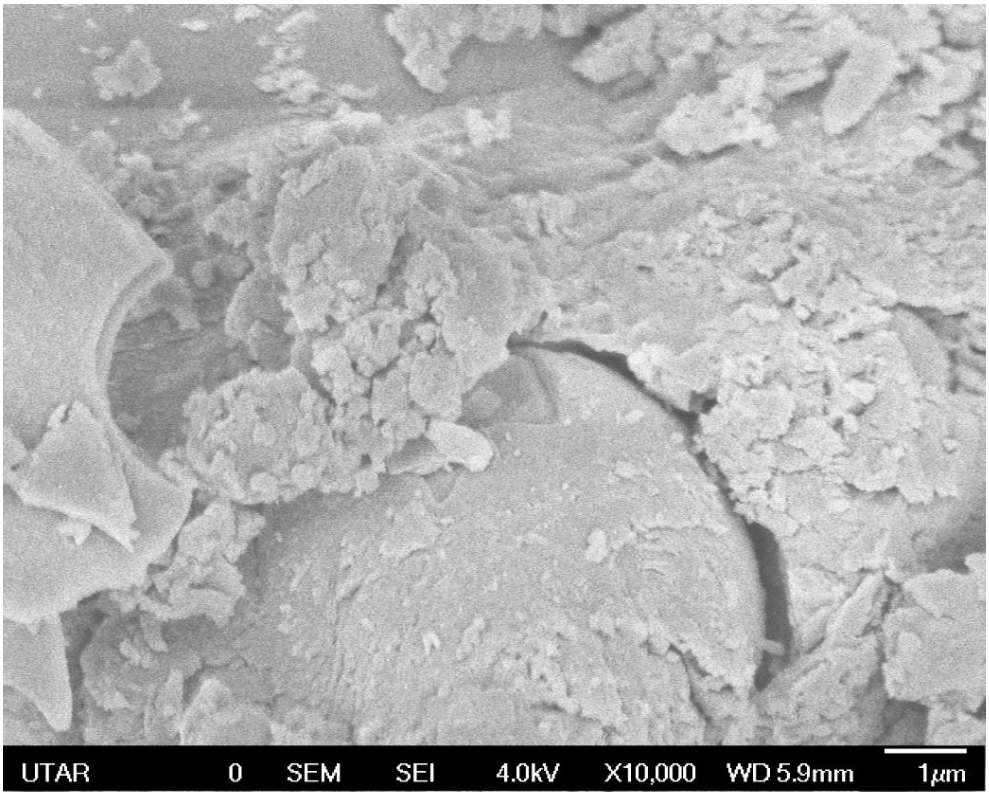


Figure 4.3: FESEM Image of Specimen 10GFW at x10000 magnification

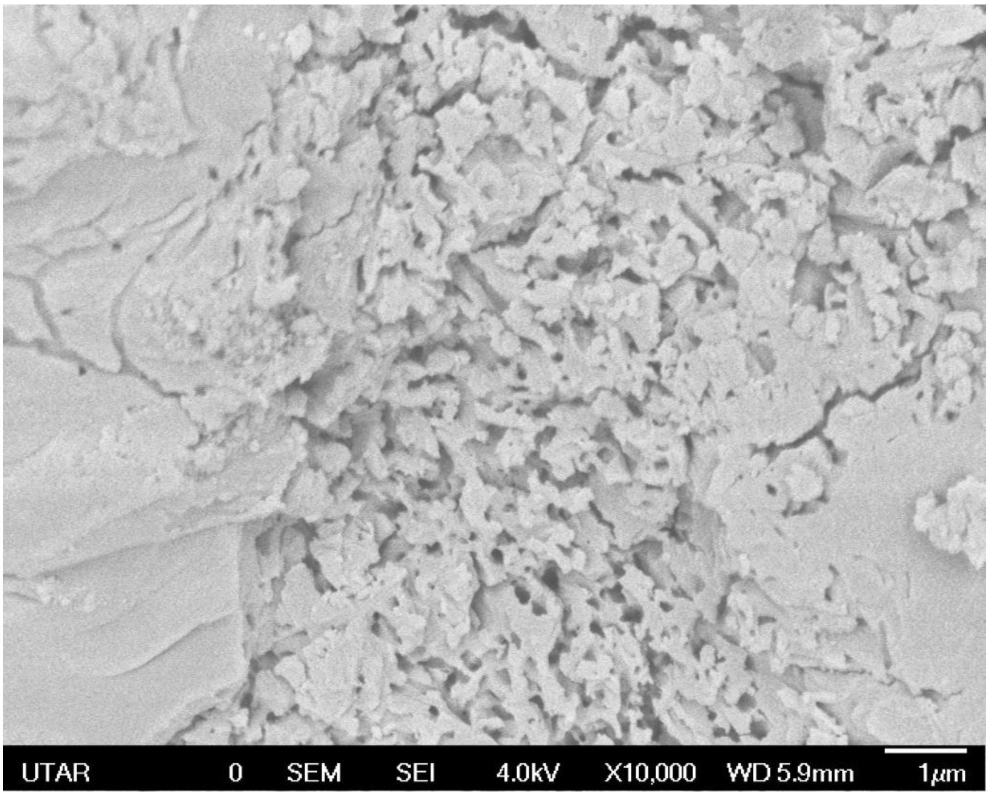


Figure 4.4: FESEM Image of Specimen 20GFW at x10000 magnification

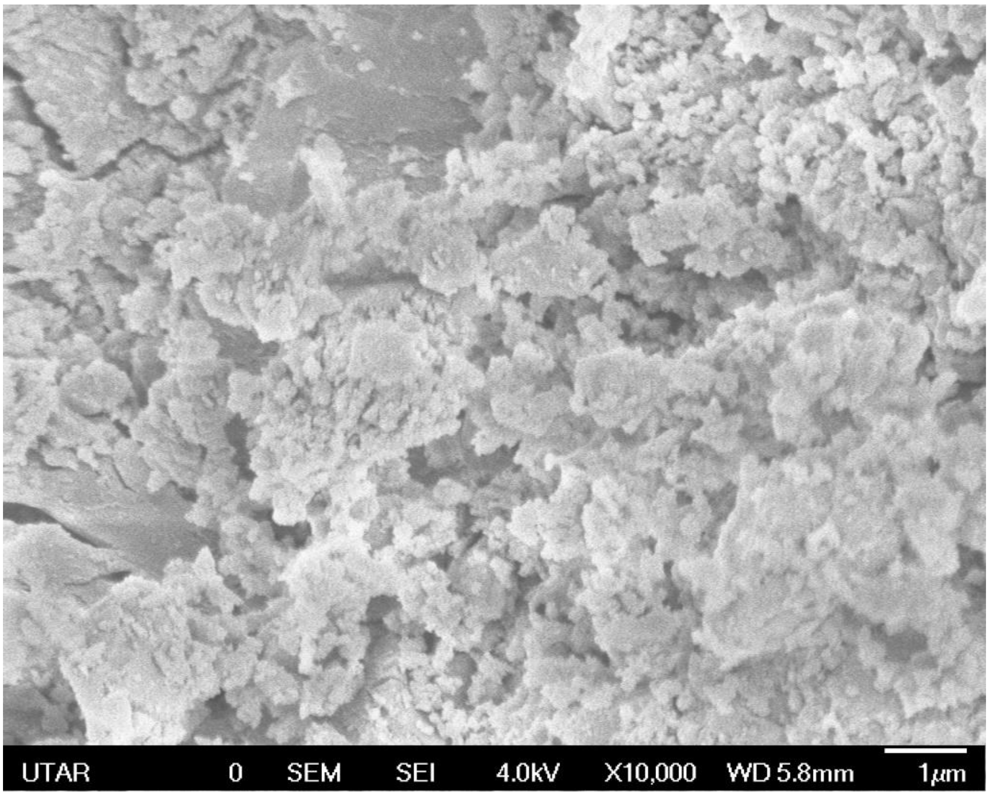


Figure 4.5: FESEM Image of Specimen 30GFW at x10000 magnification

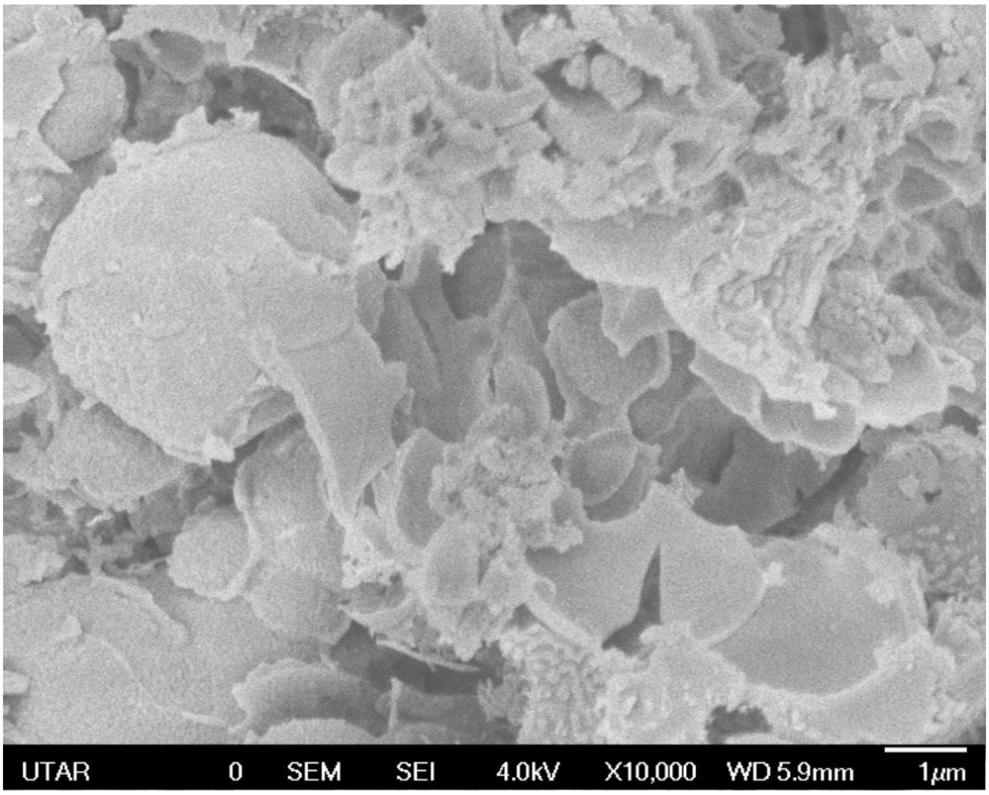


Figure 4.6: FESEM Image of Specimen 40GFW at x10000 magnification

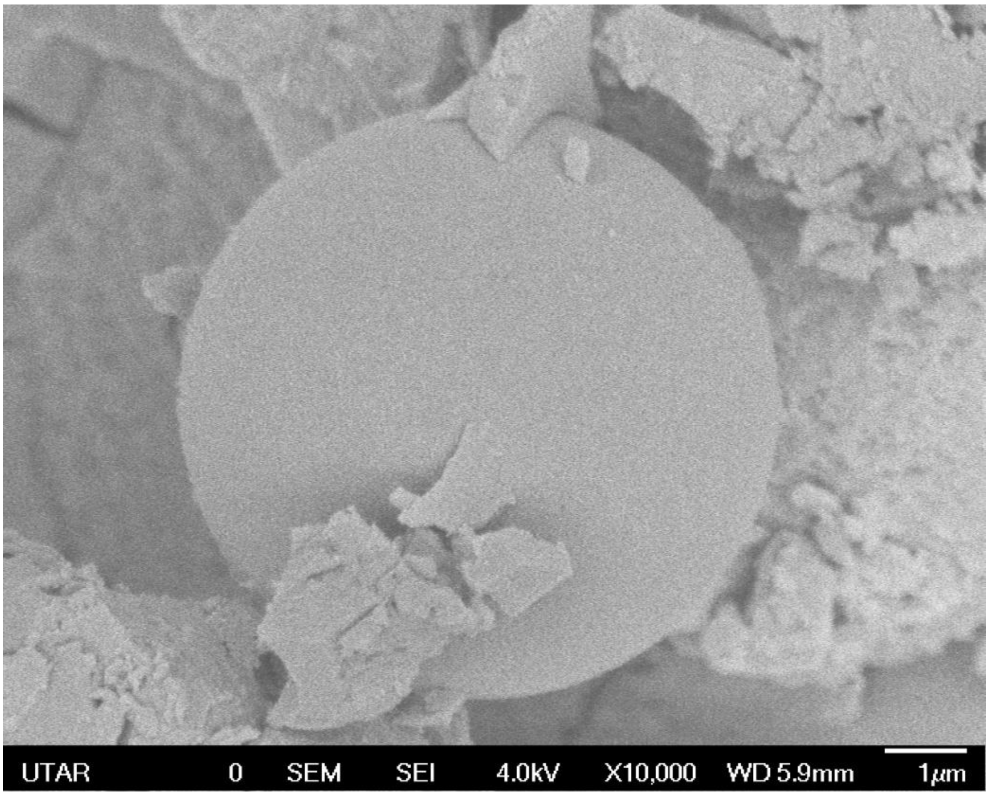


Figure 4.7: FESEM Image of Specimen 10GW at x10000 magnification

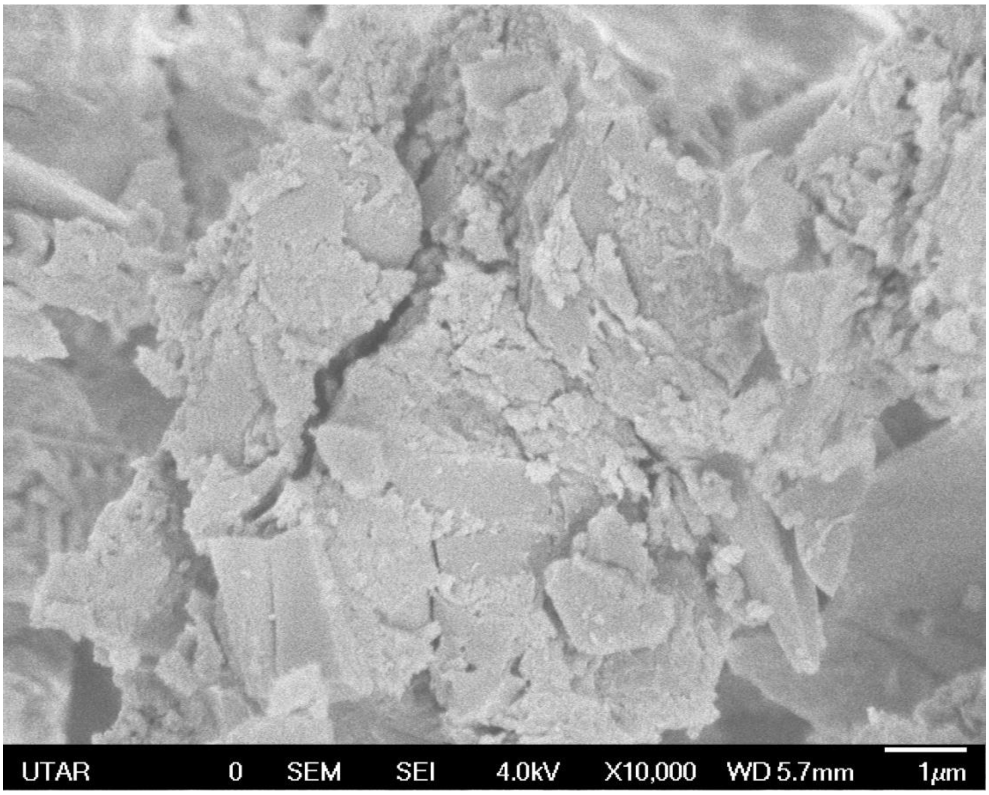


Figure 4.8: FESEM Image of Specimen 20GW at x10000 magnification

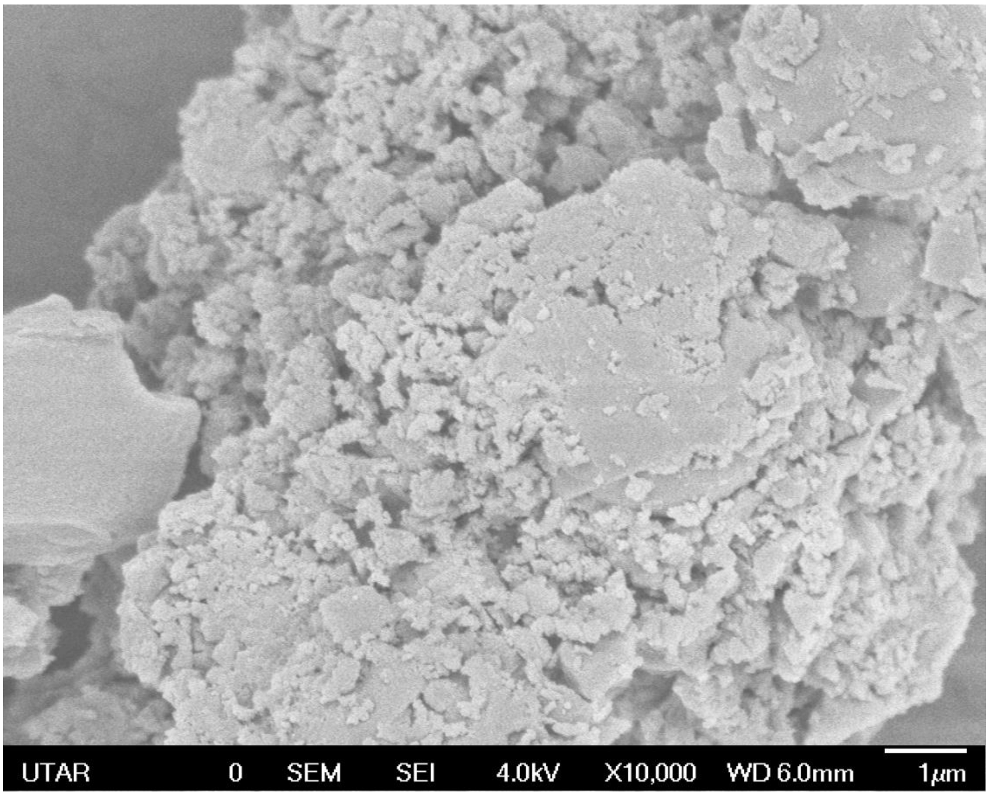


Figure 4.9: FESEM Image of Specimen 30GW at x10000 magnification

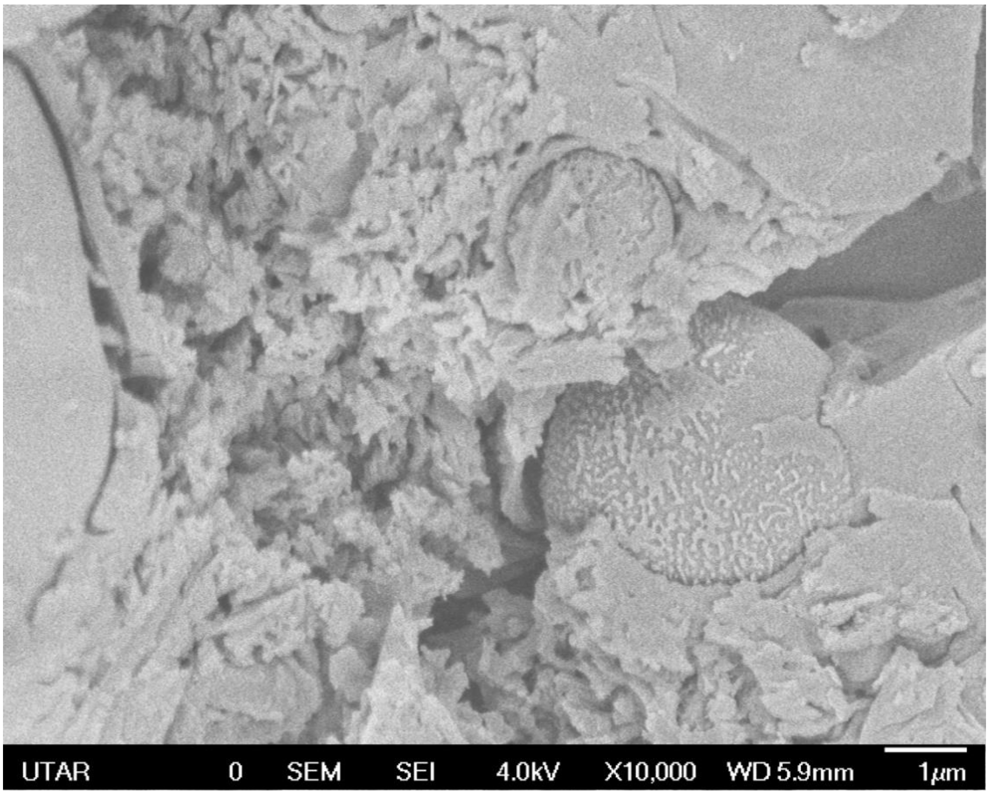


Figure 4.10: FESEM Image of Specimen 40GW at x10000 magnification.

Based on the Figure 4.2, the FESEM image ×10000 magnification shows that the geopolymer is fully synthesised by the fly ash which is without any waste substitution. From that FESEM image, a dense and compacted geopolymer structure can be observed. The better quality and homogeneity are due to the highly connection between the geopolymer gels which forms interconnection between bonds. This provides a better mechanical interlocking which will corelate to a relatively higher compressive strength.

Figure 4.3 to 4.6 and Figure 4.7 to 4.10 shows the high resolution FESEM image for the GFW and GW in different percentage of replacement to fly ash (10, 20, 30, 40%) at ×10000 magnifications. Comparing across the substitution percentage for both GFW and GW, as the higher substitution of the silica waste, the presence of the cracks and voids on the image is more obvious and increases. The respectively larger pores indicate a higher porosity which will increase the water absorption as more water can penetrate in. This resulted and correlated well with our water absorption and porosity findings where 40GFW and 40GW give rise to the highest water absorption and porosity as compare to lower substitution waste percentage. The less dense structure will lose its mechanical strength and result in lower compressive strength as more porous structure.

4.2.4 Fourier - Transform Infrared Spectroscopy (FTIR)

By evaluating the amount of infrared light absorbed, FTIR spectroscopy analyses the geopolymer paste's chemical composition and provides information on existing chemical bonds and presences chemical reactions. Figure 4.11 and 4.12 shows the FTIR spectra results for geopolymer paste synthesised by GFW and GW respectively.

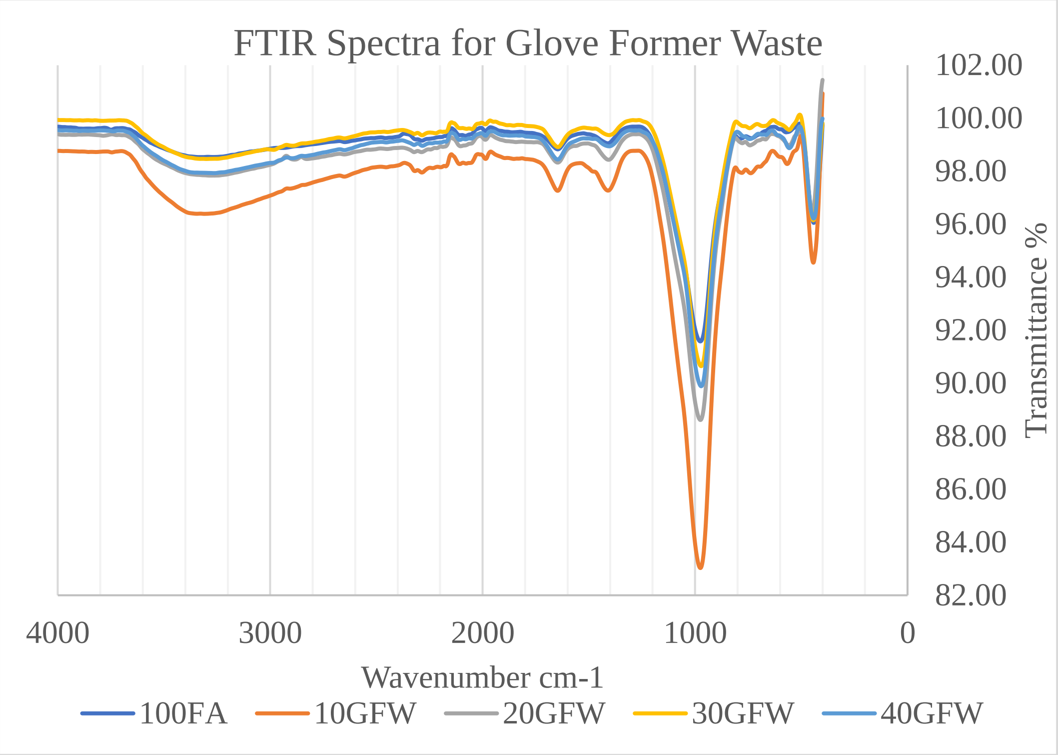


Figure 4.11: FTIR Spectra for Geopolymer Paste with GFW

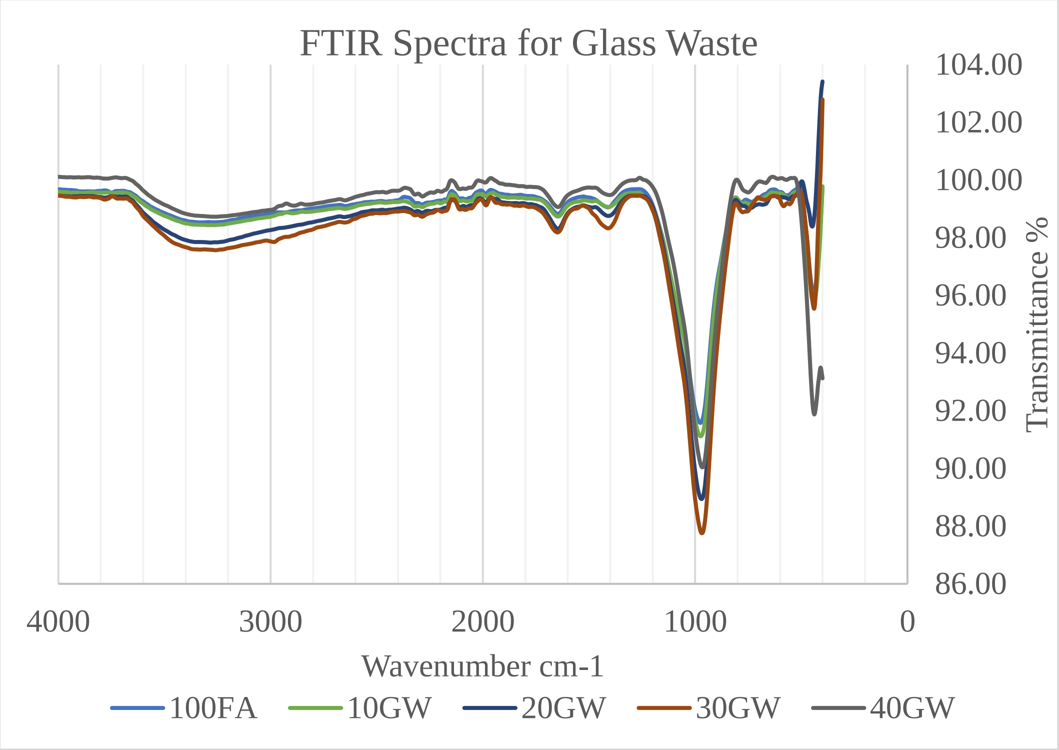


Figure 4.12: FTIR Spectra for Geopolymer Paste with GW

Based on Figure 4.11 and 4.12, the FTIR spectra of GFW and GW both show absorption bands with wave patterns which is similar with the geopolymer paste synthesised by fully conventional fly ash. From Figure 4.11 and 4.12, the specimen's FTIR spectrum after 28 days shows that the absorption band, which spans around 440cm^{-1} to 448cm^{-1}, indicates that the O – Si – O and Si – O – Si bonds are now being stretched and bent. The main absorption band, which is about 966cm^{-1} to 975cm^{-1} is indicated by the peak intensity, and the sharpest intensity denotes a high degree of the polymerization process. The fact that the Si – O and Al – O long chain bond together through the tetrahedral silicon or aluminium atom. The geopolymerization process happen as this is the main bond to connect and provides the strength to the geopolymer paste. When the metal alkaline in the alkaline activator reacts with the surrounding carbon, an absorption band in a range of 1400cm^{-1} to 1500cm^{-1} indicates the existence of carbonate stretching vibrations. A weak absorption band in the 1600cm^{-1} to 1700cm^{-1} region is recognisable, indicating the presence of water molecules throughout the hydration reaction and the geopolymerization process. The weak band at around 3309cm^{-1} indicates stretching vibrations of the hydroxyl group or precursor materials. The FTIR spectra graphs above show similarities in the broad bands, which suggests that the waste binders from GFW and GW can function as one of the sources of the precursor materials and efficiently interact with the alkaline activator to promote geopolymerization.

4.3 Mechanical Performance Test

4.3.1 Compressive Strength

Compressive strength is an important parameter in construction sector since it determines a material's ability to withstand stresses while maintaining structural integrity over time. Therefore, it is crucial to analyse compressive strength data for geopolymer specimens at different testing ages (7, 14, and 28 days).

The analysis and testing of compressive strength in geopolymer materials is crucial, especially considering its extensive application in the construction industry. Below Table 4.3 and Figure 4.13 shows the average compressive strength of the geopolymer specimen for testing age of 7 days, 14 days, and 28 days. The unit of the data obtained in kilonewton (kN) is converted to MPa by dividing the size of the specimen which is 50mm × 50mm cube.

Table 4.3: Compressive Strength of Different Mix Design of Geopolymer Paste

Specimen	Average Compressive Strength (MPa)		
	7 days	14 days	28 days
100F	28.310	54.003	79.798
10GFW	20.965	50.417	83.098
20GFW	12.348	44.583	73.898
30GFW	7.172	34.260	68.513
40GFW	3.400	25.549	39.617
10GFW	16.570	42.219	76.315
20GW	13.013	38.626	74.412
30GW	6.535	31.245	73.971
40GW	3.202	18.420	62.498

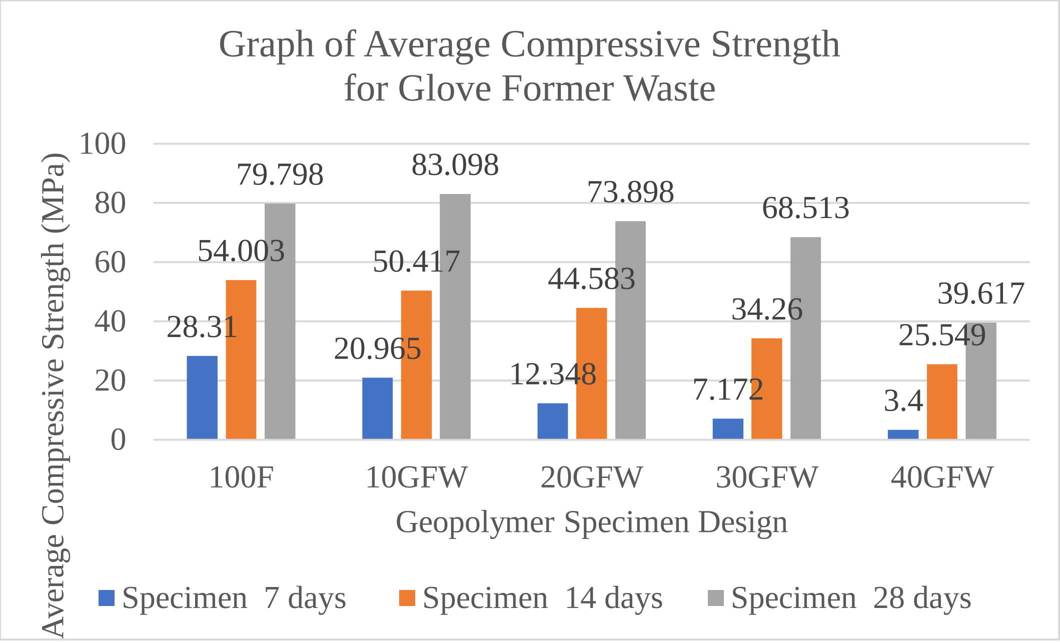


Figure 4.13: Graph of Average Compressive Strength for GFW

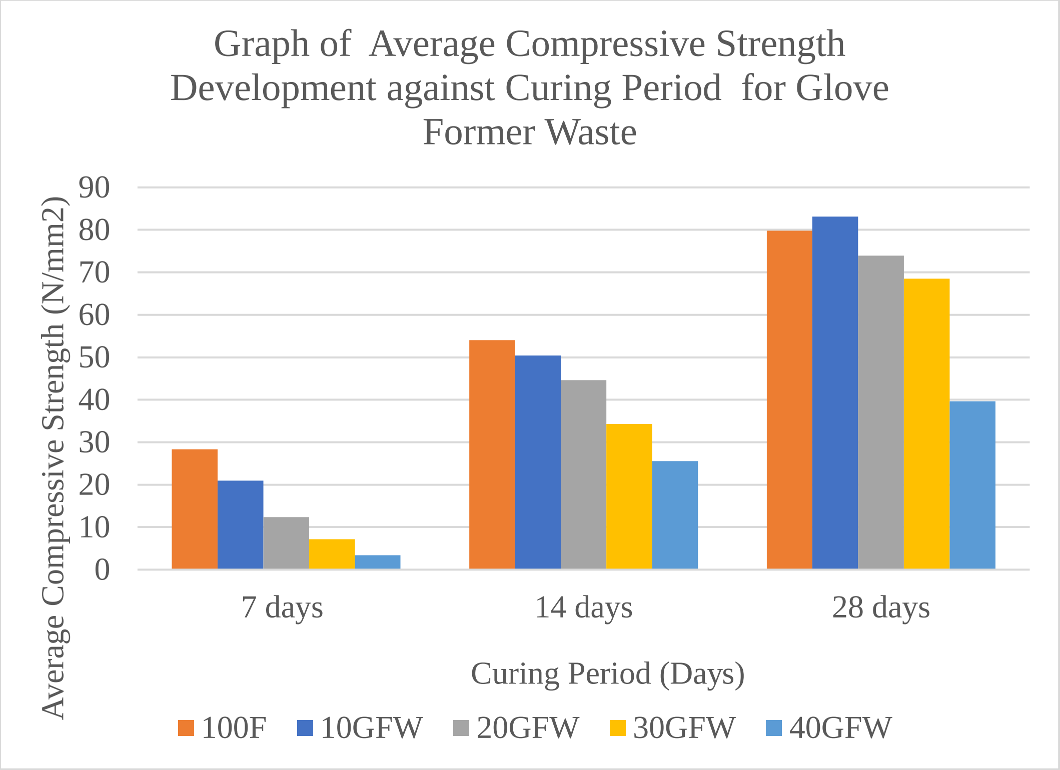


Figure 4.14: Graph of Average Compressive Strength against Curing Period for GFW.

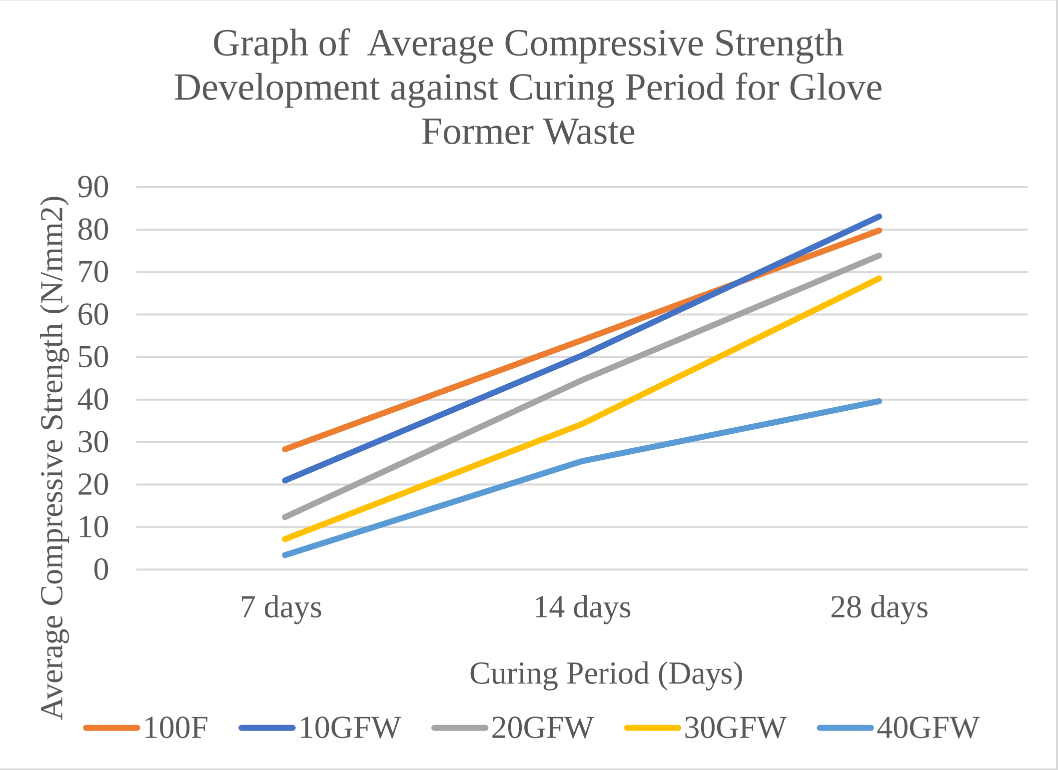


Figure 4.15: Graph of Average Compressive Strength Trend against Curing Period for GFW.

Figure 4.16: Graph of Average Compressive Strength Trend against Different Percentage of GFW.

For GFW, the average compressive strength of the geopolymer specimen is shown as the bar graph in Figure 4.13 and Table 4.3. As shown in Figure 4.14 and

4.15, geopolymer specimen 100FA, 10GFW, 20GFW, 30GFW and 40GFW gain an average compressive strength of 28.31MPa, 20.97MPa, 12.35MPa, 7.17MPa and 3.40MPa in 7 days of the testing ages and increases to the 54.00MPa, 50.42MPa, 44.583MPa, 34.26MPa and 25.549MPa in 14 days of the testing ages respectively. Over the 28 days of the curing period, the respective geopolymer specimen provide the strength of 79.80MPa, 83.10MPa, 73.898Mpa, 68.51MPa and 39.62MPa for glove former waste. This gain strength is due to the presence of silicon (SiO_2) and aluminium (Al_2O_3) species formed from precursor materials which is GFW facilitates a considerable but slow impact. The inclusion of silicon (Si) and aluminum (Al) in the binder leads to the development of a more compact arrangement, which in turn improves the compressive strength. (Temple Chimuanya Odimegwu et al., 2023).

Dissolution and Hydrolysis:

$$Al_2O_3 \cdot SiO_2 + 2NaOH \ + 4H_2O \rightarrow 2NaAl(OH)_4 + Si(OH)_4 \tag{4.1}$$

$$Si(OH)_4 + OH^- \rightarrow \ Si(OH)_3O^- + H_2O \tag{4.2}$$

$$Al(OH)_4 + OH^- \rightarrow \ Al(OH)_3O^- + H_2O \tag{4.3}$$

Polycondensation:

$$nSi(OH)_3O^- \ \rightarrow Si_nO_x(OH)^-{}_{4-(n-1)} + (n-1)H_2O \tag{4.4}$$

$$mAl(OH)_3O^- \ \rightarrow Al_mO_x(OH)^-{}_{4-(m-1)} + (m-1)H_2O \tag{4.5}$$

For a geopolymer to develop strength, Si and Al will undergoes dissolution to form (Si $(OH)_4$) and (Al $(OH)_4^-$) and react with OH- ions through polycondensation to create the Si-O-Si bond and the Al-O-Si bond which is shown in equation 4.1 to 4.5, resulting in the formation of an oligomer. These oligomers then link with each other to form a three-dimensional network structure. These bonds can be established by dissolving the precursor material and subsequently undergoing hydrolysis with the OH- ions provided by the alkaline activator. (Silva, Sagoe-Crenstil and Sirivivatnanon, 2007)

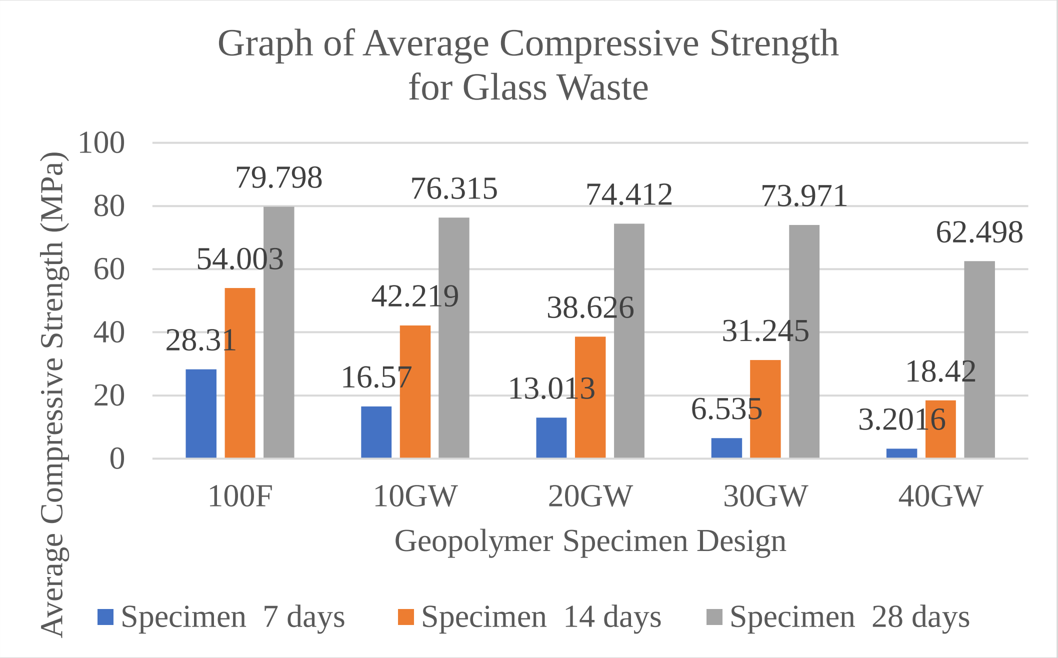


Figure 4.17: Graph of Average Compressive Strength for GW

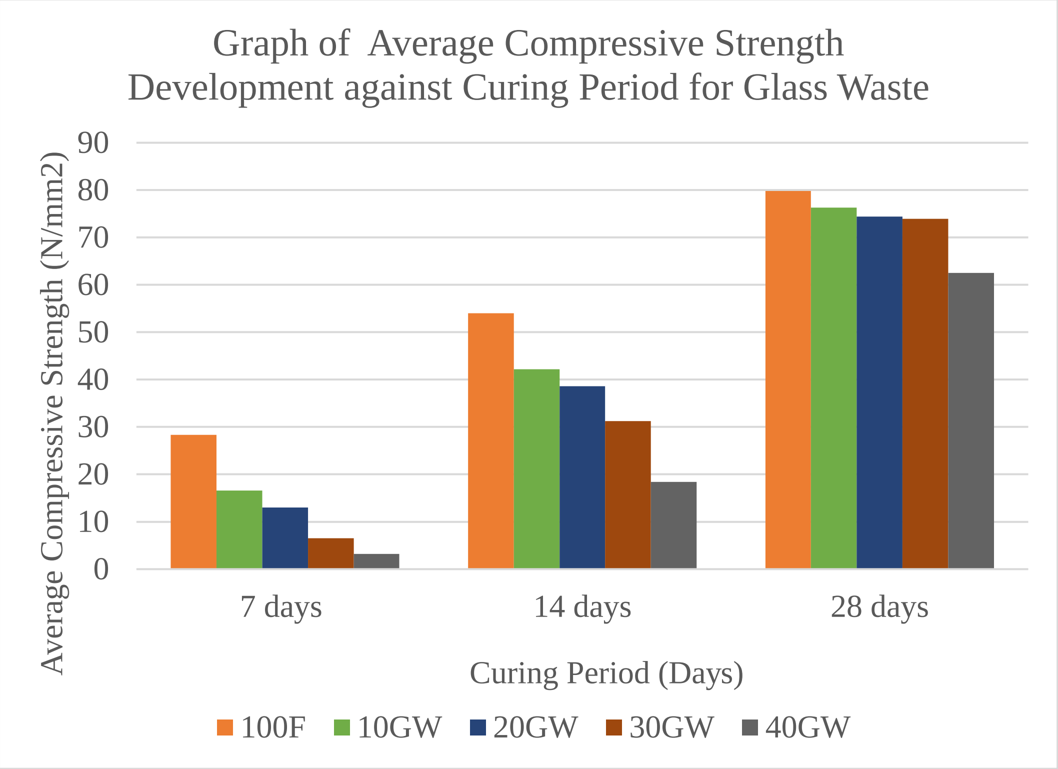


Figure 4.18: Graph of Average Compressive Strength against Curing Period for GW.

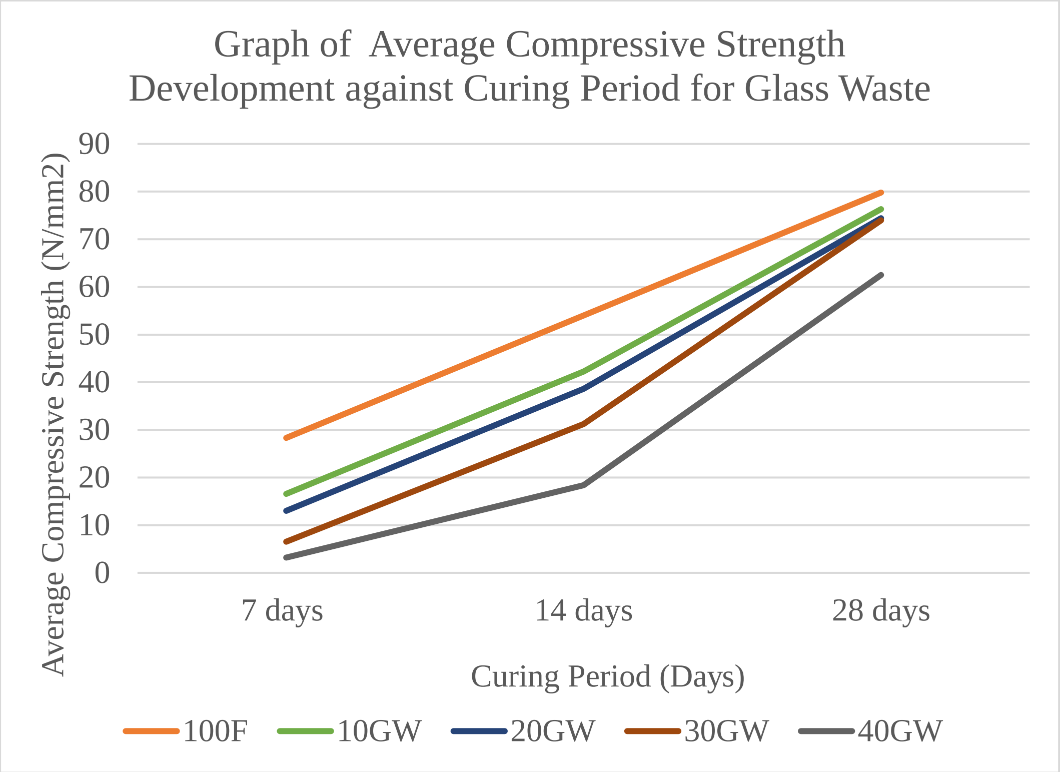


Figure 4.19: Graph of Average Compressive Strength Trend against Curing Period for GW.

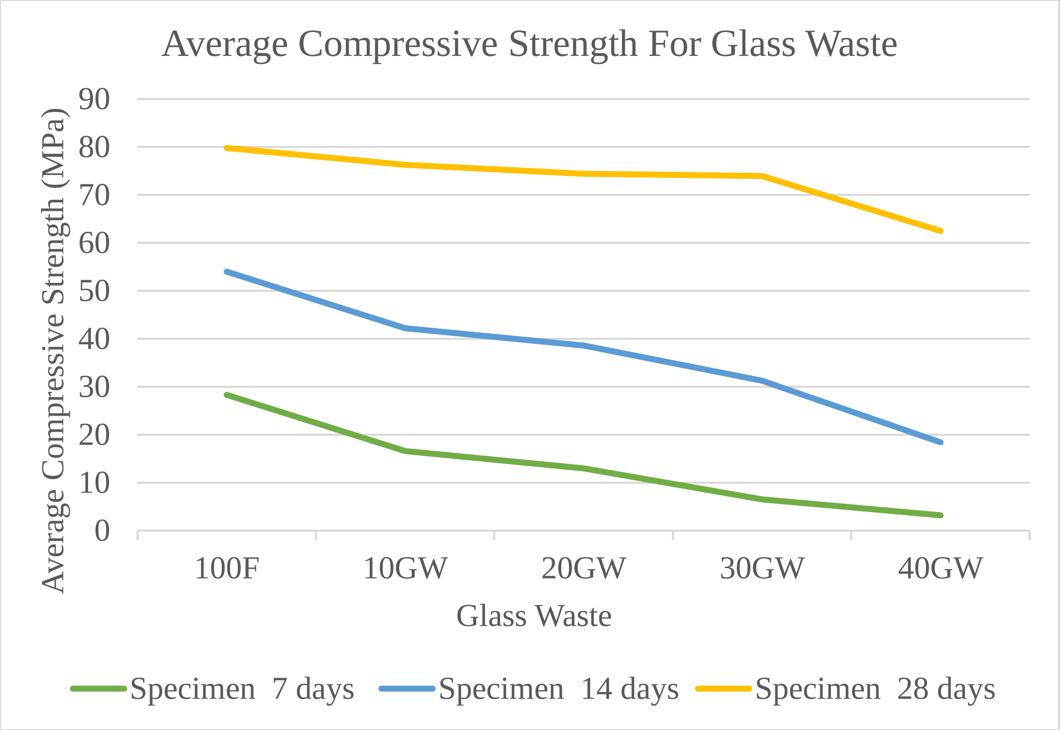


Figure 4.20: Graph of Average Compressive Strength Trend against Different Percentage of GW.

For GW, Figure 4.17 and Table 4.3 shows the average compressive strength of geopolymer paste for different percentage of substitution with GW. Based on Figure 4.18 and 4.19, the average compressive strength of 100FA, 10GW, 20GW, 30GW and 40GW increase from 28.31MPa, 16.57MPa, 13.01MPa, 6.54MPa and 3.20MPa in 7 days testing ages to the 54.00MPa, 42.22MPa, 38.63MPa, 31.25MPa and 18.42MPa in 14 days of the testing ages respectively. Until the 28 days of the testing age, the respective geopolymer specimen increase the strength to 79.80MPa, 76.32MPa, 74.41Mpa, 73.97MPa and 62.50MPa for glass waste. As shown in Figure 4.18 and 4.19, the geopolymer paste with GW shows a substantial increase from the 7th days to 14th days and end up with 28th days. This is similar for the glove former waste as the glass waste contains the similar chemical composition which is the silica and aluminium species. The abundance of these species will contribute the formation of the Si – O – Si and Al – O – Si bond. The bond will then link together to form the 3D structure which will contribute to the increase in strength.

For both GW and GFW which is shown in Figure 4.13 and Figure 4.17, it is apparent that the GFW have a significant higher average compressive strength than the GW in the 7th days and 14th days. This shows that the GFW have the higher early setting time which indicates GFW to gain strength faster than GW. The presence of aluminum (Al) in the precursor material affects the early setting time, as the production of Al – O – Si bonds is more prevalent in the early stages. The role of Al species in the geopolymer species is prevalent as it helps the rearrangement of the geopolymer structure to contribute a denser and compacted structure which increase the compressive strength of the geopolymer specimen. (Silva, Sagoe-Crenstil and Sirivivatnanon, 2007) However in the following 28th days, the overall average compressive strength of the GFW replacement percentages is significantly less than that of the GW. This is due to the amount of precursor material, which is made up of alumina and silica species, is crucial and has a direct impact on the strength of the geopolymer. According to Table 4.1, SiO_2 content of GFW is 2.22% slightly lower than GW, while Al_2O_2 content of GFW is 26.562% higher than GW. As in geopolymerisation, silica species is prevalent to form more bonds due to the silica content for GW is slightly higher than GFW. This will affect the compressive strength of GW to be slightly higher in 28th days until maturity for final gain strength.

For both GFW and GW which shown in Figure 4.16 and 4.20, average compressive strength of the GFW and GW replacement geopolymer across different percentage of the waste replacement of the fly ash as the binder. Each graph shows a substantial decrease in strength as the higher the replacement percentage of the waste for 7th day, 14th day and 28th day. This phenomenon may be clarified by the geopolymer gel formation during polycondensation, where the binding of the matrix is insufficient, resulting in a lack of cohesion and reduced strength. This leads to early failure, particularly at higher levels of substitution. According to Asante et al. (2021), The particle size of the precursor binder can affect the compressive strength of the geopolymer. Figure 4.1 illustrates that the particle distribution size of fly ash is smaller in comparison to that of GFW and GW. Smaller particles have a greater surface area, which helps to increase the rate of dissolution and polycondensation processes. As a result, when bigger particles like GFW and GW are substituted in a higher percentage, there is generally a drop in strength.

According to ASTM C 150 Compressive Strength Specifications, it specifies that ordinary cement mortar must possess a minimum compressive strength ranging from 13.76 to 16.56Mpa. (Pavement Interactive, n.d.) Thus, it proves that all the substitution (10GFW, 20GFW, 30GFW, 40GFW, 10GW, 20GW, 30GW, and 40GW) achieved the minimum required compressive strength which exceed the minimum threshold of 13.76 MPa, demonstrating the feasibility of using greater proportions of GFW and GW in the composite mixture. Hence, the optimum of is 30GFW and 30GW as per the local authority allowable of 30% of waste replace in any construction materials.

4.4 Physical Property Test

4.4.1 Water Absorption Test

The water absorption test is crucial for determining the impact of substituting geopolymer paste with waste, since this newly developed product may have different water absorption abilities that might potentially influence the long-term mechanical properties of geopolymer in the building industry. Below Table 4.4 and

Figure 4.21 shows the average water absorption rate of the different geopolymer paste with different percentage of replacement with GW and GFW. Below Figure 4.22 and 4.24 shows the average water absorption rate in a trend line graph for 7, 14 and 28 testing age specimens for both wastes respectively. The average water absorption development trend over different replacement percentage (10, 20, 30, 40%) of GFW and GW is shown in Figure 4.23 and 4.25 respectively.

Table 4.4: Water Absorption Rate of Geopolymer Specimen with different mix design

Specimen	**Water Absorption Rate (%)**		
	7 days	14 days	28 days
100F	3.990	3.121	2.539
10GFW	4.323	3.519	2.933
20GFW	4.368	3.556	2.977
30GFW	4.392	3.942	3.199
40GFW	4.488	3.981	3.519
10GW	4.305	3.098	2.513
20GW	4.309	3.203	2.739
30GW	4.344	3.227	2.811
40GW	4.381	3.613	2.888

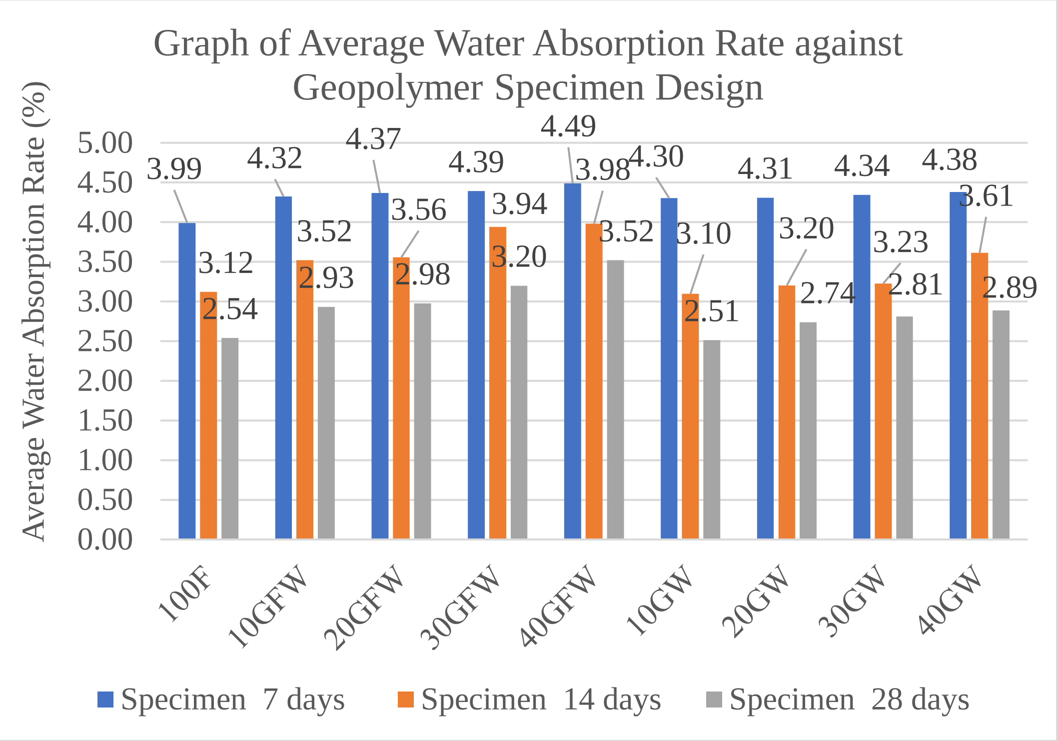


Figure 4.21: Graph of Average Water Absorption Rate for GW and GFW

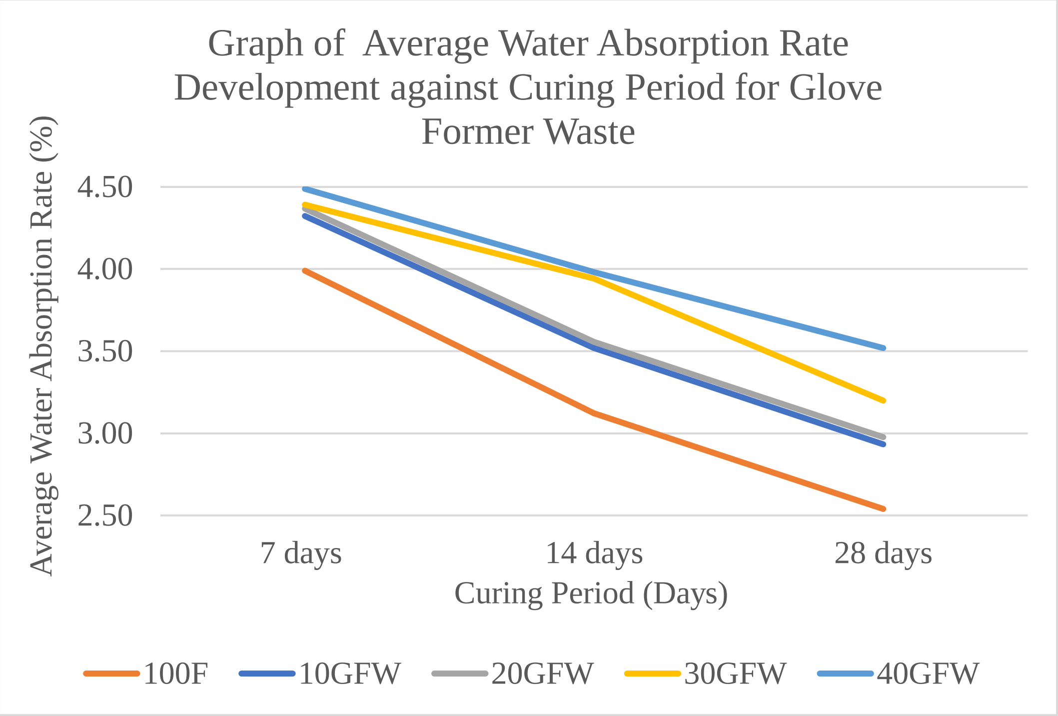


Figure 4.22: Graph of Average Water Absorption Rate Trend against Curing Period for GFW

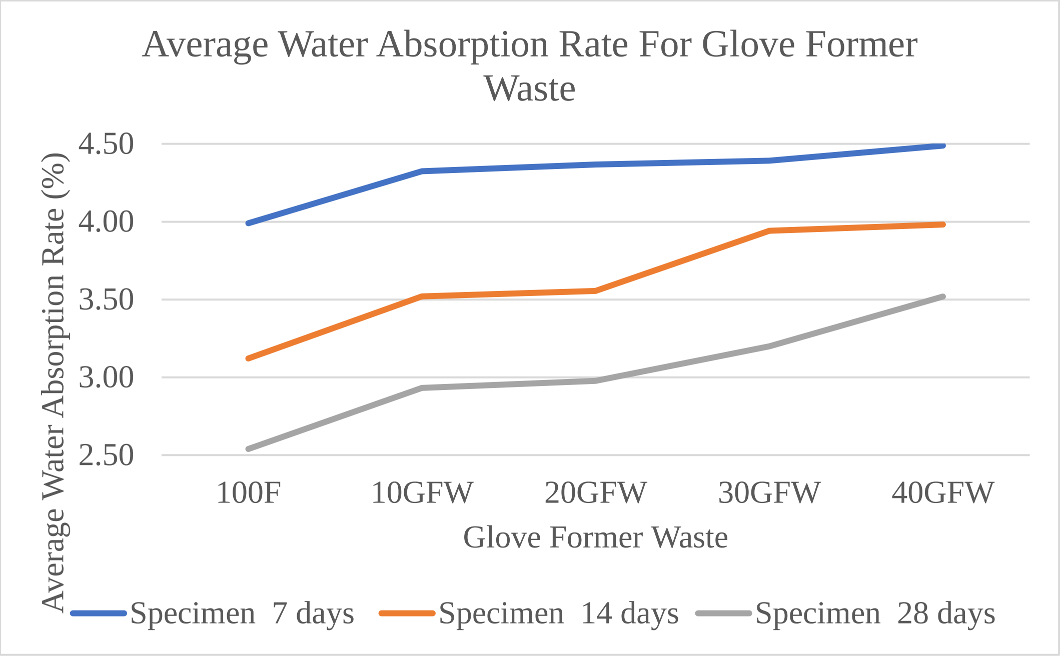


Figure 4.23: Average Water Absorption Rate for GFW

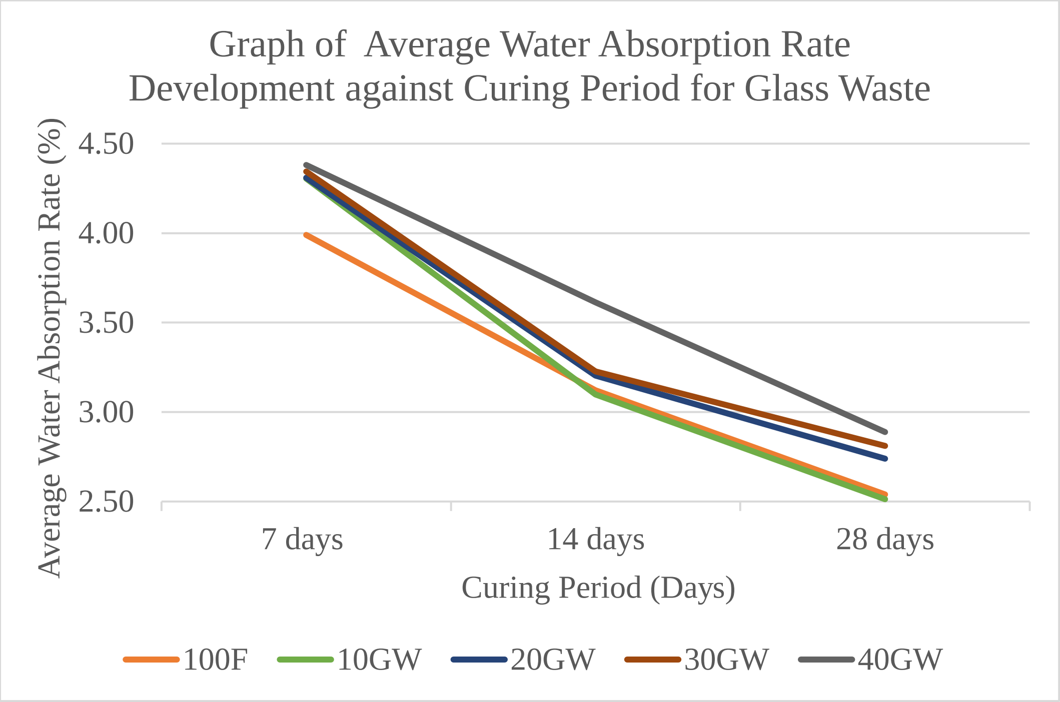


Figure 4.24: Graph of Average Water Absorption Rate Trend against Curing Period for GW

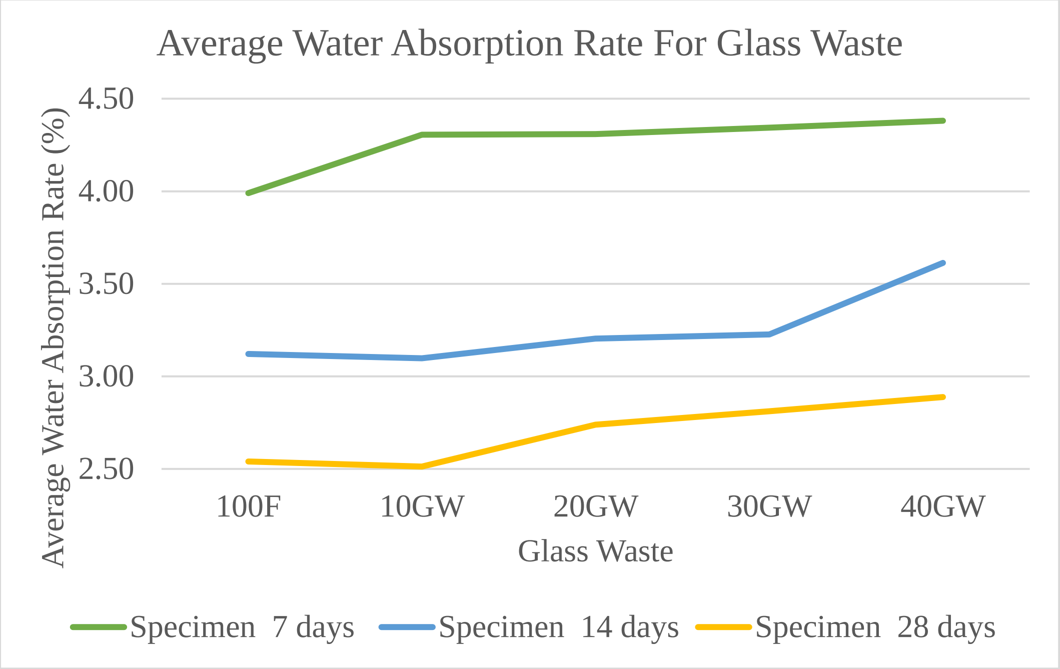


Figure 4.25: Average Water Absorption Rate for GW

For water absorption rate for GFW which is shown in Figure 4.21 and Table 4.4 100FA, 10GFW, 20GFW, 30GFW and 40GFW are having a initial water absorption of 3.99, 4.32, 4.37, 4.39 and 4.50% in the 7th day testing ages and decrease to 3.12, 3.52, 3.56, 3.94 and 3.98% in the subsequent 14th day respectively. The water absorption rate is then decrease to 2.54, 2.93, 2.98, 3.20 and 3.52 in 28th. day of testing day. Similarly for GW, 10GW, 20GW, 30GW, 40GW is drop from 4.31, 4.31, 4.34 and 4.38 for 7 days to 3.10, 3.20, 3.23 and 3.61 for 14 days respectively. The data obtained for 28th days is 2.51, 2.74, 2.81 and 2.89 respectively.

Both GFW and GW show that the geopolymer's water absorption decreases significantly when the curing test age increases from 7 to 28 days. The rise in the rate of water absorption may be attributed to the decrease in pores within the geopolymer paste, which are connected to its porosity. An elevated pore content results in more voids and capacity for water absorption. The observed phenomenon may be attributed to the maturity of the geopolymer. As the curing period progresses from 7 to 28 days, the paste matrix tends to be denser and more compacted, which promotes the steady production of additional Si – O – Si and Al – O – Si bonds which contribute to lower absorption rate over time. (Temple Chimuanya Odimegwu et al., 2023) As the polymerization process goes on, oligomers combine to create the aluminosilicate gel structure, which forms the three-dimensional network structure of the geopolymer and improve the crystallinity and microstructure of the geopolymer paste.

Figures 4.23 and 4.25 demonstrate a significant rise in the total water absorption rate for both GFW and GW. The water absorption rates for GFW and GW vary between 2.933% and 4.488%, and between 2.513% and 4.381%, respectively. However, there is no substantial variation in the rates of absorption at which GW and GFW. However, for both waste substitutes, as GW and GFW substitution levels increase, so does the rate of water absorption. This observed phenomenon may be related to the particle size of the binding material itself, as seen in Figure 4.1. It is evident that fly ash shows the lowest particle distribution, followed by GW and then GFW. The presence of smaller particles in the binder serves as fillers, enabling a more compact structure by filling the pores in the paste. Therefore, when the replacement percentages of GW and GFW are reduced, the pore filling and fitting processes are improved, resulting in a more efficient reaction to generate Si-O-Si and Al-O-Si bonds due to the increased surface area. In response, there is a reduction in the formation of pores and a decrease in water absorption rates. For a paste with a lower water absorption rate, the paste will be denser and lead to a stronger compressive strength. (Farhana et al., 2014)

Based on the report from the International Federation for Structural Concrete (CEB-FIP Model Code), concrete is classified according to its water absorption rate. The rate above 5% is of low quality and a rate between 0% and 3% is of high quality. Based on above standard, there is no geopolymer paste is categories as the poor quality but is above the ordinary level depends on the water absorption rate. For the 28th testing age for the water absorption rate, all mix design in GFW, GW is categorized as the good quality except for the 30GFW and 40GFW which is the 3.2% and 3.52 % and exceeding 3% but within 5%. Thereby, it is important to note that all mix designs fall within the acceptable and desirable range specified by the standard, thereby guaranteeing the functionality of the concrete.

4.4.2 Porosity Test

The porosity test is crucial for determining the number of voids present in the geopolymer paste. The porosity of the geopolymer paste will impact its strength, resistance to moisture, and resistance to chemical attacks. Hence, it is crucial for the building industry to guarantee long-term durability.

The average porosity of different mix design of the geopolymer paste with GW and GFW is shown in Table 4.5 and Figure 4.26. The average porosity development trend for geopolymer in 7, 14, 28 days is shown in the Figure 4.27 and 4.29. The average porosity development trend over different replacement percentage of GFW and GW is shown in Figure 4.28 and 4.30 respectively.

Table 4.5: Porosity of Geopolymer Specimen with different mix design

Specimen	**Porosity (%)**		
	7 days	14 days	28 days
100F	8.61	8.14	7.81
10GFW	8.58	8.59	8.38
20GFW	9.30	8.58	8.52
30GFW	10.20	9.96	9.70
40GFW	10.61	10.53	10.50
10GW	8.53	8.35	7.87
20GW	9.04	8.39	8.19
30GW	9.13	8.98	8.78
40GW	9.48	9.36	9.01

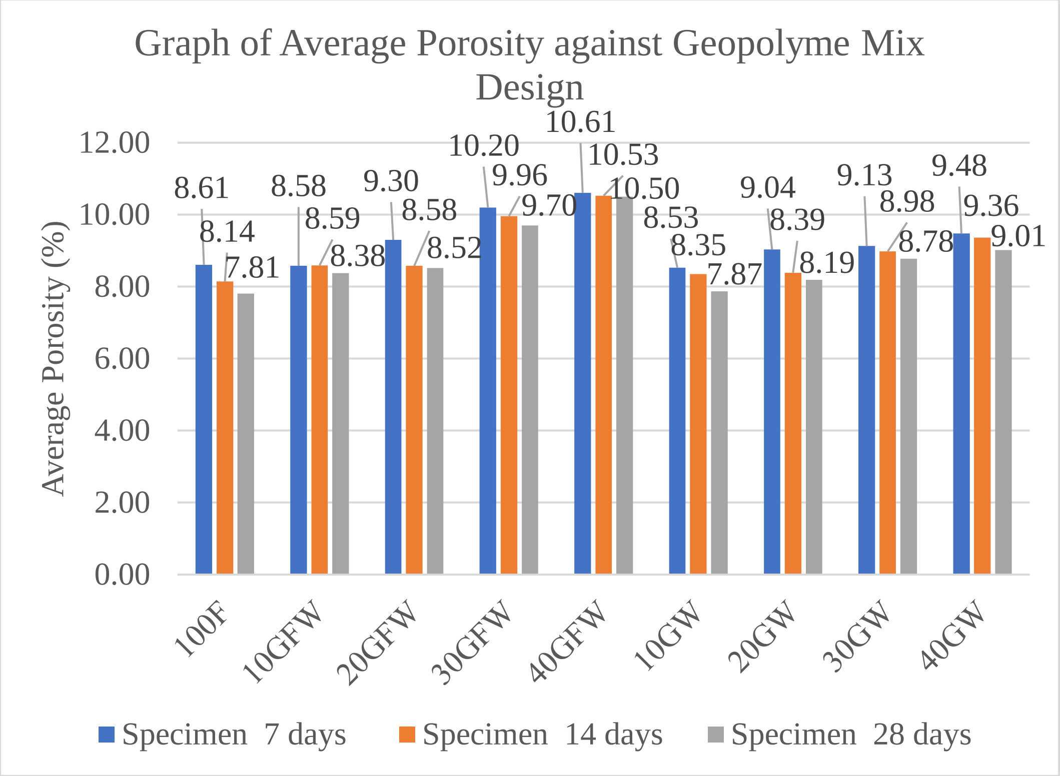


Figure 4.26: Graph of Average Porosity against Geopolymer for GFW and GW.

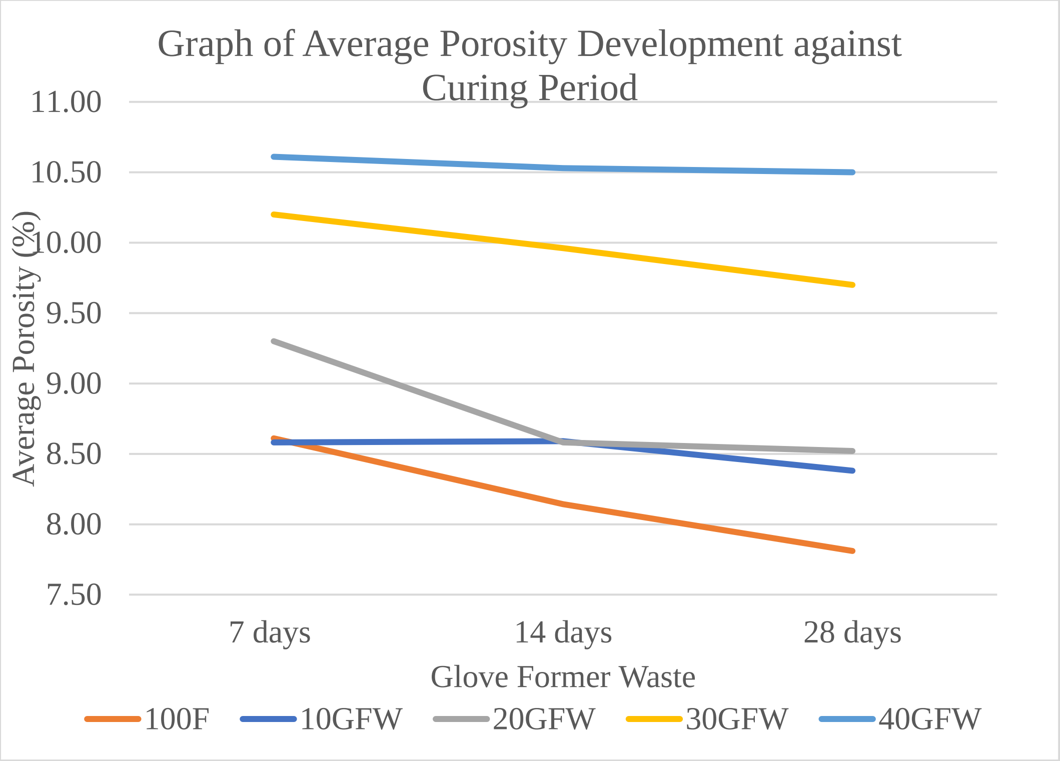


Figure 4.27: Graph of Average Porosity Trend against Curing Period for GFW.

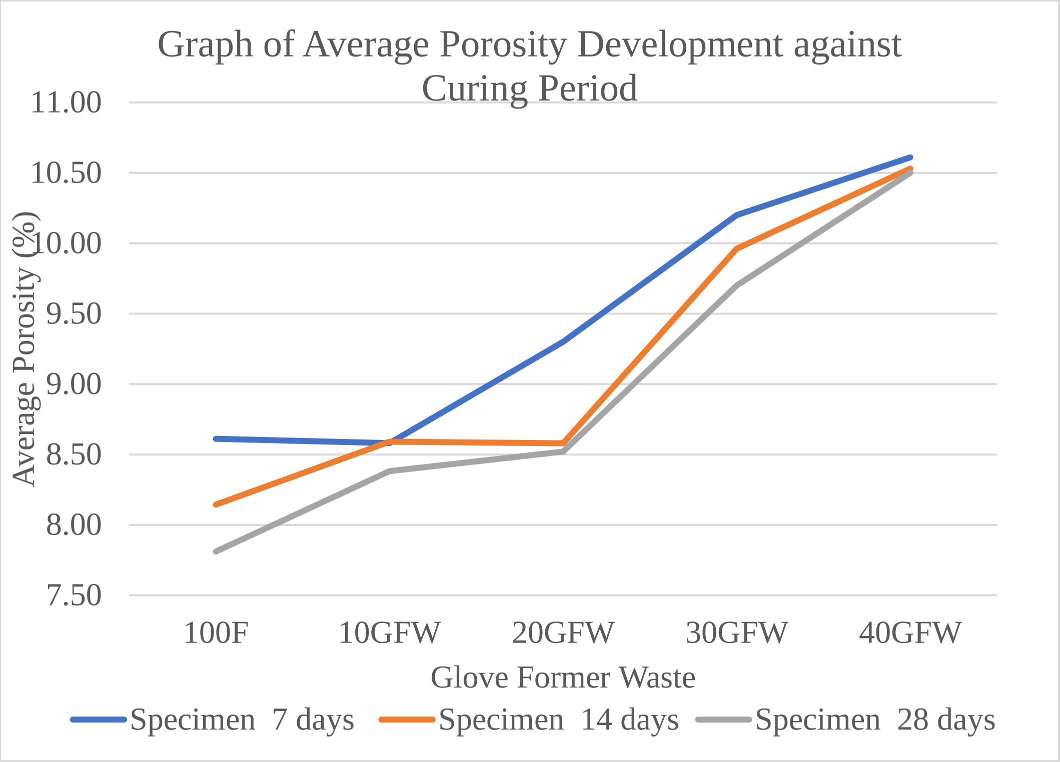


Figure 4.28: Average Porosity for GFW

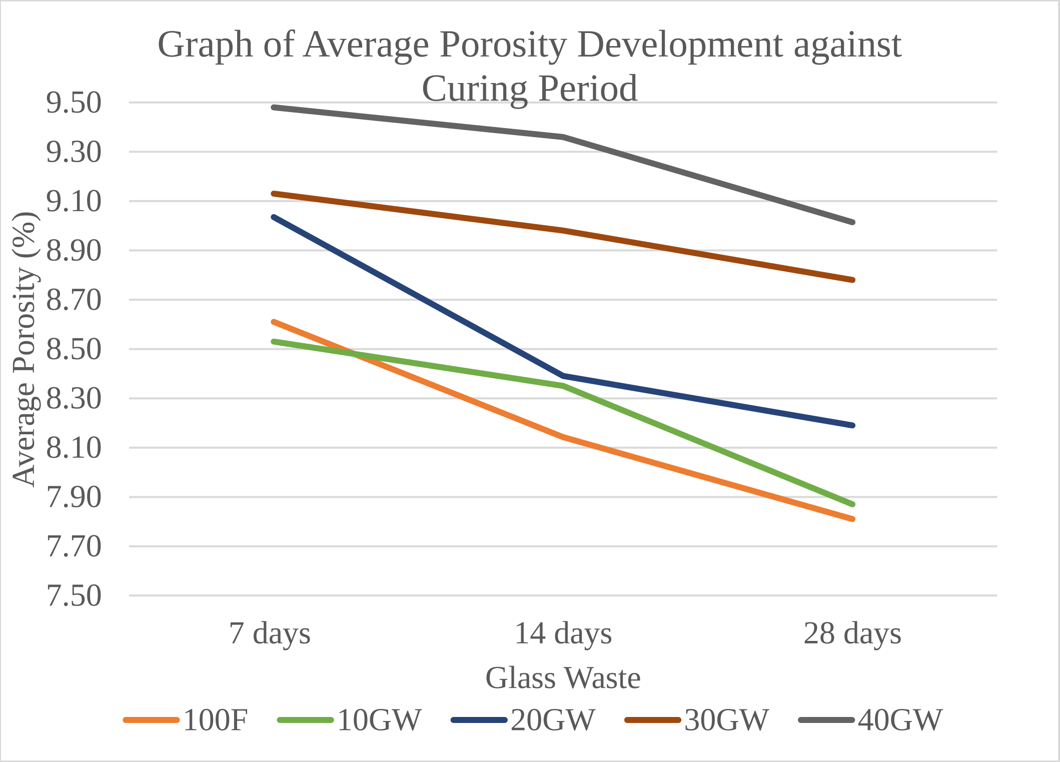


Figure 4.29: Graph of Average Porosity Trend against Curing Period for GW.

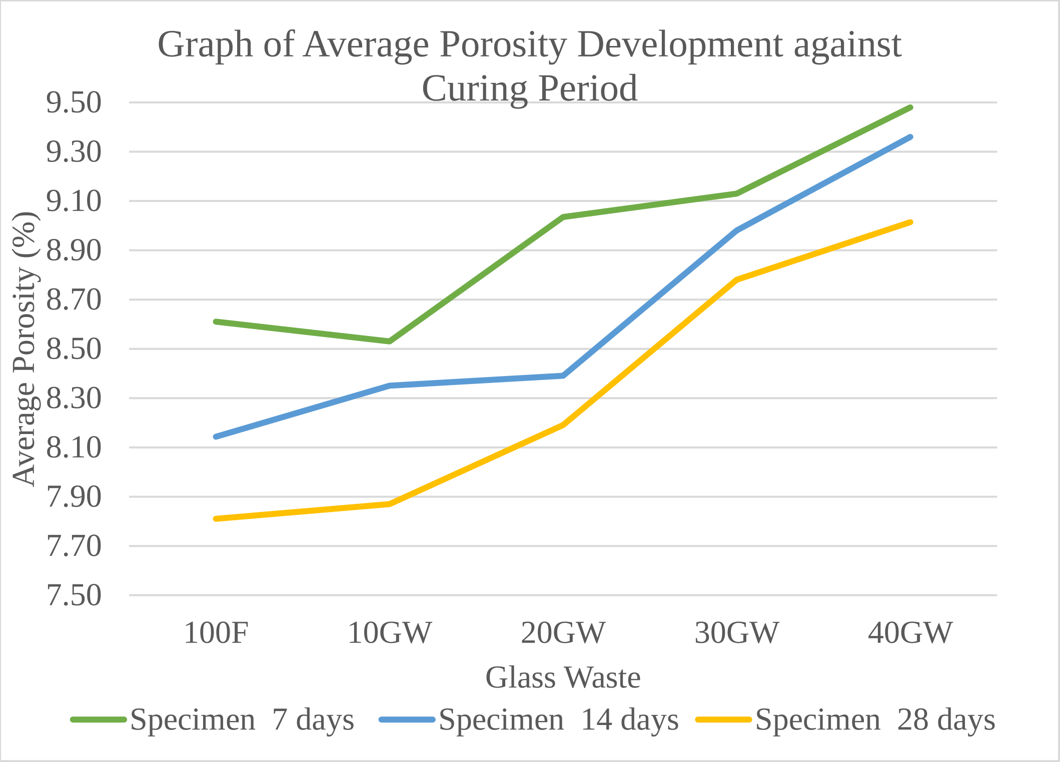


Figure 4.30: Average Porosity for GW

For water absorption rate for GFW which is shown in Figure 4.26 and Table 4.5, 100FA, 10GFW, 20GFW, 30GFW and 40GFW are having a porosity rate of 8.61, 8.58, 9.30, 10.20 and 10.61% in the 7th day testing ages and decrease to 8.14, 8.59, 8.58, 9.96 and 10.53% in the subsequent 14th day respectively. The porosity rate is then decrease to 7.81, 8.38, 8.52, 9.70 and 10.50 in 28th. day of testing day. Similarly for GW, 10GW, 20GW, 30GW, 40GW is drop from 8.53, 9.04, 9.13 and 9.48 for 7 days to 8.35, 8.39, 8.98 and 9.36 for 14 days respectively. The data obtained for 28th days is 7.87, 8.19, 8.19 and 9.01 respectively.

Both GFW and GW shows a reduction in the average porosity development over the testing age specimens of 7, 14, and 28 days. The porosity range of GFW is specifically between 8.38% and 10.61%, whereas GW has a range of 7.87% to 9.48%. Notably, there is no substantial variation observed between both groups with different percentages of waste replacement in terms of porosity. According to Mohd, Farah Farhana Zainal and Bakri (2020), the porosity is related to the water absorption rate and the compressive strength result. As the water absorption rate increases, the porosity might follow to increase due to the voids formation. Water will penetrate through the geopolymer specimen and contribute for a higher water absorption rate. Based on Figure 4.26, the overall porosity of the GFW is slightly higher than the GW. By comparing the particle size for binder particles, GFW are having a larger particle size compared to GW. According to Silva, Sagoe-Crenstil and Sirivivatnanon (2007), a larger particle size has a smaller surface area to undergoes dissolution process to form the form ($Si\ (OH)_4$) ions and ($Al\ (OH)_4^{-}$) ions which will then undergo polycondensation to form geopolymer gels. The slower reaction will affect the geopolymer matrix form and having a relatively higher porosity.

Based on Figure 4.28 and 4.30, the average porosity is increasing as more replacement of both aluminosilicate binder which is GFW and GW. If compared between fly ash and the grounded waste, the particle size is different as the fly ash is having larger average particle size than GFW and GW. From the research by Kohout et al. (2023), the smaller particle size of the aluminosilicate binder will contribute to better properties of the geopolymer paste which include lower average porosity due to a smaller pore diameter size. The synthesis of a geopolymer paste with smaller aluminosilicate binders can effectively enhance the dissolving reaction between the aluminosilicate species, leading to a reduction in the porosity structure. Therefore, any binder particles that are not dissolved act as a filler used to fill empty spaces within the structure of the geopolymer matrix. This method promotes the densification of the material, eventually improving its mechanical qualities and longevity. Therefore, denser structure will contribute to a lesser porous geopolymer paste.

Since standard requirements for ordinary cement paste or geopolymer paste do not specify porosity percentages, typical cement paste in construction has a porosity range of around 20%. Given the relationship between water absorption rate, compressive strength, and porosity, complying with compressive strength and water absorption standards implies that the mix design is acceptable. As a result, it can be stated that using 30% GFW and 30% glove former waste GFW as binder substitutes with porosity rates of 9.70% and 8.87%, respectively, remains feasible as long as the specified conditions are met with binding to the Malaysia standard.

4.5 Comparative Evaluation of Different Mix Design

Table 4.6: Comparison for Glove Former Waste Synthesised Geopolymer Paste Specimens with Standard Requirements.

Parameters	**Standard Requirement**	**Geopolymer Mix Design**				
		Fly Ash	**Glove Former Waste**			
		100FA	10GFW	20GFW	30GFW	40GFW
Compressive Strength (MPa)	13.76 - 16.56 (ASTM C 150)	79.798	83.098	73.898	68.513	39.617
Water Absorption (%)	<3% = good quality 3% - 5% = moderate quality >5% = bad quality (CEB-FIP)	2.539	2.933	2.977	3.199	3.519
Porosity (%)	No specific requirements	7.81	8.38	8.52	9.70	10.50

Table 4.7: Comparison for Glass Waste Synthesised Geopolymer Paste Specimens with Standard Requirements.

Parameters	**Standard Requirement**	**Geopolymer Mix Design**				
		Fly Ash	**Glass Waste**			
		100FA	10GW	20GW	30GW	40GW
Compressive Strength (MPa)	13.76 - 16.56 (MPa) (ASTM C 150)	79.798	76.315	74.412	73.971	62.498
Water Absorption (%)	<3% = good quality 3% - 5% = moderate quality >5% = bad quality (CEB-FIP)	2.539	2.513	2.739	2.811	2.888
Porosity (%)	No specific requirements	7.81	7.87	8.19	8.78	9.01

4.6 Economic Appraisal

Table 4.8: Cost Comparison Between One Unit Specimen of Geopolymer (50mm^3)

Composition	Price per unit (RM/g)	100FA		10GFW/GW		20GFW/ GFW		30GFW/GW		40GFW/ GFW	
		Unit (g)	Total (RM)	Unit (g)	Total (RM)	Unit (g)	Total (RM)	Unit (g)	Total (RM)	Unit (g)	Total (RM)
Fly Ash	0.00014	257	0.036	231	0.032	206	0.029	180	0.025	154	0.022
Glass Waste/ Glove Former Waste	0.00000	0	0.000	26	0.000	51	0.000	77	0.000	103	0.000
Sodium Hydroxide	0.00960	45	0.432	45	0.432	45	0.432	45	0.432	45	0.432
Sodium Silicate	0.02292	45	1.032	45	1.032	45	1.032	45	1.032	45	1.032
Overall Cost:		1.499		1.496		1.492		1.489		1.485	

4.7 Carbon Dioxide Estimation

Table 4.9: Comparison between Carbon Dioxide Emission for One Unit Specimen of OPC paste and Geopolymer Paste

Carbon Emission	OPC paste	Geopolymer Paste
Cement Powder (kg/ton)	900	0
Total Unit (kg/per one sample)	0.39375	0.257
Total CO2 Emission (kg)	0.354375	0

Above Table 4.9 shows the comparison of the overall carbon emission between OPC paste and geopolymer paste during synthesized of one unit specimen. OPC paste is estimated to release out 0.3544 kg of the CO_2 emission as one unit specimen synthesis. As geopolymer paste did not requires any cement content to synthesize, the overall carbon emission of the geopolymer will be remains as zero. It will be obvious that the geopolymer paste will produce none of the carbon dioxide to the environment. As a result, when the geopolymer paste applied into the construction sector such as the paste binder for the whole project, the difference between both pastes will be more obvious.

4.8 Sustainable Development Goals and Circular Economy

This research works contributes to the SDGs as the geopolymer is a greener substitute for cement paste. Table 4.10 below shows the SDGs which is related to the GFW and GW synthesised geopolymer paste.

Table 4.10: Sustainable Development Goals related to Industrial Waste Synthesised Geopolymer Paste

Sustainable Development Goals (SDGs)	Application
Goal 1: No Poverty	More jobs opportunity will be appeared as invention of waste utilization to synthesize the geopolymer paste in different field such as construction sector
Goal 3: Good Health and Well- Being	The utilization of the industrial waste of GW and GFW to replace fly ash to fabricate geopolymer successfully diverting the waste from the landfill which directly reduce health risk to humans from the landfill leachate.
Goal 4: Quality Education	The improvement of the education can be done as the geopolymer can be further modified to substitute more different kinds of industrial waste.
Goal 7: Affordable and Clean Energy	The utilization of the GFW and GW is more environmentally friendly compared to cement paste is more energy intensive.
Goal 9: Industry, Innovation, and Infrastructure	The optimal ratio of geopolymer paste demonstrates excellent results across compressive strength, water absorption, and porosity tests. Specifically, for 30GFW is having 68.51 MPa ,3.20% and 9.70% and 30GW is having 73.97MPa, 2.81% and 8.78% respectively.
Goal 11: Sustainable Cities and Communities	As the greener substitute geopolymer paste could provide a zero-carbon footprint to construction sector which can provide durability at the same time.
Goal 12: Responsible Consumption and Production	The implementation of the geopolymer in the construction sector could reduce the reliance the scarcity of the resources to manufacture cement powder.
Goal 13: Climate Action	Waste synthesised geopolymers significantly reduce the carbon footprint to zero when comparing to OPC

	which will contribute about 0.354kg as one paste is produced. For constructing a building, the amount of CO_2 will be prevalent which the greenhouse gases will contribute to the climate action.
Goal 17: Partnerships for the Goals	Industry, government, and communities can work well together to bring up the invention of the geopolymer paste as it could contribute towards the construction sector as it fulfilled the standard and requirements.

Based on Figure 4.30, the invention of industrial waste synthesised geopolymer paste align with the circular economy principle. As the construction sector is highly reliance on the cement paste for buildings, the process of manufacturing cement is energy consumption and brings adverse impact towards the environments. Therefore, the geopolymer is invented to replace OPC. To maximize the potential of the geopolymer paste, the industrial waste which used to replace the fly ash in this research study. Large quantities of GW produced from glass products and GFW from glove industry will be utilized to diverse the waste in landfill. To complete the circular economy for the glove and glass industry, GFW and GW will be used to synthesize the greener substitute for OPC which is the new product in the market. This waste geopolymer paste can be used in the various field mainly on the construction sector. From this new product in the market, the geopolymer will develop more business opportunities to the GW and GFW industry. This will help them in some income generation from their waste generated. To close the loop, they could use the income to invest in their industry to upgrade or expand their business as they will generate the GFW and GW.

Figure 4.30: Circular Economy for Glove and Glass Industry

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

All objectives outlined in the previous chapter have been successfully achieved. Across all mix designs (100FA, 10GFW, 20GFW, 30GFW, 40GFW, 10GW, 20GW, 30GW, and 40GW), the specimens have met the minimum requirements set by the specific standards. Through various laboratory tests categorizing mechanical performance, material characteristics, physical properties, carbon estimation, and economic appraisal, the optimum percentages of glass waste (GFW) and glove former waste (GW) substitution have been identified. Below are the findings from this research work:

1. All the geopolymer paste mix design to replace GFW and GW could maintain the compressive strength, water absorption rate and porosity rate for the geopolymer paste above the requirements and standard for OPC.
2. To maximize the potential waste substitution and align with the local authority allowable standard for waste substitution in construction buildings materials, the optimum replacement for both GFW and GW is 30%.
3. The characterisation test, which is FESEM, FTIR, XRF and sieve analysis provides support and evidence to strengthen the quantitative results in the research work by understanding the microstructure of the geopolymer. The numbers of pores, chemical composition and the particle size of the binder will affect the performance of the geopolymer.

4. Replacement of industrial waste in the geopolymer could divert the landfill and reduce carbon emissions compared to the OPC at the same time.

This study reveals that GFW and GW exhibit similar overall performance in terms of durability and mechanical properties. Although increasing substitution of GFW and GW may impact strength and performance, the results still surpass the required standards. Moreover, geopolymer outperforms OPC in all aspects, making it more competitive in the construction market. Geopolymer's sustainability to the environment aligns with the fulfilment of SDGs and contributes to a circular economy, further enhancing its appeal in construction applications.

5.2 Recommendations

After conducting this research work on geopolymer paste, there are several recommendations and improvements that could be implement in the geopolymer in the future works:

1. Delve deeper into various aspects of geopolymer paste, including environmental impacts and long-term durability, to ensure its practicality and viability in real-world applications.
2. Discover different types of waste that could be use as the substitution for geopolymer paste which provides a better strength and durability.
3. Explore the possibility of mix combination design of GW and GFW with fly ash which could provide an optimum ratio mix design.
4. Discover the possibility for GFW and GW in different aspect in contributing to construction material such as replacement sand in bricks, asphalt mix and tiles.
5. Explore the use of lower-grade alkaline activators to decrease production costs and enhance cost-effectiveness.

REFERENCES

Amran, M., Makul, N., Fediuk, R., Lee, Y.H., Vatin, N.I., Lee, Y.Y. and Mohammed, K. (2022). Global carbon recoverability experiences from the cement industry. *Case Studies in Construction Materials*, [online] 17, p.e01439. doi:https://doi.org/10.1016/j.cscm.2022.e01439.

Asante, B., Schmidt, G., Teixeira, R., Krause, A. and Savastano Junior, H. (2021). Influence of wood pretreatment and fly ash particle size on the performance of geopolymer wood composite. *European Journal of Wood and Wood Products*, 79(3), pp.597–609. doi:https://doi.org/10.1007/s00107-021-01671-9.

ASEAN Business News. (2021). *Opportunities in Malaysia's Rubber Glove Industry*. [online] Available at: https://www.aseanbriefing.com/news/opportunities-in-malaysias-rubber-glove-industry [Accessed 24 Aug. 2023].

Aziz, A., Bellil, A., El Amrani El Hassani, I.-E., Fekhaoui, M., Achab, M., Dahrouch, A. and Benzaouak, A. (2021). Geopolymers based on natural perlite and kaolinic clay from Morocco: Synthesis, characterization, properties, and applications. *Ceramics International*, 47(17), pp.24683–24692. doi:https://doi.org/10.1016/j.ceramint.2021.05.190.

Banch, T.J.H., M. Hanafiah, M., Alkarkhi, A.F.M. and Abu Amr, S.S. (2019). Statistical Evaluation of Landfill Leachate System and its Impact on Groundwater and Surface Water in Malaysia. *Sains Malaysiana*, 48(11), pp.2391–2403. doi:https://doi.org/10.17576/jsm-2019-4811-10.

Bullard, J.W., Jennings, H.M., Livingston, R.A., Nonat, A., Scherer, G.W., Schweitzer, J.S., Scrivener, K.L. and Thomas, J.J. (2011). Mechanisms of cement hydration. *Cement and Concrete Research*, [online] 41(12), pp.1208–1223. doi:https://doi.org/10.1016/j.cemconres.2010.09.011.

Burciaga-Díaz, O., M. Durón-Sifuentes, Díaz-Guillén, J.C. and Jose Ivan Escalante-Garcia (2020). Cement and Concrete Composites. *Effect of waste glass incorporation on the properties of geopolymers formulated with low purity metakaolin*, 107, pp.103492–103492. doi:https://doi.org/10.1016/j.cemconcomp.2019.103492.

civiltoday.com. (n.d.). *What is Cement? History- Chemistry- Industries - Civil Engineering*. [online] Available at: https://civiltoday.com/civil-engineering-materials/cement/81-cement-definition-and-full-details. [Accessed 24 Aug. 2023].

Concrete needs to lose its colossal carbon footprint. (2021). *Nature*, [online] 597(7878), pp.593–594. doi:https://doi.org/10.1038/d41586-021-02612-5.

Cong, P. and Cheng, Y. (2021). Advances in geopolymer materials: A comprehensive review. *Journal of Traffic and Transportation Engineering (English Edition)*, 8(3), pp.283–314. doi:https://doi.org/10.1016/j.jtte.2021.03.004.

D. Eliche-Quesada, E. Bonet-Martínez, Pérez-Villarejo, L., Castro, E. and Sánchez, P.J. (2021). Effects of an Illite Clay Substitution on Geopolymer Synthesis as an Alternative to Metakaolin. *Journal of Materials in Civil Engineering*, 33(5). doi:https://doi.org/10.1061/(asce)mt.1943-5533.0003690.

Farhana, Z.F., Kamarudin, H., Rahmat, A. and Al Bakri, A.M.M. (2014). The Relationship between Water Absorption and Porosity for Geopolymer Paste. *Materials Science Forum*, 803, pp.166–172. doi:https://doi.org/10.4028/www.scientific.net/msf.803.166.

Federico, L.M. and Chidiac, S.E. (2009). Waste glass as a supplementary cementitious material in concrete – Critical review of treatment methods. *Cement and Concrete Composites*, 31(8), pp.606–610. doi:https://doi.org/10.1016/j.cemconcomp.2009.02.001.

Ghani, L.A. (2021). Exploring the Municipal Solid Waste Management via MFA-SAA Approach in Terengganu, Malaysia. *Environmental and Sustainability Indicators*, 12, p.100144. doi:https://doi.org/10.1016/j.indic.2021.100144.

Guo, P., Meng, W., Nassif, H., Gou, H. and Bao, Y. (2020). New perspectives on recycling waste glass in manufacturing concrete for sustainable civil infrastructure.

Construction and Building Materials, 257, p.119579. doi:https://doi.org/10.1016/j.conbuildmat.2020.119579.

Hason, M.M., Al-Sulttani, A.O., Abbood, I.S. and Hanoon, A.N. (2020). Emissions Investigating of Carbon Dioxide Generated by the Iraqi Cement Industry. *IOP Conference Series: Materials Science and Engineering*, 928, p.022041. doi:https://doi.org/10.1088/1757-899x/928/2/022041.

https://newatlas.com/author/ben-coxworth (2019). *New process converts unrecyclable glass into saleable product*. [online] New Atlas. Available at: https://newatlas.com/glass-recycling-liquid-silicate/58604 [Accessed 24 Aug. 2023].

Huntzinger, D.N. and Eatmon, T.D. (2009). A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. *Journal of Cleaner Production*, [online] 17(7), pp.668–675. doi:https://doi.org/10.1016/j.jclepro.2008.04.007.

Igliński, B. and Buczkowski, R. (2017). Development of cement industry in Poland – History, current state, ecological aspects. A review. *Journal of Cleaner Production*, 141, pp.702–720. doi:https://doi.org/10.1016/j.jclepro.2016.09.139.

Jiang, X., Zhang, Y., Zhang, Y., Ma, J., Xiao, R., Guo, F., Bai, Y. and Huang, B. (2023). Influence of size effect on the properties of slag and waste glass-based geopolymer paste. *Journal of Cleaner Production*, 383, pp.135428–135428. doi:https://doi.org/10.1016/j.jclepro.2022.135428.

Kääntee, U., Zevenhoven, R., Backman, R. and Hupa, M. (2004). Cement manufacturing using alternative fuels and the advantages of process modelling. *Fuel Processing Technology*, 85(4), pp.293–301. doi:https://doi.org/10.1016/s0378-3820(03)00203-0.

Khairul Nizar Ismail, Kamarudin Hussin and Mohd Sobri Idris (2007) Physical & Chemical properties of Pulverised Fuel Ash. http://dspace.unimap.edu.my/handle/123456789/1189;jsessionid=F37138490709960E569606D775850667.

Khan, Md.N.N., Kuri, J.C. and Sarker, P.K. (2021). Effect of waste glass powder as a partial precursor in ambient cured alkali activated fly ash and fly ash-GGBFS mortars.

Journal of Building Engineering, 34, p.101934. doi:https://doi.org/10.1016/j.jobe.2020.101934.

Kohout, J., Koutník, P., Hájková, P., Kohoutová, E., Soukup, A. and Vakili, M. (2023). Effect of Aluminosilicates' Particle Size Distribution on the Microstructural and Mechanical Properties of Metakaolinite-Based Geopolymers. *Materials*, [online] 16(14), p.5008. doi:https://doi.org/10.3390/ma16145008.

La Scalia, G., Saeli, M., Adelfio, L. and Micale, R. (2021). From lab to industry: Scaling up green geopolymeric mortars manufacturing towards circular economy. *Journal of Cleaner Production*, 316, p.128164. doi:https://doi.org/10.1016/j.jclepro.2021.128164.

Lin, K.-L., Shiu, H.-S., Shie, J.-L., Cheng, T.-W. and Hwang, C.-L. (2012). Effect of composition on characteristics of thin film transistor liquid crystal display (TFT-LCD) waste glass-metakaolin-based geopolymers. *Construction and Building Materials*, 36, pp.501–507. doi:https://doi.org/10.1016/j.conbuildmat.2012.05.018.

Luhar, S., Cheng, T.-W., Nicolaides, D., Luhar, I., Panias, D. and Sakkas, K. (2019). Valorisation of glass wastes for the development of geopolymer composites – Durability, thermal and microstructural properties: A review. *Construction and Building Materials*, 222, pp.673–687. doi:https://doi.org/10.1016/j.conbuildmat.2019.06.169.

Mallum, I., Mohd.Sam, A.R., Lim, N.H.A.S. and Omolayo, N. (2021). Sustainable Utilization of Waste Glass in Concrete: a Review. *Silicon*, 14(7). doi:https://doi.org/10.1007/s12633-021-01152-x.

Marchon, D. and Flatt, R.J. (2016). Mechanisms of cement hydration. pp.129–145. doi:https://doi.org/10.1016/b978-0-08-100693-1.00008-4.

Mohd, D., Farah Farhana Zainal and Bakri, A. (2020). Effect of geopolymer paste on compressive strength, water absorption and porosity. *AIP conference proceedings*. doi:https://doi.org/10.1063/5.0023099.

Nodehi, M. and Taghvaee, V.M. (2021). Alkali-Activated Materials and Geopolymer: a Review of Common Precursors and Activators Addressing Circular Economy.

Circular Economy and Sustainability. doi:https://doi.org/10.1007/s43615-021-00029-w.

Odler, I. (1998). Hydration, Setting and Hardening of Portland Cement. *Elsevier eBooks*, pp.241–297. doi:https://doi.org/10.1016/b978-075066256-7/50018-7.

Oss, H.G. and Padovani, A.C. (2003). Cement Manufacture and the Environment Part II: Environmental Challenges and Opportunities. *Journal of Industrial Ecology*, 7(1), pp.93–126. doi:https://doi.org/10.1162/108819803766729212.

Oyebisi, S., Olutoge, F., Kathirvel, P., Oyaotuderekumor, I., Lawanson, D., Nwani, J., Ede, A. and Kaze, R. (2022). Sustainability assessment of geopolymer concrete synthesized by slag and corncob ash. *Case Studies in Construction Materials*, 17, p.e01665. doi:https://doi.org/10.1016/j.cscm.2022.e01665.

Pavement Interactive. (n.d.). *Portland Cement Compressive Strength*. [online] Available at: https://pavementinteractive.org/reference-desk/testing/cement-tests/portland-cement-compressive-strength/.

Piccolo, F., Andreola, F., Barbieri, L. and Lancellotti, I. (2021). Synthesis and Characterization of Biochar-Based Geopolymer Materials. *Applied Sciences*, [online] 11(22), p.10945. doi:https://doi.org/10.3390/app112210945.

Ruth, M. and Dell'Anno, P. (1997). An industrial ecology of the US glass industry. *Resources Policy*, [online] 23(3), pp.109–124. doi:https://doi.org/10.1016/s0301-4207(97)00020-2.

Sajedi, F. and Razak, H.A. (2011). Effects of curing regimes and cement fineness on the compressive strength of ordinary Portland cement mortars. *Construction and Building Materials*, 25(4), pp.2036–2045. doi:https://doi.org/10.1016/j.conbuildmat.2010.11.043.

Samarakoon, M.H., Ranjith, P.G. and De Silva, V.R.S. (2020). Effect of soda-lime glass powder on alkali-activated binders: Rheology, strength and microstructure characterization. *Construction and Building Materials*, 241, p.118013. doi:https://doi.org/10.1016/j.conbuildmat.2020.118013.

Shi, C., Jiménez, A.F. and Palomo, A. (2011). New cements for the 21st century: The pursuit of an alternative to Portland cement. *Cement and Concrete Research*, 41(7), pp.750–763. doi:https://doi.org/10.1016/j.cemconres.2011.03.016.

Silva, P.D., Sagoe-Crenstil, K. and Sirivivatnanon, V. (2007). Kinetics of geopolymerization: Role of Al2O3 and SiO2. *Cement and Concrete Research*, 37(4), pp.512–518. doi:https://doi.org/10.1016/j.cemconres.2007.01.003.

Singh, N.B. and Middendorf, B. (2020). Geopolymers as an alternative to Portland cement: An overview. *Construction and Building Materials*, 237, p.117455. doi:https://doi.org/10.1016/j.conbuildmat.2019.117455.

Tan, A.H. (2022). Glove Manufacturing: Opportunities and Challenges in Control Engineering. *IFAC-PapersOnLine*, 55(1), pp.872–877. doi:https://doi.org/10.1016/j.ifacol.2022.04.143.

Temple Chimuanya Odimegwu, A. B. M. A. Kaish, Jamil, M., Muhammad, Asset Turlanbekov and Al, A.W. (2023). Mechanical Characterization of Geopolymer Paste and Mortar Fabricated from Alum Sludge and Fly Ash. *Buildings*, 13(8), pp.2118–2118. doi:https://doi.org/10.3390/buildings13082118.

Tho-In, T., Sata, V., Boonserm, K. and Chindaprasirt, P. (2018). Compressive strength and microstructure analysis of geopolymer paste using waste glass powder and fly ash. *Journal of Cleaner Production*, 172, pp.2892–2898. doi:https://doi.org/10.1016/j.jclepro.2017.11.125.

Topark-Ngarm, P., Tho-In, T., Sata, V., Chindaprasirt, P. and Cao, T. (2019). Influence of Glass and Limestone Powders in High Calcium Fly Ash Geopolymer Paste on Compressive Strength and Microstructure. *Key Engineering Materials*, 801, pp.397–403. doi:https://doi.org/10.4028/www.scientific.net/kem.801.397.

Torres-Carrasco, M. and Puertas, F. (2015). Waste glass in the geopolymer preparation. Mechanical and microstructural characterisation. *Journal of Cleaner Production*, 90, pp.397–408. doi:https://doi.org/10.1016/j.jclepro.2014.11.074.

Torres-Carrasco, M. and Puertas, F. (2017). Waste glass as a precursor in alkaline activation: Chemical process and hydration products. *Construction and Building Materials*, 139, pp.342–354. doi:https://doi.org/10.1016/j.conbuildmat.2017.02.071.

United Nations (2020). *Causes and Effects of Climate Change*. [online] United Nations. Available at: https://www.un.org/en/climatechange/science/causes-effects-climate-change.

United Nations (2020). *Causes and Effects of Climate Change*. [online] United Nations. Available at: https://www.un.org/en/climatechange/science/causes-effects-climate-change.

V. Saraswathy, S. Karthick, Han Seung Lee, Kwon, S.-J. and Yang, H.-M. (2017). Comparative Study of Strength and Corrosion Resistant Properties of Plain and Blended Cement Concrete Types. 2017, pp.1–14. doi:https://doi.org/10.1155/2017/9454982.

Wang, Y., Cao, Y., Zhang, P. and Ma, Y. (2020). Effective Utilization of Waste Glass as Cementitious Powder and Construction Sand in Mortar. *Materials*, 13(3), p.707. doi: https://doi.org/10.3390/ma13030707.

Worrell, E., Price, L., Martin, N., Hendriks, C. and Meida, L.O. (2001). CARBON DIOXIDE EMISSIONS FROM THE GLOBAL CEMENT INDUSTRY. *Annual Review of Energy and the Environment*, 26(1), pp.303–329. doi:https://doi.org/10.1146/annurev.energy.26.1.303.

Zhang, T., Gao, P., Gao, P., Wei, J. and Yu, Q. (2013). Effectiveness of novel and traditional methods to incorporate industrial wastes in cementitious materials—An overview. *Resources, Conservation and Recycling*, 74, pp.134–143. doi:https://doi.org/10.1016/j.resconrec.2013.03.003.