DEVELOPMENT OF GLASS WASTE AND GLOVE FORMER-BASED GEOPOLYMERS FOR CARBON EMISSION REDUCTION

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A project report submitted in partial fulfilment of the
requirements for the award of the degree of
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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.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"DEVELOPMENT OF GLASS WASTE AND GLOVE FORMER-BASED GEOPOLYMERS FOR CARBON EMISSION REDUCTION"** was prepared by **LOO DUN XUE** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons) Civil Engineering (Environmental) at Universiti Tunku Abdul Rahman.

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Specially dedicated to
my beloved mother and father

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ABSTRACT

Exploration of geopolymers as substitutes for regular Portland cement (OPC), which emits a lot of carbon dioxide (CO_2), has been spurred by the growing need for environmentally friendly building materials. This study investigates the feasibility of utilizing glove former waste (GFW) and glass waste (GW) as aluminosilicate precursors in geopolymer production, with the aim of reducing cement dependency and mitigating environmental impacts. Three mix designs were prepared: 100% GFW, 100% GW, and a blended mix containing 50% GFW and 50% GW. The specimens were cured under ambient conditions for 7, 14, and 28 days, with an additional 24 hours of oven curing at 100 °C after 28 days to assess strength enhancement. Compressive strength tests revealed limited early-age performance (0.2–0.4 MPa), but strength improved at 28 days, with the blended mix achieving the highest value of 1.32 MPa, followed by GFW (1.10 MPa) and GW (0.95 MPa). The oven curing process further enhanced strength development, confirming the positive influence of thermal activation. Chemical and environmental analysis indicated that GFW and GW are rich in silica and alumina, making them suitable precursors for geopolymerization, while also offering a pathway to waste valorization and carbon footprint reduction. The findings suggest that GFW and GW can serve as viable alternative raw materials in geopolymer binder systems, contributing to sustainable construction practices and climate change mitigation.

Keyword: geopolymer, glass waste, glover former waste, ordinary portland cement, carbon emission

Subject area: TA401-492 Materials of engineering and construction. Mechanics of materials

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LIST OF SYMBOLS / ABBREVIATIONS

%	Percentage
ρ	Density, kg/m^3
+	Plus
$<$	Lesser than
$>$	Bigger than
×	Times
$\leq$	Lesser or equal to
°C	Degree Celsius
g	Gram
kg	Kilogram
µm	Micrometre
mm^2	Millimetre square
mm^3	Millimetre cubic
cm	Centimetre
cm^{-1}	Reciprocal centimetre or inverse centimetre
MPa	Megapascal
N	Newton
N/mm^2	Newton per millimetre square
$[Al\ (OH)_4]^-$	Aluminium hydroxide
$[Si\ (OH)_4]$	Orthosilicic acid
Al	aluminium
Al_2O_3	Aluminium oxide
AlO_2	Aluminate
ASR	Alkali-Silica Reaction
ASTM	American Society for Testing Materials
C_2S	Dicalcium silicate

C_3A	Tricalcium aluminate
C_3S	Tricalcium silicate
C_4AF	Tetracalcium aluminoferrite
Ca	Calcium
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
CH	Calcium hydroxide
Cl	Chloride
CO_2	Carbon dioxide
C-S-H	Calcium silicate hydrate
Cu	Copper
EF	Emission Factor
Fe	Iron
Fe_2O_3	Iron (III) oxide or ferric oxide
FTIR	Fourier-Transform Infrared Spectroscopy
GFW	Glove Former Waste
GHG	Greenhouse Gas Emissions
GPC	Geopolymer Concrete
GW	Glass Waste
H_2O	Water or Dihydrogen monoxide
Hg	Mercury
HT	Hot Temperature
K	Potassium
K^+	Potassium ion
K_2O	Potassium oxide
KOH	Potassium hydroxide
MARGMA	Malaysia Rubber Glove Industry Association
MgO	Magnesium oxide
N	Nitrogen
Na^+	Sodium ion
Na_2CO_3	Sodium carbonate
Na_2O	Sodium oxide
Na_2O	Sodium oxide

Na_2SiO_3	Sodium silicate
NaOH	Sodium hydroxide
NH	Ammonium
OPC	Ordinary Portland Cement
P_2O_5	Phosphorus pentoxide
PO_4	Phosphate
PPE	Proper Personal Protection Equipment
RT	Room Temperature
SDGs	United Nations Sustainable Development Goals
SEM	Scanning Electron Microscopy
Si	Silicon
SiO_2	Silica
Si-O-Al	Silicon- oxygen- Aluminium
Si-O-Si	Siloxanes or silicon- oxygen- silicon
SO_3	Sulphuric anhydride
SO_4	Sulphate
SWcorp	Solid Waste Management and Public Cleansing Corporation
TiO_2	Titanium dioxide
XRF	X-Ray Fluorescence
Zn	Zinc

CHAPTER 1

INTRODUCTION

1.1 Research Background

Concrete is a composite material made up of a variety of fine and coarse aggregate that are bound together by cement with water (H_2O) and, if required, additional admixtures like gypsum. Of these ingredients, cement is the most cost-effective binding element which maintains the structure of the other elements. It helps create long-lasting structures, and enhances the durability of a building. Cement is the foundation of modern construction, and it is indispensable in creating strong foundations and sturdy buildings and roads that enable our urban world. Its extensive use in the construction of buildings, bridges, roads, and other engineering structures demonstrates its importance for the construction industry. With well-known strength, versatility, and the ability to adhere to other substances, cement is still indispensable for maintaining the strength and durability of structures.

Cement is considered to be one of the key elements in the construction industry, the material allows for the development of bridges, roads, canals, dams, and buildings. But it has a significant impact on global carbon emissions, with over 4 billion tonnes of CO_2 being added every year. Although they are responsible for a vast majority of concrete, consisting of sand and stone that need to be sourced and processed with a low level of emissions, the greatest concern from behind the green curtain falls on cement production. Cement, a key binding agent, is manufactured by heating limestone, clay, and other materials in a kiln, a process that generates significant CO_2 emissions both from fuel consumption and chemical reactions. This makes the concrete industry responsible for approximately 8% of global carbon emissions. According to the National Ready Mixed Concrete Association, each pound of concrete releases 0.93 pounds of CO_2, highlighting the urgent need for sustainable alternatives (Ramsden, 2020).

Waste is commonly defined as any material that is unwanted, unusable, or considered to have no further value or purpose. According to *The Star*, quoting the Solid Waste Management and Public Cleansing Corporation (SWCorp), Malaysians generate approximately 39,078 tonnes of solid waste daily, which translates to around 1.17 kilograms per person (International Trade Administration, 2024). Food waste accounts for 30.6% of all trash generated, with plastic (21.9%), paper (15.3%), and disposable diapers (8.2%) following closely behind. Hazardous home garbage makes up 4.2%, while other categories like textiles (2.3%), glass (2.7%), metal (2.4%), yard debris (2.9%), and commingled waste (3.6%) also make a substantial contribution. Additionally, beverage cartons (1.7%), rubber (1.1%), wood (1.0%), and face masks (0.7%) form smaller fractions of the total waste stream. (Zainal, 2024) These figures highlight the urgent need for sustainable waste management practices and innovative reuse strategies to reduce environmental burden.

Glass waste originates from two primary sources: industrial by-products from the glass manufacturing process and post-consumer products such as bottles, jars, and other discarded glass items. According to glass manufacturer O-I, Malaysia's domestic glass market is projected to reach approximately 200,000 tonnes by 2025, equivalent to around 800 million 330ml soft drink bottles. Despite this significant volume, glass recycling rates in Malaysia remain low, at only 10%, in stark contrast to the European Union's average of 74% and the United States' average of 33%. This underlines a major gap in post-consumer waste management and recycling practices. The Asia Pacific International Spirits and Wines Alliance (Apiswa), through its report titled *"Advancing Asean's Environmental Agenda"*, emphasizes its members' commitment to sustainability and the urgent need to address post-consumption glass waste (thesun.my, 2024). Given the abundance of unused glass waste and its high silica content, there is a strong potential to repurpose this waste into geopolymer binders, contributing both to environmental sustainability and material innovation in the construction sector.

The heightened demand for gloves during the COVID-19 pandemic has contributed to the accumulation of glove former waste, highlighting a growing environmental issue within the industry. Malaysia holds a prominent position in the global rubber glove industry, supported by major manufacturers such as Top Glove, Kossan, Hartalega, and Supermax, which collectively contribute to the country's strong international market presence. From *The Straits Times*, Malaysia remained the world's leading producer of rubber gloves in 2024, holding approximately 45% of the global market share, followed by China at 28% data from the Malaysian Rubber Glove Manufacturers Association shows (Zunaira Saieed, 2025). This dominant role in the glove manufacturing industry results in a substantial amount of industrial waste, particularly from glove formers—ceramic moulds used in the production process. Glove former waste refers to discarded ceramic or aluminium moulds used in glove production. These formers often become damaged or obsolete and are commonly disposed of in landfills due to their non-biodegradable nature. However, this method of disposal poses environmental risks, including increased landfill use and potential contamination of soil and groundwater. As a result, there is a growing interest in exploring sustainable alternatives, such as repurposing glove former waste in geopolymer material development.

Geopolymers are a class of inorganic, synthetic materials formed through the chemical reaction of aluminosilicate-rich materials with alkaline solutions. Unlike traditional Portland cement, geopolymers create a hardened, stone-like structure without the need for high-temperature processing, resulting in significantly lower carbon dioxide emissions during production. The process involves dissolving silicon (Si) and aluminium (Al) from source materials like fly ash, metakaolin, or slag in an alkaline activator such as sodium hydroxide and sodium silicate. These elements then reorganize into a three-dimensional network through a process called polymerization. Geopolymers offer several advantages over conventional materials: they are environmentally friendly, possess high compressive strength, and exhibit excellent resistance to fire, chemicals, and harsh environmental conditions. Geopolymer is an environmentally friendly cementitious material that offers a sustainable alternative to traditional cement. Its development plays a key role in reducing carbon dioxide emissions associated with the conventional cement industry (Cong and Cheng, 2021).

Figure 1.1: Sustainable Development Goals (United Nations, 2015)

As a result, they are used in a variety of applications including construction (e.g., geopolymer concrete and bricks), fireproof materials, toxic waste encapsulation, historical artifact restoration, and even in high-performance components for aerospace and automotive industries. According to *National Institutes of Health (NIH)*, highlights the rapid advancement of eco-friendly construction technologies, with geopolymer concrete (GPC) emerging as a sustainable alternative to Ordinary Portland Cement (OPC). GPC reduces environmental impact by utilizing industrial by-products such as fly ash and slag, which lowers CO_2 emissions and supports waste minimization (Sbahieh, McKay and Al-Ghamdi, 2023). In addition to its enhanced strength and durability, Geopolymer Concrete (GPC) contributes directly to several United Nations Sustainable Development Goals (SDGs), as illustrated in Diagram 1. Specifically, GPC supports SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action) by offering a sustainable alternative to conventional construction materials. Life-cycle assessments confirm GPC's significantly lower carbon footprint compared to Ordinary Portland Cement (OPC), although some minor environmental concerns such as human toxicity and ecotoxicity remain. Additionally, GPC performance is influenced by factors such as silicate content, curing temperature, and the alkaline solution-to-binder ratio, positioning geopolymer technology as a key innovation for environmentally responsible and future-ready construction practices.

1.2 Problem statement

The construction industry is one of the largest contributors to global carbon emissions, primarily due to the production of ordinary Portland cement (OPC), which is responsible for around 8% of global CO_2 emissions. This high carbon output stems from both the energy-intensive manufacturing process and the chemical decomposition of raw materials like limestone. As a result, the industry plays a significant role in accelerating climate change, contributing to rising global temperatures, sea-level rise, and extreme weather patterns. Despite ongoing discussions on sustainability, the widespread use of OPC persists due to its cost-effectiveness and long-established performance, making it difficult to transition toward greener construction practices.

At the same time, Malaysia faces growing environmental challenges linked to ineffective waste management. The nation produces about 39,078 tonnes of solid waste each day, with a large quantity being glass and glove former waste that goes to landfills. Low recycling rates were attributed to glass waste (10%) and glove formers (constructed of nonbiodegradable ceramic or aluminium) which consumed valuable landfill space and presented long term environmental threats. The incorrect handling can cause soil and water pollution in the cold season, worsened by environmental degradation. Additionally, because landfills continue to grow, and rates of decay are slow, these wastes contribute indirectly to the emissions of greenhouses gases, aggravating the climate crisis further and thwarting the nation's strides towards sustainability.

Although geopolymeric technology has been proven to offer advantages, including reduced CO_2 emissions, enhanced durability, and the utilization of industrial by-products, the use of this technology is limited. This can be attributed mainly to the lack of local studies, awareness and more importantly a sustainable alternative raw material to use that is not dependent on common components such as fly ash which is not readily available or environmentally friendly.

There is thus a pressing need to look at other geopolymer systems using locally sourced waste materials like glass waste and glove former waste. It is deemed that this binder alternative, if successfully produced from the above-mentioned materials may offer solution to the current environmental problems related to waste and the industries' carbon footprint as a whole, support circular economy and Malaysian green technology agenda.

1.3 Aim and Objectives

The objective of this study is to investigate the possibility of using silica and alumina-rich glass waste and glove former waste as substitute raw materials for geopolymers. In this study, an attempt is made to develop an eco-friendly polymeric cementitious binder which can act as an alternate to Ordinary Portland Cement (OPC) and thus can help in reduction of carbon emission as well as waste management.

i. To study the chemical properties of glove former and glass waste
ii. To study the optimization of geopolymerization composition by incorporating with glove former and glass wastes.
iii. To evaluate the mechanical and durability properties of fabricated geopolymer.

CHAPTER 2

LITERATURE REVIEW

2.1 Ordinary Portland cement

The Ordinary Portland Cement (OPC) is among the most widely used and distributed cement types in the world and is the cornerstone for contemporary construction activities. It is produced by grinding Portland cement clinker with gypsum, a hydraulic material that helps control the setting time. The manufacturing process involves heating limestone and clay in a kiln to form clinker, which is then finely ground. Chemically, OPC is composed primarily of lime (CaO), silica (SiO_2), alumina (Al_2O_3), and magnesia (MgO), which are responsible for its key properties. Upon mixing with water, OPC undergoes a hydration process, where its main compounds—such as tricalcium silicate (C_3S) and dicalcium silicate (C_2S)—react with water to form calcium silicate hydrate (C-S-H) and calcium hydroxide (CH), which contribute to strength development and binding (Administrator, 2024). This process gives OPC high compressive strength, long term durability and resistance to weathering, setting quickly and hardening while retaining workability good for building large structures like multistore, Industrial / Process plants, Dams, roads and bridges. However, the large-scale usage of OPC also creates serious environmental problems, mainly because of high energy consumption and carbon dioxide (CO_2) emissions from its production. In order to overcome these drawbacks, eco-efficient alternatives and based cements are sought to reduce its environmental impact.

2.1.1 Composition and manufacturing process of Ordinary Portland Cement

Table 2.1: Compounds in Ordinary Portland Cement (OPC) (Cementplantequipment. com, 2019).

Compound / Oxide	Approximate Content	Function / Role
Lime (CaO)	Major (>60%)	Main source of calcium for cement compounds
Silica (SiO_2)	Major	Reacts to form silicates (C_3S and C_2S)
Aluminia (Al_2O_3)	Moderate	Forms C_3A, affects setting time
Iron oxide (Fe_2O_3)	Moderate	Forms C_4AF, contributes to color and early strength
Mangesia (MgO)	<5%	Minor role, can affect soundness if in excess
Sulphuric anhydride (SO_3)	<5%	Regulates setting, mostly from gypsum
Potassium oxide (K_2O)	Trace	Alkali content, affects durability in excess
Sodium oxide (Na_2O)	Trace	Alkali content, can affect long-term durability

Basic composition of Portland cement is based on four oxides, calcium oxide (CaO), silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3), which collectively form more than 95%. Besides such essential constituents, small amounts of other oxides like MgO (magnesium oxide), SO_3 (sulfur trioxide), TiO_2 (titanium dioxide), P_2O_5 (phosphorus pentoxide), K_2O (potassium oxide) and Na_2O (sodium oxide) are also found, generally comprising as a whole less than 5% by mass in total. In the production process, limestone and other raw materials undergo a high-temperature reaction in a kiln that produces these, and other, key compounds: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF). The constituents described above have the greatest impact on the physical properties and end use performance of Portland cement. Tricalcium silicate is the major initial source for early strength development, while dicalcium silicate is for later strength growth. Tricalcium aluminate is the most important component for the early setting characteristics of the cement. These reactions have an impact on the strength, setting time and durability of OPC based materials (Cementplantequipment. com, 2019).

Stages of production of cement. Cement process and production types Ordinary Portland Cement (OPC) It is necessary to transform raw materials for OPC into the final cement product. At first, the raw materials (mainly limestone, clay, shale and iron ore) are crushed and ground into a powder in powder preparation process. These ground materials are then mixed in proper proportions, in order to obtain the desired chemical composition for making clinker. The blended mixture is then fed into a rotary kiln, where it is heated to temperatures between 1400°C and 1450°C, initiating a series of chemical reactions which form clinker, a small hard marble-sized nodules. The hot clinker is cooled and transferred to the grinding mill, depending on the amount of mixing air the clinker cooling may take place in the mill itself. Incorporating gypsum is important because it controls the setting time of the finished cement. In some cases, additional materials such as fly ash or slag are added, either regrinding or during grinding, to change the properties of the cement. Finally, the resultant OPC product is packed and preserved for delivery. According to the process utilized in the preparation of the raw material before being feed to the kiln, the production of OPC can be classified as either wet, dry or semi-dry process. Raw materials in the wet process are mixed with water to create a slurry, whereas in the dry process, the materials are crushed, ground and processed into powder. The semi-dry process involves forming nodules from the dry ground materials before they are fed into the kiln. Each method has its own energy consumption characteristics and influences the efficiency of the cement production (Encyclopedia Britannica, n.d.). A visual overview of this process is illustrated in Figure 2.1. This figure illustrates the key stages involved in OPC production, from raw material extraction and clinker formation to final grinding, storage, and shipping.

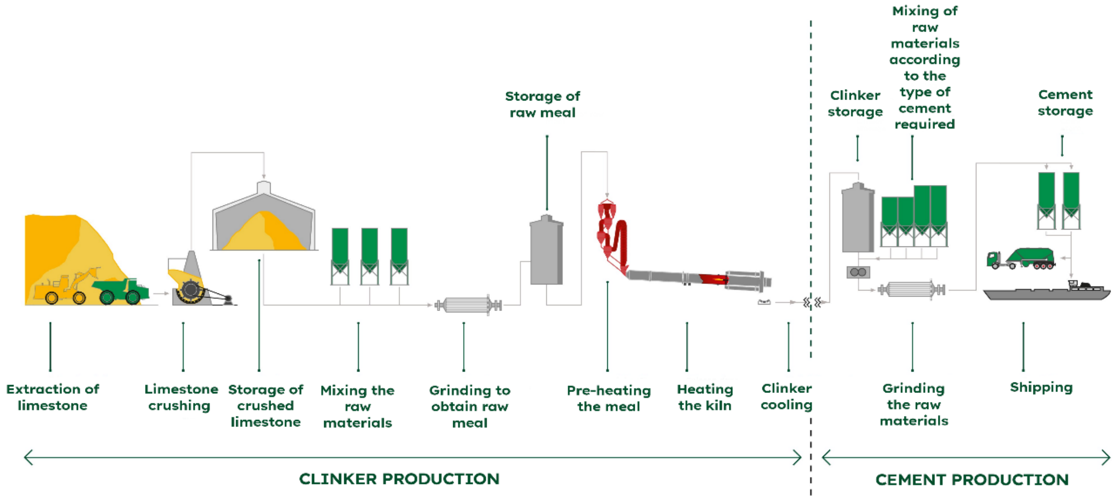


Figure 2.1: Clinker and cement production (Heidelberg Materials, 2024).

2.1.2 Limitation of Ordinary Portland Cement (OPC)

Ordinary Portland Cement (OPC) is the most commonly used construction material worldwide, with broad applications across residential, commercial, and industrial infrastructure. Ordinary Portland Cement (OPC) has long been the dominant binder in the construction industry, but its widespread use poses significant environmental, technical, and durability challenges.

However, despite its engineering advantages, OPC production poses significant environmental challenges. Globally, cement manufacturing contributes approximately 4–8% of total carbon dioxide (CO_2) emissions. For instance, India, the second largest cement producer in the world, contributes to almost 7–8% of the global cement production, having an annual capacity of 234 million tonnes (IEA, 2023). Under these projections, by 2050 cement industry would emit 835 million tonnes of CO_2 in India—over five times their current levels. On average, 1 kg of cement production releases 0.95 kg of CO_2, from which, 0.55 kg is usually attributed to the chemical process of cement production, and 0.40 kg is attributed to fuel combustion in kilns (Yadav et al., 2020). These figures emphasize the necessity of greener solutions to reduce environmental consciousness caused by traditional cement usage.

Aside from its environmental effect, OPC as major constituent of concrete has several technical and marginal drawbacks. On one hand, the production of cement is extremely energy intensive because of the very high kiln temperatures (about 1400–1450°C) needed in the process, which results in an extremely high consumption of fossil fuel and substantial emissions of greenhouse gases (IEA, 2023). In addition, OPC can shrink and crack during curing. These cracks can affect the durability and long-term integrity of concrete members, in some occasions requiring the use of reinforcement or expansion joint systems to avoid damage (Siddika et al., 2021). A further drawback is the slow setting of the material which can lengthen the timescale of construction and in turn the project delivery, particularly for time critical applications.

Furthermore, OPC has poor resistance to corrosive environments. It is susceptible to sulfate attack and other chemical deteriorations especially at an early stage and therefore unsuitable in applications which necessitate high chemical durability unless protective treatments or alternative binders are used (Anon, 2023). The abovementioned limitations clarify the necessity of using more sustainable and durable solutions for the building sector, among which geopolymer-based materials may be included.

2.2 Glass Waste

What was regarded as worthless glass waste until recently, is now an important source material for environmental and material recycling. It has high transparency, inherent strength and low permeability to gases. These properties, in addition to being long-lasting, have made waste glass a potential candidate for reuse in construction materials such as geopolymers.

Commercial glass is primarily divided into soda–lime–silica glass and specialty glass, with the majority of production focusing on soda–lime–silica types. These glasses are typically made from silicon dioxide (SiO_2), calcium carbonate ($CaCO_3$), and sodium carbonate (Na_2CO_3). To lower silica's high melting point (~1700°C), soda ash is added as a flux, reducing the temperature significantly but increasing solubility. Lime is then added to improve durability and water resistance. The typical composition for soda–lime glass is approximately 75% silica, 15% soda, and 10% lime. In addition to the basic components, other oxides like magnesium oxide (MgO), aluminium oxide (Al_2O_3), selenium, and cobalt oxide are also used to improve colour, formability, and refining. Despite efforts to use low-iron sand, impurities can cause an unwanted green tint, which can be neutralized using these additives to produce clear or "white" glass (The Editors of Encyclopedia Britannica, 2019). Table 2.2 shows the chemical composition of glass waste.

Table 2.2: The chemical composition of glass waste (Bekerė and Malaiškienė, 2025).

Chemical Formula	Typical % Composition	Function
SiO_2	60–75%	Main glass former; provides strength and durability
Na_2O (from Na_2CO_3)	12–15%	Acts as a flux to lower melting point

CaO (from $CaCO_3$)	5–12%	Improves chemical durability and water resistance
MgO	3–5%	Enhances chemical resistance and thermal stability
Al_2O_3	1–3%	Increases durability and chemical resistance
Fe_2O_3	<0.2%	Naturally present; affects color

2.2.1 Limitation of glass waste

Despite its potential as a sustainable supplementary material in cementitious and geopolymer binders, the use of glass waste presents several limitations that restrict its large-scale application.

The wide range in quality and chemical makeup of recycled glass, which is frequently obtained from industrial or mixed post-consumer streams, is a major cause for worry. The reactivity and performance of geopolymer systems can be greatly impacted by variations in silica content, impurities, and particle size distribution, leading to uneven mechanical and durability properties (Maaty, Ghazy, and Eldmarny, 2025). Especially in large-scale production, this heterogeneity makes quality control and mix design optimization more difficult.

Another challenge is the low inherent reactivity of glass waste in its untreated form. Glass waste would need fine grinding, or enhancing processes to attain sufficient pozzolanic activity, which are contributed toward the extra energy and money consumption (Siddika et al., 2021). This partially cancels the environmental, economic and social benefits that it would be possible to address by using recycled glass as a precursor of a binder. An alkali-silica reaction (ASR) is also an important limitation. When glass serves as the fine aggregate or binder precursor, high-alkali conditions, such as in a geopolymer system, may induce ASR when ASR leads to expansive gel formation and subsequent cracking (Eu et al., 2024). It remains challenging to get the optimum composition, even if partial glass powder replacement or the inclusion of other materials may decrease the risk of ASR.

Moreover, the smooth non-porous morphology of glass particles leads to a weaker interlocking with the cementitious matrix, reducing the mechanical interlock and thus, the strength of the composite may decrease (Eu et al., 2024). This problem becomes more pronounced at higher glass replacement ratios with certain degrees of degradation in mechanical behavior.

Lastly, the collection, segregation, and processing of glass waste present logistical and economic barriers. Specialized facilities are often required to process glass into a fine, reactive powder suitable for geopolymer applications. Combined with contamination from organics, ceramics, and metals, this raises production costs and limits its commercial viability (Siddika et al., 2021).

2.3 Glove Former Waste

Malaysia is one of the world's largest producers and exporters of rubber and nitrile gloves, accounting for over 60% of global glove supply (MARGMA | Malaysia Rubber Glove Industry Association, 2025). Glove formers, which are hand-shaped moulds usually made of ceramic or aluminium, are used in the glove production process. These moulds are repeatedly dipped into solutions of natural rubber or synthetic latex. Glove formers are regularly replaced as they chip, crack, or lose surface quality due to ongoing industrial use, which results in significant amounts of industrial waste annually. Large amounts of industrial waste are produced when glove formers are replaced on a regular basis. As Malaysia's glove manufacturing grew, especially during and after the COVID-19 pandemic, the majority of these broken or damaged formers were dumped in landfills, raising environmental concerns (MARGMA | Malaysia Rubber Glove Industry Association, 2025).

Ceramic glove formers are composed primarily of alumina (Al_2O_3), which provides high-temperature resistance and mechanical strength, and silica (SiO_2), which enhances durability and contributes to the glassy matrix of the ceramic structure. Other materials such as kaolin and feldspar are often incorporated to improve workability, thermal performance, and surface finish (Fu and Lee, 2024). While aluminium glove formers are lighter and easier to handle, they are less common and present recycling difficulties due to coatings and surface contamination. Both ceramic and aluminium glove formers are chemically stable and non-biodegradable, which makes them suitable for glove manufacturing but poses significant waste management challenges.

The potential of using glove former waste in the building industry has been investigated recently, especially as a raw material for geopolymer composites and sustainable cementitious. Ceramic glove former waste can also be used as a precursor material in alkali-activated binders or as a substitute for cement as it is rich in aluminosilicate and becomes pozzolanic upon finely crushing it (Amin Al-Fakih et al., 2023). As per international sustainability objectives, the use of ceramic waste materials in geopolymer systems not only reduces the dependence on natural raw materials, but also reduces CO_2 emissions when compared to ordinary Portland cement (OPC).

Previous studies conducted on ceramic industrial waste indicated that it could be used as an effective material for improving the microstructural density, durability, and mechanical properties of concrete, thereby improving product value in construction work.

By utilizing the waste glove former to develop geopolymer binder, it will assist the glove making industry towards a circular economy as end-of-life glove former disposal is converted to value-added construction materials. This approach has a low surface area, which is the greatest challenge for sorption experiments, since it would significantly limit the number of active sites. This work extends this idea by exploring GFWs as one of the major precursors in the development of geopolymers and, as a result, fills a huge gap in the literature and proves that it is possible use this waste for the design of sustainable material in substitution to traditional cementitious ones.

The glove manufacturing industry in Malaysia is also in a position to support the circular economy concept by value-adding industrial waste to a high-value building material through recycling the glove former waste as geopolymer binders. This approach is a feasible reply to sustainable material development as it reduces the environmental impact, waste disposal, and optimal utilization of resources. Building on such a concept, this work aspires to explore glove former waste as an essential precursor in geopolymers production to fill a gap in knowledge and demonstrate it as a replacement candidate for conventional cementitious materials.

2.3.1 Limitation of glove former waste

Environmental concern regarding glove former waste is the fact that it is intractable and difficult to be degraded which are non-biodegradable along with the type of fillers in which are used during a manufacturing process. Ceramic and aluminium glove formers are created to be long-lasting and heat-resistant, so that they could not naturally degrade. They take decades to decompose in landfills, adding to the accumulation from industrial waste, and long-term land pollution that they cause.

The environmental impact of glove former disposal is also significant. At the outset, the manufacturing of these formers entails a high temperature firing or energy-consuming casting, leading to a significant share of greenhouse gas (GHG) emissions. Typically, replaceable as they no longer hold the glove together cleanly, glove formers are disposed of when old or worn through (once removed from the glove they are un-biodegradable and thus do not breakdown in landfills). The final carbon footprint involves the extraction (or harvest) of raw materials, the manufacturing, transportation, use, and disposal of the resource, and contributes to environmental destruction at every step. Furthermore, their waste leads to industrial solid waste pollution, as waste ceramic is bulky and difficult to handle in terms of recycling, while the aluminum modes need re-processing at high energy cost to recover materials. If managed irresponsibly, this waste stream contributes to environmental problems since it adds to landfill loads, energy use, and emissions and demonstrates the necessity to investigate alternative recycling routes including recycling of these products into construction materials in order to reduce waste and implement the circular economy (Preserve Earth, 2025). Furthermore, the increase in volume of glove former waste is a waste of potential of valuable raw materials of alumina and silica, which are required for various industrial uses.

Another significant limitation is the lack of well-established recycling or reusing process of glove former waste. The production concern is the main focus of glove industry, while little focus is on waste valorization and environmentally friendly waste management methods. Since there is no established guideline for recycling of glove formers, people throw away glove formers as industrial waste without recycling, wasting valuable expensive raw materials and increasing the burden on dumping sites. It is these constraints that bring the desperate going a call for new ideas to recycle glove formers. Studying other applications, such as converting waste aluminum or ceramic to a building material, provides an effective route to reducing dependence on ladles and promoting more environmentally-friendly industrial processes. These problems can be challenged by circular economy projects, through which glove waste could be converted from environmental harm to a valuable resource.

2.4 Overview of Geopolymer

Geopolymer as an environmentally friendly binder presents an alternative to Ordinary Portland Cement (OPC). While OPC is burned at very high temperature and is a substantial emitter of global CO_2, geopolymers consists of aluminosilicate-rich materials in a low-energy reaction with an alkali activator. These raw materials--often industrial (by-)products such as fly ash, slag, (waste) glass, and (waste) ceramic like glove former waste--contain a high Si content and Al. Geopolymers are produced in geopolymerization from the aluminosilicate materials which are dissolved in the alkali-activator solution at RT or HT, and this reacts to yield a amorphous phase and 3D silicoaluminate network structure. The Si and Al containing compounds were decomposed by the alkaline activator solution (the mixture of NaOH and Na_2SiO_3), and then reacted and reassembled into a compact gel-like matrix (Cong and Cheng, 2021).

The production and use of geopolymer materials offer significant environmental and engineering benefits. Most importantly, geopolymer manufacture involves much lower CO_2 emissions than Ordinary Portland Cement (OPC), thereby contributing to the reduction of global greenhouse gas emissions. The use of geopolymer technology is growing and is recognized as a major driver for sustainable construction and will be in keeping with global trends toward green buildings. In addition, geopolymers can incorporate and recycle industrial by-products such as fly ash and glass waste, reducing the need for landfill disposal and mitigating related environmental problems (Provis and S.J, 2014). Beyond environmental protection, geopolymers exhibit high compressive strength, excellent chemical resistance, fire resistance, and durability in harsh environments (Duxson et al., 2005). These properties make geopolymer concrete an ideal choice for infrastructure exposed to marine, industrial, or acidic conditions.

2.4.1 Geopolymerization

Geopolymerization is the chemical process responsible for converting aluminosilicate materials into stable, cement-like binders through a series of reactions in an alkaline environment. These binders are formed by dissolving raw materials containing silica (Si) and alumina (Al) in a solution of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), either at Alkali-activated materials are cementitious materials formed by a series of reactions with an alkaline medium and aluminosilicates due to the geopolymerization which is the chemical process occurring when aluminosilicate raw materials are converted into a stable cement. The binders are produced by dissolving raw materials, which contain silica (Si) and alumina (Al), in a sodium hydroxide (NaOH)-sodium silicate (Na_2SiO_3) solution at room temperature or at higher temperatures. This reaction results form a precipitation of an amorphous phase and a 3D silico aluminate network which provides the mechanical strength and durability of geopolymers.

The process of geopolymerization is generally divided into three main stages (Cong and Cheng, 2021):

1. **Aluminosilicate source was dissolved into the alkaline solution** and then reactive silicate and aluminate were leached.
2. **Gelation and condensation**, where the dissolved species undergo polycondensation reactions to form a gel-like geopolymer network.
3. **Polymerization and hardening**, where the gel transforms into a solid, interconnected matrix with long-term stability.

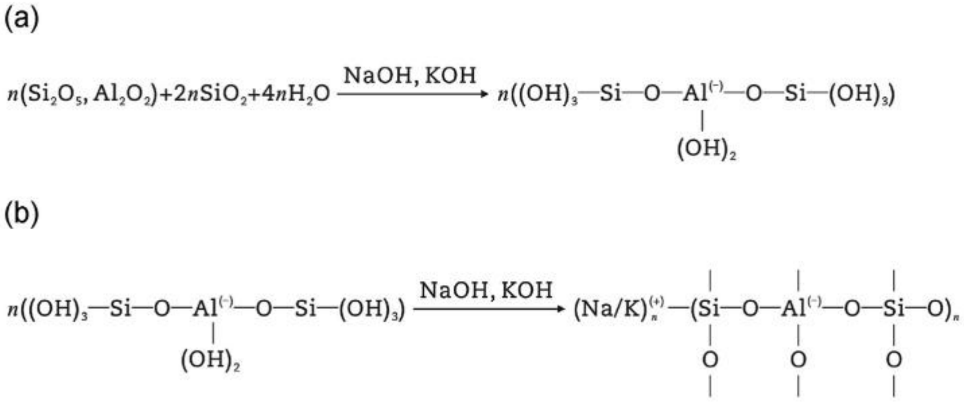
(a) Geopolymer Precursor

As shown in equation 2.1(a), the geopolymer precursor is formed when aluminosilicate materials (e.g., $Si_2O_5 \cdot AlO_2$) react with an alkaline solution of NaOH or KOH. This reaction breaks the existing Si-O-Si and Si-O-Al bonds in the raw materials and leads to the formation of reactive species such as $[Si(OH)_4]$ and $[Al(OH)_4]^-$. These species undergo initial condensation to form linear or branched oligomeric units like

$(OH)_3$–Si–O–Al $(OH)_2$–O–Si $(OH)_3$, which represent the early-stage molecular structure of the geopolymer precursor.

(b) Geopolymer Backbone

In the next stage, shown in equation 2.1(b), further reaction and condensation of the precursor units result in a highly crosslinked three-dimensional geopolymer backbone. This backbone consists of repeating units of silicate and aluminate tetrahedra (Si–O–Al–O–Si), stabilized by cations such as Na^+ or K^+. The presence of alkali cations balances the negative charge introduced by Al in the tetrahedral framework. This final structure gives geopolymers their characteristic durability, chemical resistance, and mechanical strength.



(a)

$$n(Si_2O_5, Al_2O_2) + 2nSiO_2 + 4nH_2O \xrightarrow{NaOH,\ KOH} n((OH)_3—Si—O—\underset{(OH)_2}{\underset{|}{Al^{(-)}}}—O—Si—(OH)_3)$$

(b)

$$n((OH)_3—Si—O—\underset{(OH)_2}{\underset{|}{Al^{(-)}}}—O—Si—(OH)_3) \xrightarrow{NaOH,\ KOH} (Na/K)^{(+)}_n—(\underset{\underset{|}{O}}{\underset{|}{\overset{|}{Si}}}—O—\underset{\underset{|}{O}}{\underset{|}{\overset{|}{Al^{(-)}}}}—O—\underset{\underset{|}{O}}{\underset{|}{\overset{|}{Si}}}—O)_n$$

Equation 2.1: (a) Geopolymer precursor. (b) Geopolymer backbone (Cong and Cheng, 2021).

2.5 Benefits of Geopolymers over OPC

Geopolymers offer significant environmental advantages over Ordinary Portland Cement (OPC), particularly in terms of carbon emissions. The production of OPC is one of the largest contributors to global CO_2 emissions, accounting for around approximately 4–10% due to limestone calcination and the high energy requirements of clinker production (Madirisha, Dada and Ikotun, 2024). In comparison, geopolymer synthesis uses aluminosilicate-rich materials and avoids high-temperature kilns, resulting in a much lower carbon footprint (Davidovits, 2015). This makes geopolymer technology a more sustainable option for reducing greenhouse gas emissions in the construction sector.

Another significant environmental advantage is the fact that geopolymers can use industrial waste. Precursors, like fly ash, ground granulated blast furnace slag (GGBFS), waste glass, and glove former waste, have the potential to put huge amounts of waste out of landfills (Singh and Middendorf, 2020). It is a circular economy concept as it valorises industrial byproducts into high quality construction materials, decreasing the environmental footprint and the consumption of sometimes-scarce virgin raw materials.

Besides low emission, waste and being waste recycled, geopolymer concrete manufacturing process is also more energy-efficient than OPC. During conventional cement production temperatures over 1400°C are necessary for clinker production, while geopolymers can be produced at room or at slightly increased curing temperatures (Singh and Middendorf, 2020). This not only reduces energy usage, but it also renders geopolymer a cost-effective alternative in the long run.

As far as performance is concerned, geopolymer concrete presents better mechanical and durability characteristics than OPC concrete. It is demonstrated to have the higher compressive, tensile, and flexural strength and the higher modulus of elasticity for its dense and even structure. Its performance characteristics are further enhanced on its resistance to acid attack, sea water and high temperature making it compatible to extreme conditions (Ijraset. com, 2024). The strength capacities of steel

RC beams with geopolymer concrete under bending, shear and torsion are satisfactory and will be durable in use. Although there are difficulties in standardizing the sources of materials and also to obtain proportion of mix of materials, but the geopolymer as a new material is an effective substitute for the OPC due to its ecofriendly nature, excellent mechanical properties and long-term durability (Adnan and Anas, 2025).

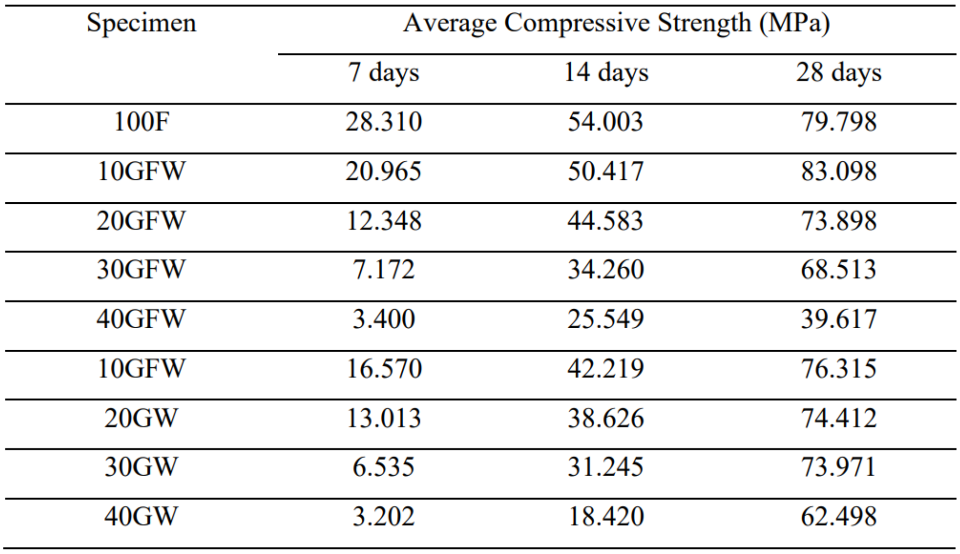
2.6 Studies on Waste-Based Geopolymers

The study on waste-based geopolymers has received considerable attention recently due to the demand from industry for new sustainable building materials, in replacement of Ordinary Portland Cement (OPC). Numerous studies have utilized waste glass as primary aluminosilicate precursor due to its high silica content. When it is ground finely, the waste glass has pozzolanic activity which will result in densification of the matrix and Distillery spent wash geopolymerization reaction. Using some of that waste as a partial substitute for fly ash in the production of concrete can thus not only significantly improve early strength development and the resulting longevity of concrete, but also has sustainable benefit by keeping discarded glass out of our landfills. According to the studies. This demonstrates that high performance geopolymer binders could be made with waste glass.

Apart from glass waste, different industrial by-products including ceramic waste, slag, and glove former waste, have been investigated as raw materials for geopolymer production. For example, the addition of silica- and alumina-rich ceramic waste, when ground into fine powders, has been reported to increase the chemical stability and the mechanical strength of the geopolymer precursor paste (Awoyera et al., 2018). Glove former waste, which is a byproduct of the glove making industry, also has reactive oxides capable of producing geopolymer. It has been proven that adding these industrial wastes leads to improve the sustainability in the material, and reduces in the production costs, which makes geopolymer technology more affordable and environmentally friendly.

Comparing between the OPC-based concrete and the geopolymer-based concrete in all previous comparative studies, there is always strength and durability superiorities in favor of the geopolymer in some extent. Geopolymers exhibit enhanced chemical resistance, particularly against acid and sulfate attacks, and maintain strength at elevated temperatures. Their dense microstructure contributes to reduced permeability and improved long-term durability. These properties position geopolymers as a promising alternative to traditional cement, especially in harsh or aggressive environments where conventional concrete may deteriorate more rapidly. Despite these advances, research gaps remain, particularly regarding large-scale implementation and the optimization of mix designs using multiple waste streams. Variability in the chemical composition of industrial by-products poses challenges in achieving consistent performance, and there is a need for further studies on durability, shrinkage, and long-term behavior under field conditions.

Table 2.3: Result of geopolymer average compressive strength (Kelvin, 2024).



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

**** Note: the original “40 GFW” label was a typographical error and has been corrected to “10 GW” to reflect the proper series of glass-waste specimens.**

Furthermore, table 2.3 investigated the development of geopolymer specimens incorporating glove former waste (GFW) and glass waste (GW) as partial replacements for fly ash to promote sustainable construction. The compressive strength results showed that the control mix (100% fly ash) achieved 79.80 MPa at 28 days, establishing a strong reference benchmark. Introducing 10% GFW slightly improved strength to

83.10 MPa, suggesting enhanced reactivity at lower substitution levels. However, increasing GFW content from 20% to 40% led to a significant reduction in strength, with the 40% mix dropping to 39.62 MPa. A similar trend was observed with GW substitution, where mixes containing 10–30% GW maintained compressive strengths between 73.97 and 76.32 MPa, but the 40% GW mix decreased to 62.50 MPa. These findings emphasize that low levels of GFW and GW (≤10%) can maintain or improve performance, while excessive replacement compromises matrix cohesion due to the dilution of reactive aluminosilicates. This highlights the importance of optimizing industrial waste proportions for sustainable yet structurally sound geopolymer formulations (Kelvin, 2024).

While compressive strength provides a clear measure of load-bearing capacity, geopolymer performance depends on a wider range of physical, chemical and mechanical properties. Past studies have shown that particle size distribution, specific surface area and density influence the dissolution of aluminosilicates and the formation of binding gels (Duxson et al., 2007). Chemical analysis through X-ray fluorescence (XRF) and Fourier-transform infrared (FTIR) spectroscopy typically reveals the formation of N-A-S-H and C-A-S-H gels, which are responsible for long-term durability and chemical resistance (Provis, Palomo and Shi, 2015). Microstructural observations using scanning electron microscopy (SEM) often show a denser matrix and reduced porosity at lower substitution levels, correlating with the higher strengths measured in this study.

Compared with the earlier work of Kelvin (2024), the present results display a broadly similar trend of strength gain with small additions of GFW or GW, but some differences in magnitude can be attributed to variations in precursor fineness, activator concentration and curing conditions. These observations confirm that while compressive strength remains the primary structural benchmark, comprehensive product evaluation should also encompass microstructural density, gel chemistry, and durability characteristics to fully demonstrate the environmental and engineering advantages of waste-based geopolymer

Table 2.4: Past Relevant Research on Different Types of Binder for Geopolymer

Binder Type	Percentage of Substitution (%)	Age (curing)	Particle size used for the binder	Compressive Strength (MPa)	References
Waste glass powder (WGP) + Fly Ash (FA)	WGP: 10 – 40%	7-days	< 80 µm	34-48 (in 20%)	(Tho-In et al., 2018)
Ground Granulated Blast Furnace Slag (GGBFS) + Corncob Ash (CCA)	(CCA): 0-100%	28-days	< 45 µm	30-40 (in 20-40%)	(Oyebisi et al., 2022)
FA +GGBFS	GGBFS:10-50%	28-days	-	63.5 (in 50%)	(Sitarz, Hager and Choińska, 2020)
Alum Sludge (AS) + FA	AS: 0-100%	28-days	-	Improve 80% (in 50%)	(Temple Chimuanya Odimegwu et al., 2023)
FA + Metakaolin (MK)	MK: 30%	28-days	-	63 (in 30%)	(Barbhuiya and Pang, 2022)

The table 2.4 shows the relevant past research that utilizing different type of waste materials as binders in geopolymer production, highlighting their substitution levels, curing ages, particle sizes, and compressive strength outcomes. Across the listed studies, physical characteristics such as particle fineness emerge as a key factor in reactivity: for instance, waste glass powder blended with fly ash achieved 34–48 MPa at seven days when particles were below 80 µm (Tho-In et al. 2018), while ground granulated blast furnace slag combined with corncob ash reached 30–40 MPa at 28 days with particles finer than 45 µm (Oyebisi et al. 2022). Mechanical performance is consistently high, with compressive strengths ranging from 30 MPa to over 63 MPa; the fly-ash/slag mixture reported by Sitarz et al. (2020) achieved 63.5 MPa at 50 % slag, and Temple et al. (2023) observed an 80 % strength improvement when incorporating 50 % alum sludge.

Chemically, X-ray fluorescence and FTIR analyses in these and related studies confirm the formation of sodium-alumina-silicate-hydrate (N-A-S-H) and calcium-alumina-silicate-hydrate (C-A-S-H) gels, which provide the dense microstructure, low permeability and superior acid, sulfate and chloride resistance that distinguish geopolymers from ordinary Portland cement. Taken together with additional reports on red mud, palm oil fuel ash and ceramic waste (He and Zhang, 2011), the evidence clearly shows that a wide variety of industrial by-products can be transformed into high-performance, low-carbon binders, underscoring the environmental and engineering significance of waste-based geopolymer technology.

2.7 SGDs and Circular Economy for geopolymer

The integration of Sustainable Development Goals (SDGs) and circular economy principles plays a crucial role in shaping the future of the construction industry. SDG 12 (Responsible Consumption and Production) is directly supported by the circular economy, which places an emphasis on reducing waste, increasing resource efficiency, and encouraging material reuse and recycling. By using industrial by-products like glass waste, glove forming waste, and other recycled materials in building materials, the construction industry may drastically lessen its environmental impact by embracing a circular strategy (Kinga Korniejenko et al., 2025). This promotes innovation in resource use and waste management and is consistent with global sustainability initiatives.

Geopolymer technology embodies these principles by transforming industrial wastes into high-value construction products, reducing the demand for virgin raw materials. In promoting technological innovations and sustainable industrial practices, this advances SDG 9 (Industry, Innovation, and Infrastructure). Furthermore, compared to ordinary Portland cement, geopolymers take less energy to create, which lowers carbon emissions and advances SDG 13 (Climate Action). Geopolymer research shows the door to climate-resilient building methods by reducing greenhouse gas emissions related to cement production (Korniejenko et al., 2025).

The implementation of circular economy models in construction also enhances social and economic sustainability, aligning with SDG 11 (Sustainable Cities and Communities). By diverting waste from landfills and repurposing it into eco-friendly building materials, urban development projects can achieve greater resource efficiency while improving environmental quality (Korniejenko et al., 2025). This approach not only reduces landfill pressure but also fosters green job creation and encourages innovation in material processing technologies.

Overall, linking SDGs with circular economy practices highlights the potential of geopolymer technology as a transformative solution for sustainable development. Geopolymers offer a practical means of accomplishing several SDG goals by incorporating energy efficiency, pollution reduction, and the recycling of industrial waste into building procedures. Driving the global shift toward a more sustainable and circular construction sector requires ongoing study and application in this area and the Figure 2.2 concludes with the circular economy of geopolymers, highlighting a sustainable lifecycle. This reduces waste overall and promotes environmental sustainability by establishing a closed-loop system in which industrial waste is valorised to clean wastewater and the resulting byproducts are then sustainably managed.

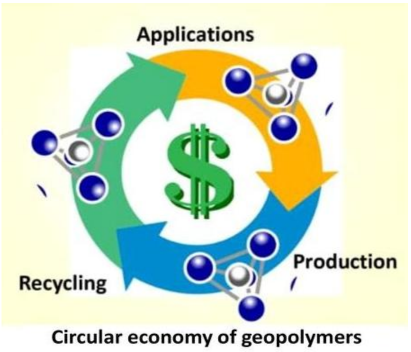


Figure 2.2: Circular Economy of Geopolymer Paste (Elgarahy et al., 2023)

Figure 2.3: Sustainable Development Goals (SDGs) 9, 11, and 12 (United Nations, 2015)

Figure 2.4: Sustainable Development Goals (SDGs) 13 (United Nations, 2015)

2.8 Climate change and the importance of CO_2 reduction

The quality of life, growth, and development of all living beings are closely linked to the natural environment. However, human-driven activities such as urbanization, industrialization, agriculture, and the use of fossil fuels have significantly contributed to climate change. These processes increase greenhouse gas emissions, particularly carbon dioxide (CO_2), which in turn accelerates global warming and alters key environmental components such as air, water, and soil.

The consequences of climate change are evident in rising global temperatures, extreme weather patterns, biodiversity loss, and the degradation of ecosystems. Industrial emissions and untreated waste disposal further compound these issues by polluting air and water sources, while rapid population growth without corresponding increases in green cover reduces the natural capacity of ecosystems to absorb pollutants. Plants, which act as natural purifiers, are essential in maintaining ecological balance, yet deforestation and land-use changes continue to limit their role in mitigating CO_2 levels (Kabir et al., 2023).

Achieving net-zero CO_2 emissions and limiting global warming to 1.5°C, compared to 2°C, offers significant benefits by reducing the frequency and severity of extreme weather events, lowering sea level rise impacts, and protecting ecosystems, human health, and livelihoods. Warmer conditions beyond 1.5°C would intensify heatwaves, heavy rainfall, and droughts, while a 0.1 m lower sea level rise by 2100 could spare up to 10 million people from coastal risks. Limiting warming also cuts the probability of tipping points like ice sheet collapse, reduces land and ocean ecosystem degradation, and lessens risks to coral reefs, fisheries, and water resources. Furthermore, achieving net-zero improves air quality, reduces pollution-related diseases, and promotes healthier lifestyles through sustainable practices such as active transport and dietary changes. It also decreases the severity of droughts and floods, safeguarding water, food security, and community resilience worldwide (Hartley and Turnock, 2021).

As cement production alone contributes 7–8% of global carbon emissions, the building industry is essential to lowering CO_2 emissions in light of these issues (IEA, 2023). In addition to using industrial by-products like glass waste and glove forming waste, the use of alternative binders like geopolymers offers a viable answer because it greatly lessens dependency on energy-intensive Ordinary Portland Cement (OPC).

Therefore, tackling climate change, reducing CO_2 emissions, and promoting long-term environmental resilience all depend on the move toward sustainable materials.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter outlines the methodology employed throughout the study. It describes the equipment and materials used, the methodical processes for creating geopolymer from glass and glove former waste, and the laboratory experiments carried out to evaluate its characteristics and functionality. As precursor materials for the geopolymerization process, the study investigates varying ratios of glass and glove former waste. A number of experimental tests were conducted in order to identify the optimal mix ratios.

The methodology adopted in this study is summarized in Figure 3.1, which illustrates the sequential process followed throughout the experimental work. The first step is material preparation, where the main binders are glass and glove former waste.

An alkaline activator made of sodium hydroxide and sodium silicate solution is added to them. The intended binder to-activator ratio is then taken into consideration while creating the mix design. After being cast into 50 mm³ cube moulds, the new geopolymer paste is then demoulded. Every sample is allowed to cure in the open air for 7, 14, 28 days with an additional 24 hours of oven curing at 100 °C applied after 28 days for selected samples. The resulting geopolymer specimens are next subjected to a battery of laboratory tests to assess their mechanical and physical characteristics.

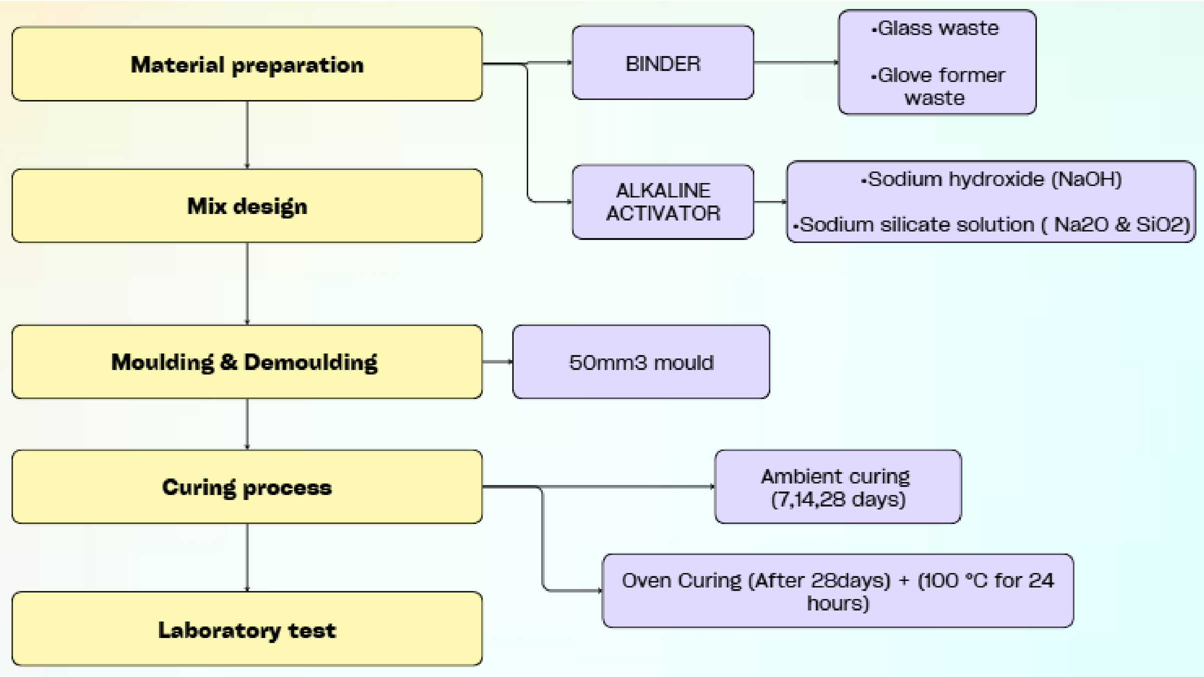


Figure 3.1: Research Methodology flow chart

3.2 Material Preparation

3.2.1 Sodium Hydroxide

Sodium hydroxide functions as one of the alkaline activators in the geopolymer synthesis process. It is an essential component in starting the chemical reactions that create the geopolymer matrix. The proper personal protection equipment (PPE), such as gloves, safety goggles, and a lab coat, must be used during handling because of its extremely caustic and corrosive nature. As seen in Figure 3.2, sodium hydroxide pellets under the R&M Chemical brand were utilized in this investigation. The sodium hydroxide solution was made by dissolving the pellets in distilled water. Using a stirring rod and an electromagnetic stirrer to guarantee thorough mixing, the dissolving procedure was conducted in a beaker. The sodium hydroxide's chemical makeup is shown in Table 3.1.

Analytical-grade sodium hydroxide pellets (≥98 % purity) were used to prepare a 12 M alkaline solution. The required mass of NaOH was calculated using:

$$Mass\ (g) = 12\ molL^{-1} \times 40.0\ gmol^{-1} \times Desired\ Volume\ (L) \tag{3.1}$$

The pellets were slowly added, in small portions, to approximately 70 % of the final volume of distilled water contained in a high-density polyethylene (HDPE) beaker while continuously stirring with a Teflon-coated rod. The addition was performed inside a fume hood while wearing chemical-resistant gloves, goggles, and a lab coat because the dissolution of NaOH is strongly exothermic. The solution was allowed to cool to ambient temperature (≈28 °C) and then topped up with distilled water to the final required volume to achieve the exact 12 M concentration. The prepared solution was stored in a sealed HDPE container for a minimum of 24 hours prior to mixing to ensure complete dissolution and thermal equilibrium.

Figure 3.2: Sodium Hydroxide from R&M Chemical Brand

Table 3.1: Chemical Composition of Sodium Hydroxide

Specification	Percentage (%)
Assay (alkalimetric titration)	99.0
Aluminium (Al)	0.005
Ammonium (NH)	0.001
Carbonate (Na_2CO_3)	1.0
Chloride (Cl)	0.005
Calcium (Ca)	0.002
Phosphate (PO_4)	0.001
Heavy metal (as Pb)	0.0001
Iron (Fe)	0.001
Silicate (SiO_2)	0.001
Sulphate (SO_4)	0.002
Total Nitrogen (N)	0.0005

Copper (Cu)	0.0005
Mercury (Hg)	0.0001
Potassium (K)	0.1
Zinc (Zn)	0.0025

3.2.2 Sodium Silicate Solution

Sodium silicate solution, commonly referred to as “water glass,” is an essential component in the production of geopolymer materials. By providing silicate ions, which are essential for the geopolymerization process, it acts as one of the alkaline activators. To provide the best possible reaction efficiency and material performance, sodium silicate must be measured precisely. As it is an alkaline substance, appropriate personal protective equipment (PPE), such as gloves, must be worn when handling it. In this research, the sodium silicate solution used was sourced from R&M Chemical Brand, as illustrated in Figure 3.3. The chemical composition of the sodium silicate solution is summarized in Table 3.2.

For the alkaline activator, the pre-cooled 12 M sodium hydroxide solution was measured separately and slowly poured into the sodium silicate solution at a 1: 1 mass ratio (as established in the mix design). The combined solution was stirred continuously for approximately 2–3 minutes with a Teflon-coated stirrer to obtain a clear, uniform activator. Because the reaction between NaOH and Na_2SiO_3 is mildly exothermic, the blended activator was left to equilibrate at room temperature (≈28 °C) for about 10 minutes before being added to the dry binder.

Figure 3.3: Sodium Silicate used from R&M Chemical

Table 3.2: Chemical Composition of Sodium Silicate Solution

Specification	Contains
SiO_2	**34.5%-36.5%**
Na_2O	**16.5%-17.5%**

3.2.3 Glass waste

In this research, glass waste is utilized as a key material, contributing to the aluminosilicate composition essential for its aluminium and silicon content. The glass waste used in this study was primarily sourced from green glass bottles, including soft drink, wine, and liquor bottles, with a significant proportion collected from beer bottles. Prior to processing, each bottle was thoroughly cleaned both internally and externally to remove stains and contaminants (Figure 3.4).

As illustrated in Figure 3.4, the cleaned glass was initially broken into smaller pieces using a hammer with wear the safety goggles and safety glover. The resulting fragments were then ground using a grinder to produce fine glass powder. To achieve uniform particle size, the powder was sieved through a No. 128 sieve with the aid of a sieve shaker. This systematic preparation process ensured that the glass waste was properly processed and refined for use in geopolymer fabrication.

Figure 3.4: Glass bottle waste

3.2.4 Glove Former Waste

In this study, glove former waste is also incorporated as a key material, contributing to the aluminosilicate composition essential for its aluminium and silicon content. Similar to glass waste, glove former waste plays a vital role in the experimental work. The glove former waste, supplied by Kitaran Recovery Sdn. Bhd., was already processed and ground into a fine powder upon receipt. As shown in Figure 3.5, this powder was further refined through a regrinding process to achieve greater uniformity. To ensure consistency in particle size, the glove former waste was subsequently sieved using a No. 128 sieve with the aid of a sieve shaker. This refinement process guarantees a uniform particle size distribution, making the material suitable for integration into the geopolymer formulation.

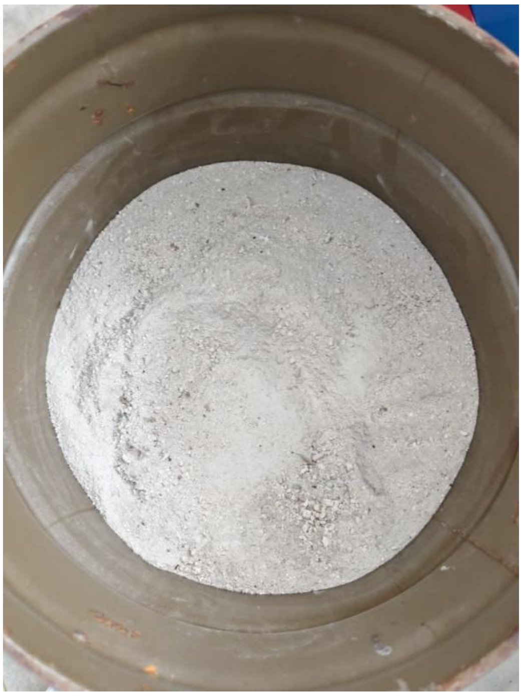


Figure 3.5: Glove former waste

3.3 Mix design

Based on findings from past studies relevant to this research, three geopolymer mix designs were developed using varying proportions of glove former waste and glass waste as the primary binder materials. These mix designs include: (1) 100% glove former waste, (2) 100% glass waste, and (3) a 50:50 blend of glove former and glass waste. These alternative binder compositions were compared against standard Ordinary Portland Cement (OPC) mortar in terms of performance and sustainability. The quantities of aluminosilicate source materials and alkaline activators used in each mix are detailed in Table 3.3. In all mix designs, the binder-to-alkaline activator ratio was fixed at **0.38**, while the ratio of sodium hydroxide to sodium silicate was maintained at **1:1**, with **12 moles** of sodium hydroxide used consistently.

Although there is no single universal standard for geopolymer proportioning, these values are supported by both previous optimisation studies and accepted research practice. Specifically, Kelvin (2024) conducted a parametric study on glove-former/glass-based geopolymers and identified this combination as giving the highest early- and 28-day compressive strength while maintaining workable consistency (Kelvin, 2024). The selected ratios also lie within commonly reported ranges in the literature—binder/activator ratios of 0.30–0.45 and NaOH molarities of 8–14 M are frequently used in fly-ash and waste-glass geopolymers (e.g., Davidovits 2008; ASTM C618 guidance on pozzolanic materials) (Kalombe et al., 2020).

By adopting Kelvin's optimised parameters, this research ensured comparability with earlier work on the same raw materials and avoided unnecessary re-optimisation while remaining consistent with published best-practice ranges.

To prepare the alkaline activator, sodium hydroxide solution (figure 3.6) and sodium silicate solution were mixed thoroughly using a mechanical stirrer. Separately, the glove former waste and glass waste powders were dry-mixed according to the desired binder ratio. Once the powders were uniformly blended, the alkaline activator solution was gradually added while maintaining continuous mixing. This process ensured a homogenous geopolymer mortar suitable for subsequent casting and testing.

Table 3.3: Mix design of the geopolymer

Mix design code	**Mass(g)**			
	Binder		Alkaline Activator	
	Glass waste	Glove former Waste	Sodium hydroxide	Sodium silicate
100GW	842	0	160	160
100GFW	0	842	160	160
(50+50) GW/GFW	421	421	160	160

Figure 3.6: Preparation of 12M Sodium hydroxide solution

3.4 Moulding & Demoulding

Two types of moulds were used for casting the geopolymer specimens: cube moulds (50 mm × 50 mm × 50 mm) and cylindrical moulds (50 mm height × 50 mm diameter). Prior to casting, all moulds were thoroughly cleaned to ensure they were free from dust, debris, and residues. A thin layer of release agent (such as oil) was applied to the inner surfaces of the moulds to facilitate easy demoulding later. The freshly prepared geopolymer mortar was then carefully poured into the moulds, ensuring that they were completely filled without causing overflow. As shown in Figure 3.7, compaction was carried out to eliminate trapped air and achieve uniform density throughout the specimen. The surface was levelled using a flat board to ensure a smooth finish.

After sufficient curing time, and once the specimens had gained adequate strength, the demoulding process was carried out. The moulds were gently inverted, and compressed air (using a demould air gun) was applied to assist in smoothly releasing the samples without causing damage.

Figure 3.7: Moulding Process for Geopolymer

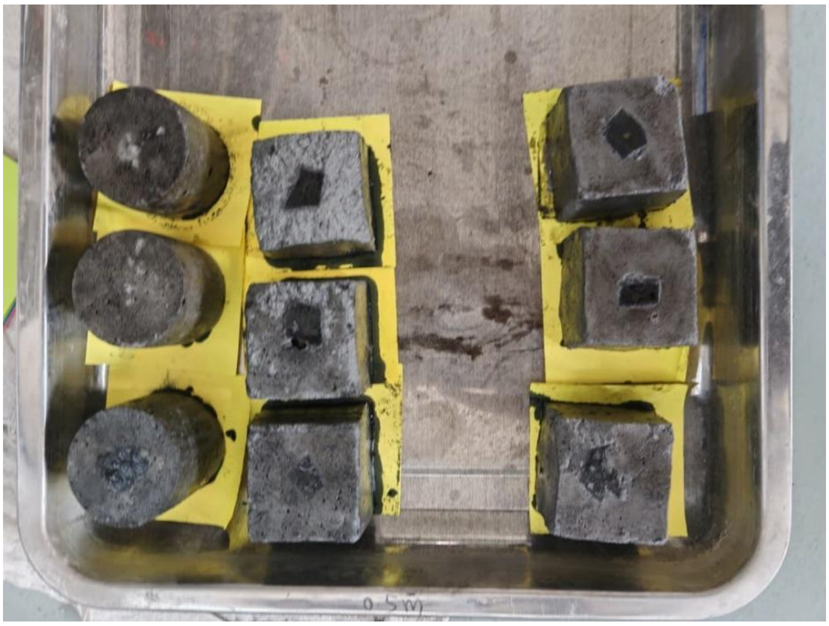


Figure 3.8: Demoulding Process for Geopolymer

3.5 Curing process

In this research, ambient curing was adopted as the curing method for all geopolymer specimens. After casting, the samples were wrapped with plastic sheets to minimize moisture loss and left to cure under room conditions. Ambient curing allows the geopolymerization process to proceed under controlled temperature without external heating, enabling the development of strength and desirable physical properties.

Curing durations of 7, 14 and 28 days were selected to match the standard strength-testing ages specified for Ordinary Portland Cement (OPC) concretes (e.g., ASTM C150), where 7 days represents early-age strength, 14 days captures the main hydration period, and 28 days provides the industry benchmark for design strength. Using these intervals enables direct comparison with OPC performance while also monitoring the progression of geopolymerization over time.

The specimens were left to rest overnight to initiate early strength gain and subsequently stored in a controlled environment maintained at 28 °C. Curing durations were set at 7, 14, and 28 days, aligning with standard testing intervals. Each specimen was clearly labelled with its respective mix designation to ensure proper identification throughout the curing and testing phases. For compressive strength evaluation at 28 days, two curing conditions were adopted: (i) specimens tested directly after 28 days of ambient curing, and (ii) specimens subjected to an additional 24 hours of oven curing at 100 °C following the 28-day ambient curing period.

3.6 Laboratory Tests

Based on figure 3.9, a comprehensive testing program was conducted, encompassing material characterization and physical property evaluation. The material analysis included Sieve Analysis for particle size distribution, alongside advanced techniques such as X-ray Fluorescence (XRF) for chemical composition, Scanning Electron Microscopy (SEM) for microstructural imaging, and Fourier-transform infrared spectroscopy (FTIR) for chemical bonding identification. Physical property assessment featured Compressive Strength testing to determine load-bearing capacity, supplemented by Porosity Test to quantify void spaces and Water Absorption Test to evaluate hygroscopic behaviour. This multi-faceted approach ensures thorough understanding of both compositional and mechanical attributes of the material.

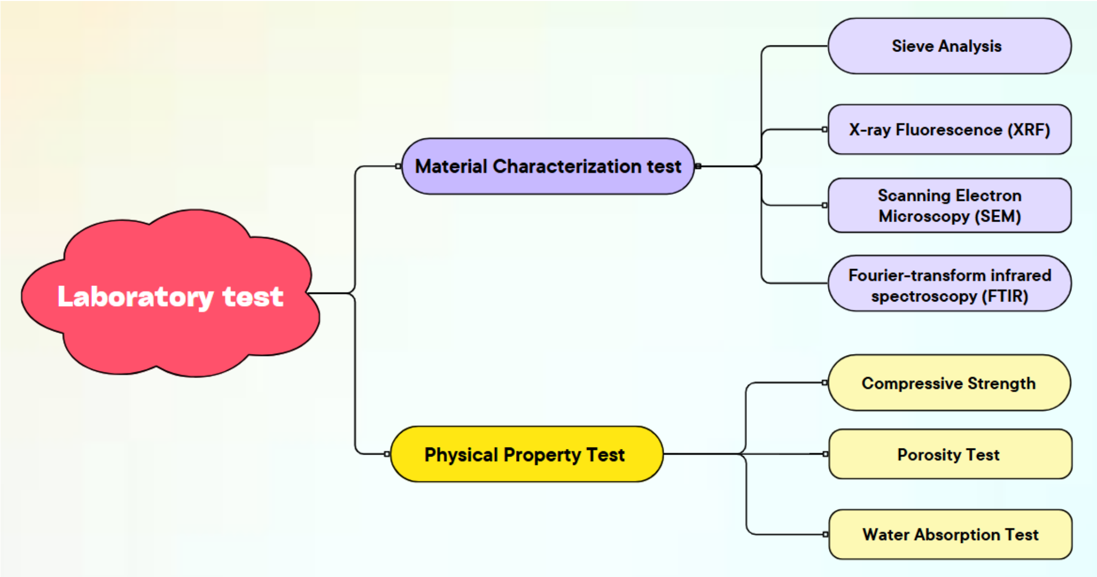


Figure 3.9: Laboratory Test

3.6.1 Sieve Analysis

Sieve Analysis was performed to assess the particle size distribution of the binder powder, comprising glass waste and glove former waste after grinding. The test utilized a series of sieves with mesh sizes of 0.3, 0.25, 0.125, 0.106, 0.09 and 0.063µm, arranged in descending order from top to bottom. The stacked sieves were secured in a sieve shaker and agitated for 15 minutes (as shown in Figure 3.10). Following sieving, the retained powder on each sieve was carefully weighed using an electronic balance to determine the particle size distribution.

Figure 3.10: Sieve Analysis

3.6.2 X ray Fluorescence (XRF)

X-ray Fluorescence (XRF) was employed to analyze the chemical composition of the geopolymer, providing critical insights for quality assurance, research validation, and formulation optimization. For this test, geopolymer samples were prepared and sent to an external specialized facility. During XRF analysis, the material was exposed to X-rays, generating characteristic fluorescence energy spectra. These spectra were then evaluated to identify and quantify the elemental constituents of the geopolymer, ensuring precise compositional determination.

3.6.3 Scanning Electron Microscopy Test (SEM)

In the geopolymer Scanning Electron Microscopy (SEM) test, the material's microstructure and surface morphology are examined. After the geopolymer sample is ready, it is put on a specimen holder and lightly covered with conductive material. After that, the coated sample is placed inside the scanning electron microscopy chamber, where its surface is scanned by an electron beam. High-resolution images that provide precise details on the material's surface properties, particle sizes, and distribution are formed by collecting the signals produced by the electron beam's interactions with the sample. SEM analysis provides crucial information about the material's overall composition and its performance possibilities by assisting in the understanding of its texture, porosity, and microstructure.

3.6.4 Fourier-transform infrared spectroscopy (FTIR) analysis

Fourier Transform Infrared (FTIR) spectroscopy was utilized to characterize the geopolymers by capturing high-resolution spectral data across a broad range, revealing their infrared absorption and emission profiles. This technique identifies key functional groups—such as Si-O, Al-O, hydroxyl (-OH), and amine (-NH) bonds—enabling detailed analysis of the geopolymer's molecular structure. In this study, Attenuated Total Reflectance (ATR)-FTIR spectroscopy was employed due to its versatility in analyzing both solid and liquid samples.

Figure 3.11: Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) spectroscopy.

3.6.5 Compressive Strength

Compressive strength testing evaluates a geopolymer specimen's ability to withstand axial loading. In this study, three specimens aged 7, 14, and 28 days were subjected to controlled compression using a universal testing machine (Figure 3.15). To ensure uniform load distribution, metal plates were placed beneath each specimen. The compressive strength was calculated by dividing the maximum failure load by the specimen's cross-sectional area, requiring precise dimensional measurements prior to testing. This test provides critical insights into the material's structural integrity and load-bearing capacity, with results quantified using Equation 3.2 (compressive strength formula).

$$P = \frac{F}{A} \tag{3.2}$$

Where,

P = Compressive Strength, N/mm^2

F = Maximum load applied on specimen, N

A = Specimen surface area, mm^2

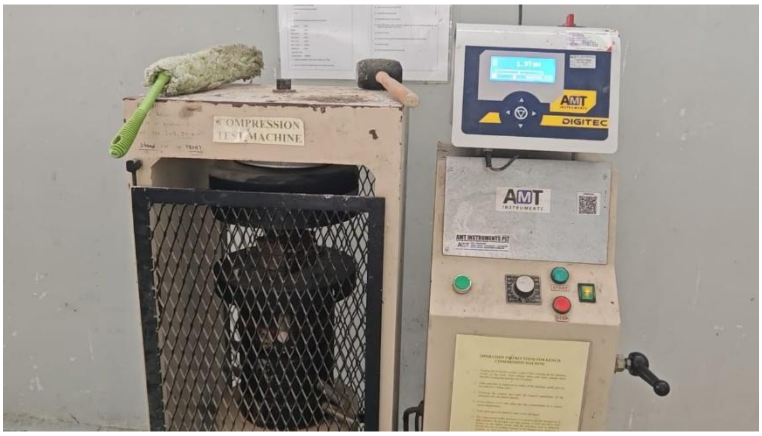


Figure 3.12: Compressive Test Machine

3.6.6 Porosity Test

Porosity testing was performed to quantify void content in geopolymer specimens, which directly influences material durability and strength, with higher porosity adversely affecting long-term performance. Three specimens (aged 7, 14, and 28 days) were oven-dried for 24 hours, then vacuum-saturated in a desiccator with water maintained 1 cm above sample height. The process involved an initial 15-minute evacuation, 3-hour water immersion, a second 15-minute evacuation, and final 24-hour submersion. After saturation, specimens were surface-dried and weighed in both immersed and suspended states to calculate porosity using Equation 3.3, providing critical data on the geopolymer's void structure and quality.

$$n = \frac{w_w - w_d}{w_w - w_s} \times 1000 \tag{3.3}$$

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 3.13: Vacuuming Machine

3.6.7 Water Absorption Test

The water absorption test quantifies a geopolymer's capacity to absorb water when fully submerged, directly reflecting its porosity and water retention properties. Fully cured specimens were initially weighed (w_0) using a digital scale, then completely immersed in distilled water for 24 hours. After immersion, specimens were surface-dried with absorbent material to remove excess water and reweighed (w_1) to determine mass gain. This measured difference between w_1 and w_0 provides critical data on the material's hydrophilic behavior and pore structure integrity.

$$M = \frac{w_1 - w_0}{w_0} \times 100 \tag{3.4}$$

Where,

M = Percentage of water absorption, %

w_0 = Weight of dry specimen, g

w_1 = Weight of saturated specimen, g

3.7 Carbon Dioxide Estimation

The carbon footprint of the created geopolymer mixtures will be assessed in order to determine their environmental sustainability. The objective of this analysis is to measure the greenhouse gas (GHG) emissions related to the processing of the raw materials, the creation of the mix, and the curing phases of the geopolymer samples. In order to highlight possible benefits for carbon reduction, the main goal is to compare the carbon emissions of the production of geopolymers with those of conventional systems based on Ordinary Portland Cement (OPC). According to *Global strategies and potentials to curb CO_2 emissions in cement industry,* one ton of cement requires 900 kg of CO_2 to produce, the cement industry has long been one of the biggest producers of CO_2 emissions (Benhelal et al., 2013).

Where,

Emission Factor (EF):

- Glass waste (GW): 0.16 kg CO_2 / kg, (Climatiq.io, 2020)
- Glove former waste (GFW): 0.25 kg CO_2 / kg, (Carbonfact.com, 2025)
- NaOH (12M solution): 1.12 kg CO_2 / kg, (Carboncloud.com, 2025)
- Sodium Silicate solution: 0.68 kg CO_2 / kg, (Neupane, 2022)

Mix design (per batch = 1.162 kg total):

- 50%Mix: 421 g GW + 421 g GFW + 160 g NaOH (12M) + 160 g sodium silicate
- 100% GFW: 842 g GFW + 160 g NaOH + 160 g sodium silicate
- 100% GW: 842 g GW + 160 g NaOH + 160 g sodium silicate

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The chapter will examine and outline several types of laboratory tests related to physical and material characterization qualities. Sieve analysis, FESEM, XRD, FTIR, compressive strength, porosity, and water absorption tests can all be used to accomplish this test.

4.2 Material characterization

4.2.1 Sieve Analysis

The particle size distribution of the raw precursor materials is a fundamental physical characteristic that critically influences the geopolymerization process. To create baseline data, this part examines the fineness of the glass and glove former waste. In order to ascertain the binder's overall particle size distribution, sieve analysis is performed in Table 4.1.

Table 4.1: Percentage Finer for the glove former waste and glass waste in different sieve size.

Sieve size (mm)	Percentage Finer %	
	Glover former waste	Glass waste

0.3	100.00	100.00
0.25	93.45	97.23
0.125	74.32	87.67
0.106	52.31	66.75
0.09	39.03	50.31
0.063	25.31	35.44
Pan	0.00	0.00

Based on Table 4.1, the overall particle sizes of the glove former waste and glass waste vary between 300 μm and 63 μm. Particle retaining at the 0.25 mm mesh size is minimal for both materials. The dominant particle size range for glove former waste is 0.125 mm - 0.090 mm, while for glass waste, it is slightly finer, within the range of 0.125 mm - 0.106 mm.

This is quantitatively supported by the percentage of mass passing through the finest sieve (0.063 mm), which is 25.31% for the glove former waste and significantly higher, at 35.44%, for the glass waste. This conclusively demonstrates that the glass waste possesses a greater degree of fineness overall.

Finer particles have larger specific surface area and dissolve faster in alkaline activator, producing more reactive Si or Al species for geopolymer gel formation. That tends to shorten setting times and increase early-age strength. Coarser particles dissolve slower; they may act partially as inert filler or require longer curing to react.

4.2.2 X-ray Fluorescence (XRF)

X-Ray Fluorescence (XRF) analysis was conducted to determine the elemental oxide composition of the glove former waste and glass waste. This is crucial because the availability of essential reactive oxides, namely silica (SiO_2) and alumina (Al_2O_3), which dissolve in the alkaline activator to produce the binding geopolymer gel to controls the geopolymerization process.

Table 4.2: The Composition Conc. Unit (wt%) Present in Glove Former Waste and Glass Waste

Compound Name	Concentration Unit (wt%)	
	Glove Former Waste	Glass Waste (Wang et al., 2020)
SiO_2	63.75	65.97
Al_2O_2	29.892	3.33
Na_2O	-	11.08
K_2O	3.171	0.35
Fe_2O_3	1.401	0.62
CaO	0.469	11.85
P_2O_5	0.459	-
TiO_2	0.292	-
Cr_2O_3	0.155	-
ZrO_2	0.041	-
MnO_2	0.04	-
Rb_2O	0.037	-
BaO	0.025	-
MgO	0.017	1.11
V_2O_5	0.006	-
SrO	0.006	-
Y_2O_3	0.006	-
SnO_2	0.006	-
TeO_2	0.006	-
PbO	0.006	-
Ga_2O_3	0.005	-
Nb_2O_5	0.005	-
ThO_2	0.005	-
NiO	0.003	-
CuO	0.003	-

Yb_2O_3	0.002	-

As shown in Table 4.1 above, the main chemical composition of glove former waste is SiO_2 (63.750%), Al_2O_2 (29.892%), K_2O (3.171%), and Fe_2O_3 (1.401%). Glass trash is mostly composed of SiO_2 (65.97%), Al_2O_2 (3.33%), Na_2O (11.08%), and CaO (11.85%). SiO_2, or the silica content, of glove former trash is somewhat lower than that of glass waste when compared to the two distinct waste types, but Al_2O_2, or the alumina concentration, is comparatively higher.

The major component of glass waste, SiO_2 (65.97%), is ideal for the synthesis of geopolymers. Significant concentrations of flux oxides, particularly NaO (11.08%) and CaO (11.85%), are also present. Soda-lime silicate glass, which is frequently seen in windows and containers, has this combination. Its exceptional potential as a source of soluble silicate is confirmed by its high silica concentration (Wang et al., 2020). It is especially significant if CaO is present because it may cause calcium silicate hydrate (C-S-H) gel to form in addition to the aluminosilicate (N-A-S-H) gel, creating a denser and more robust hybrid binder system. The resultant gel is likely to be silicate-based due to the low alumina level (AlO_3 ~3.33%).

The glove former waste's composition is astounding and goes against what is typically assumed. It is an alumina-silicate resource with a high AlO_3 content (29.89%) and a sizable SiO_2 content (63.75%), not an inert organic material. This implies that the "glove former waste" is probably not the glove itself but rather a byproduct of its production, like a powder or slurry made of clay that is applied to ceramic formers. This is a crucial discovery. This material will mainly provide the Al^{2+} ions required for the formation of the Si-O-Al linkages that define the geopolymer network because of its high alumina concentration (Davidovits, 2005).

4.2.3 Field Emission Scanning Electron Microscopy (FESEM)

Field Emission Scanning Electron Microscopy (FESEM) analysis was conducted to examine the morphology, microstructure, and phase distribution within the synthesized geopolymer composites. Porosity, water absorption, compressive strength, and other macroscopic mechanical and physical characteristics seen in later testing are all directly explained by the microstructure. In this research works, FESEM is conducted on 100 GFW, 100 GW, 50MIX, Oven 100 GFW, Oven 100 GW, and Oven 50MIX at ×10000 magnification.

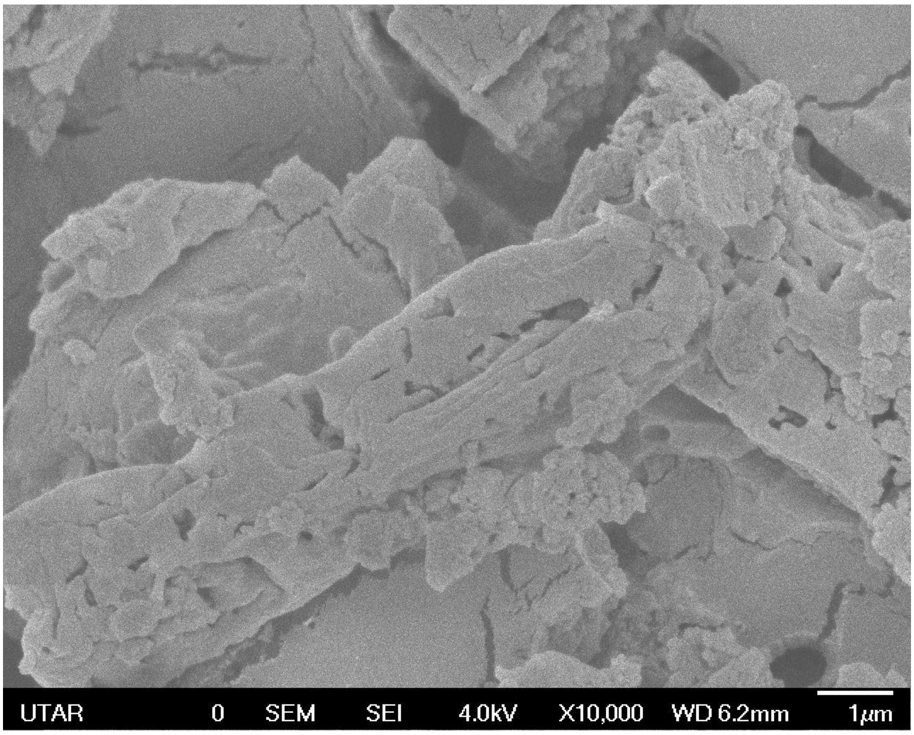


Figure 4.1: FESEM Image of Specimen 100 GW at x10,000 magnification

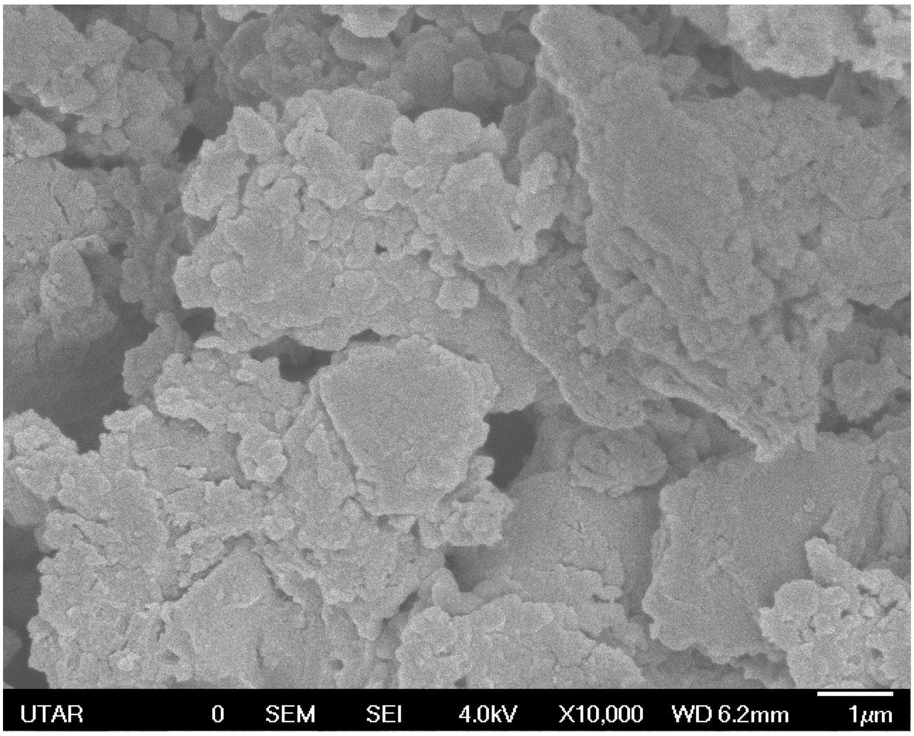


Figure 4.2: FESEM Image of Specimen 100 GFW at x10,000 magnification

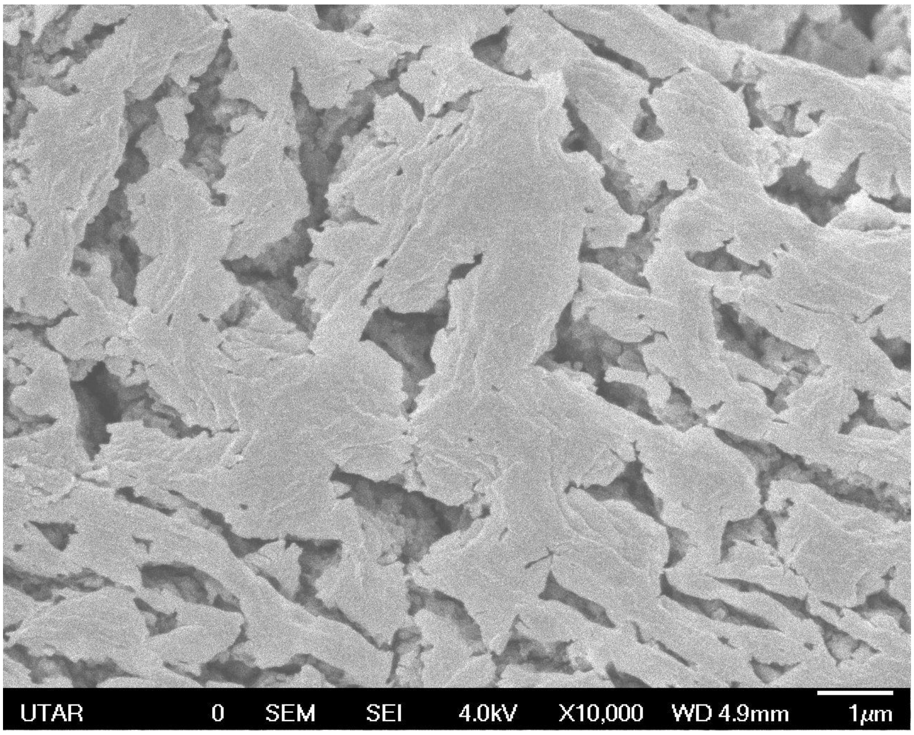


Figure 4.3: FESEM Image of Specimen 50 MIX at x10,000 magnification

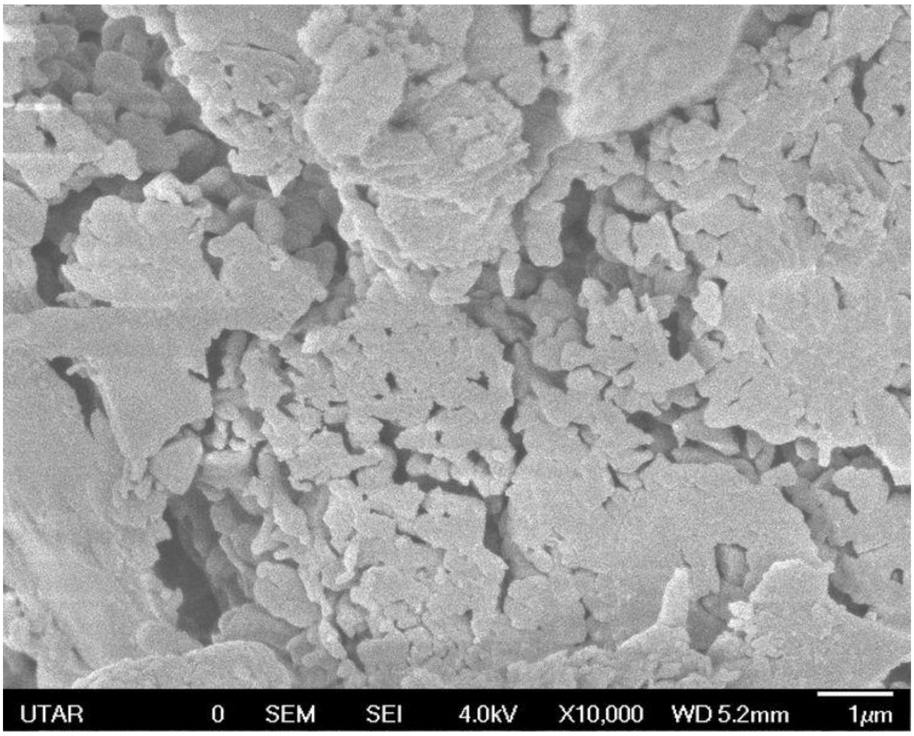


Figure 4.4: FESEM Image of Specimen Oven 100 GW at x10,000 magnification

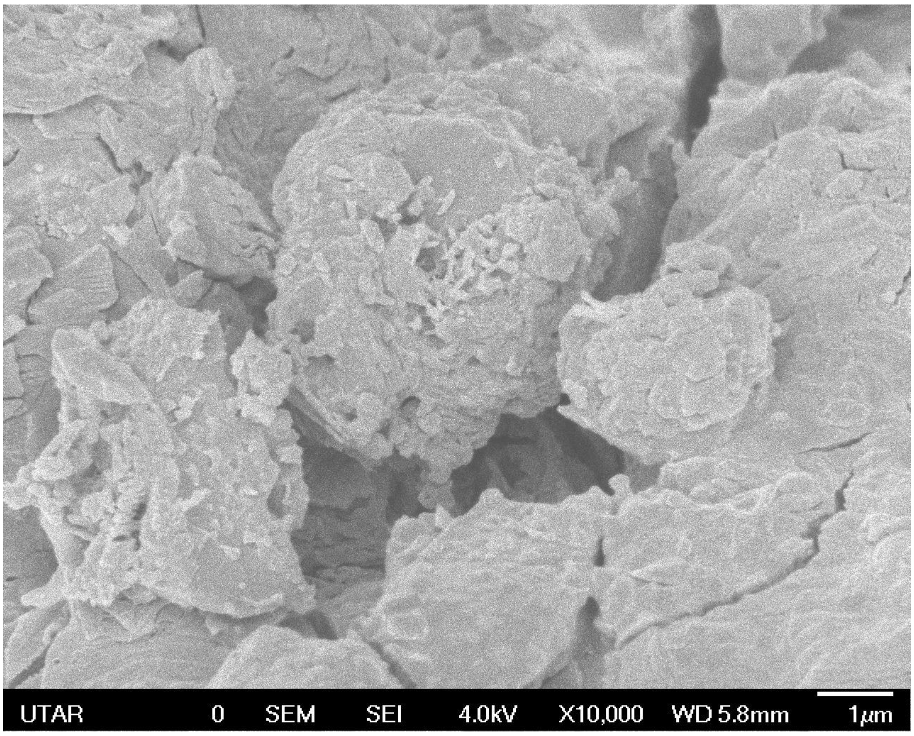


Figure 4.5: FESEM Image of Specimen Oven 100GFW at x10,000 magnification

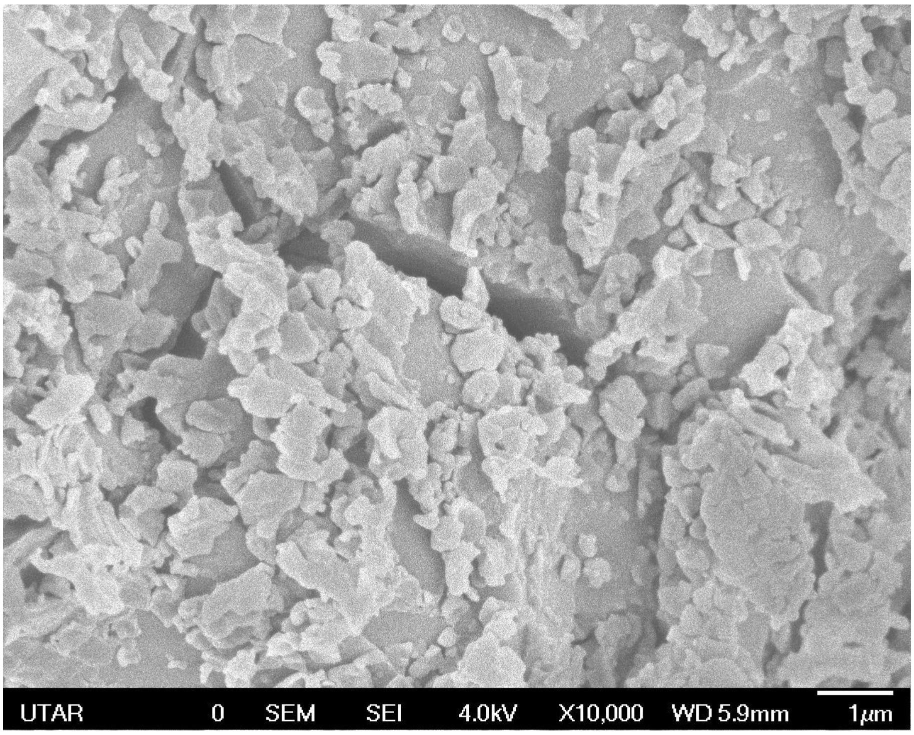


Figure 4.6: FESEM Image of Specimen Oven 50 MIX at x10,000 magnification

The composition has a considerable impact on the microstructural properties. The high resolution FESEM image for the oven and room temperature curing methods in various mix designs (100GW, 100GFW, and 50MIX) at ×10000 magnifications is displayed in Figures 4.1 to 4.3 and 4.4 to 4.6.

Figure 4.1 (100% Glass Waste) likely shows a combination of a partially formed geopolymer gel and numerous unreacted or angular glass particles. These unreactive cores indicate partial breakdown, resulting in holes and gaps at the particle-gel interface. This leads to the formation of an interparticle pore network that easily absorbs water. On the other hand, Figure 4.2 (100% Glove Former Waste) may reveal a weak, fragmented, or highly porous matrix. A honeycomb-like structure of remaining pores that would produce extraordinarily high permeability could be left behind after organic components burnt off during curing. Although Figure 4.3 (50%Mix) might show better consolidation, microcracking is probably still present because of the two distinct waste particles' varying rates of shrinkage, which effectively creates channels for water flow.

In addition to the negative effects of rapid water loss, oven-cured specimens (Figures 4.4, 4.5, and 4.6) probably exhibit indications of an accelerated reaction. They might show more microcracking and shrinkage than their ambient-cured counterparts. This happens because the gel isn't strong enough to withstand the forces that result from rapid evaporation, which leaves empty spaces and cracks behind. Thus, the characteristics seen in the FESEM images interparticle porosity from unreacted particles, intra gel porosity from water evaporation and microcracks from shrinkage

4.2.4 Fourier - Transform Infrared Spectroscopy (FTIR)

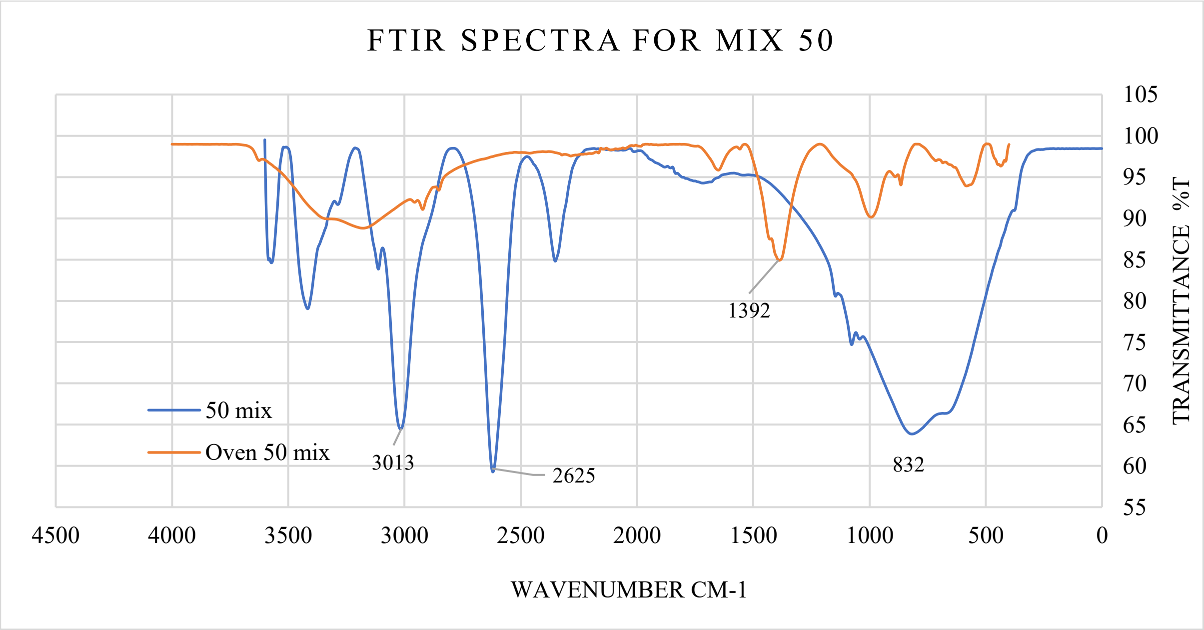


Figure 4.7: FTIR Spectra for Geopolymer Paste with Mix 50 (50% glass waste + 50% glover former waste)

Figure 4.7 shows the FTIR spectra of the geopolymer paste containing 50% glass waste and 50% glove former waste, comparing the uncured and oven-cured samples. Both spectra display broad absorption bands at around 3013 cm^{-1} and 2625 cm^{-1}, attributed to O–H stretching vibrations of water molecules and hydroxyl groups. The intensity of these peaks decreased after oven curing at 100 °C, indicating the loss of physically bound water and further condensation of the aluminosilicate network. A carbonate band was observed at 1392 cm⁻¹, reflecting atmospheric carbonation of alkali species during handling.

The most significant feature appears in the 1200–800 cm⁻¹ region, where the Si–O–T (Si or Al) asymmetric stretching band is detected. In Mix 50, the band is centered at approximately 832 cm⁻¹, which represents a downshift compared to raw precursor values, confirming the incorporation of aluminum into the silicate network. This shift, along with the clearer band profile in the oven-cured spectrum, demonstrates the formation of a geopolymer gel and a higher degree of geopolymerization after heat curing.

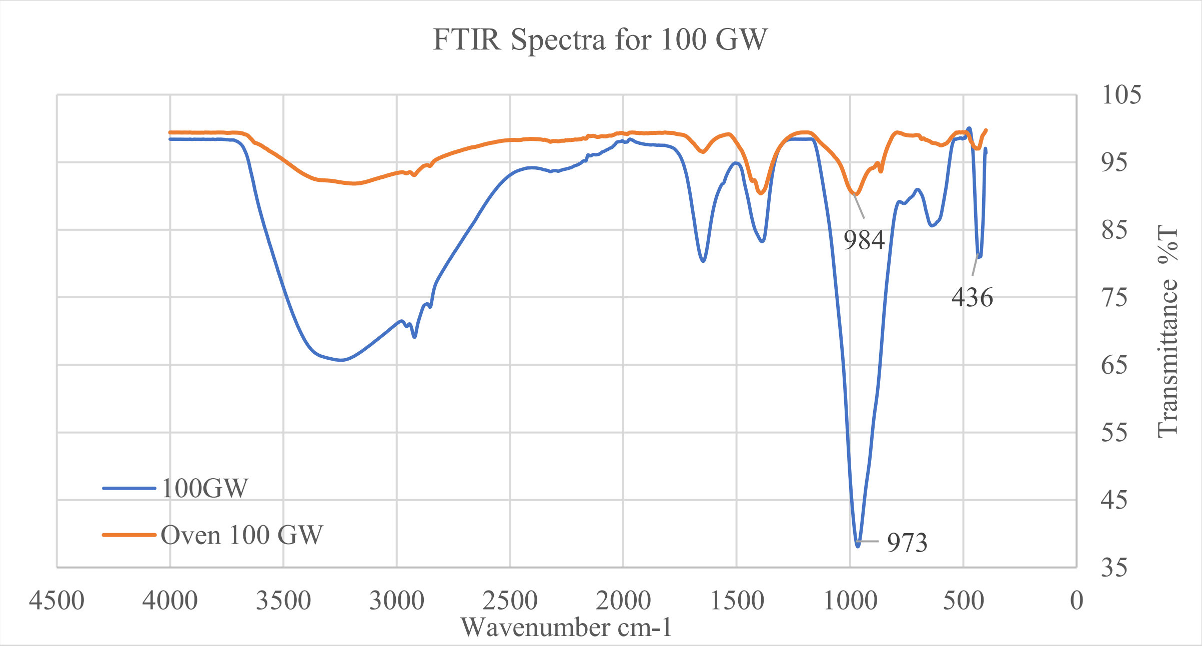


Figure 4.8: FTIR Spectra for Geopolymer Paste with 100GW (100% glass waste)

Figure 4.8 presents the FTIR spectra of the geopolymer paste prepared with 100% glass waste before and after oven curing. A broad O–H stretching band is visible in the region of 3000–3500 cm⁻¹, which decreases in intensity upon oven curing, indicating the removal of physically bound water and further condensation of the aluminosilicate gel. The oven-cured sample also shows lower transmittance overall, suggesting structural reorganization and densification of the matrix.

The most prominent absorption appears in the range of 1200–800 cm⁻¹, corresponding to asymmetric stretching of Si–O–T bonds. For 100GW, the main band is observed at ~973–984 cm⁻¹, slightly shifted compared to typical raw glass waste (~1050 cm⁻¹), confirming the dissolution of silica and the incorporation of Al into the network during geopolymerization. A smaller band at 436 cm⁻¹ is assigned to Si–O bending vibrations, supporting the presence of aluminosilicate frameworks. These spectral changes demonstrate that geopolymer gel formation occurred in the 100% glass waste mix, with curing at 100 °C enhancing the reaction.

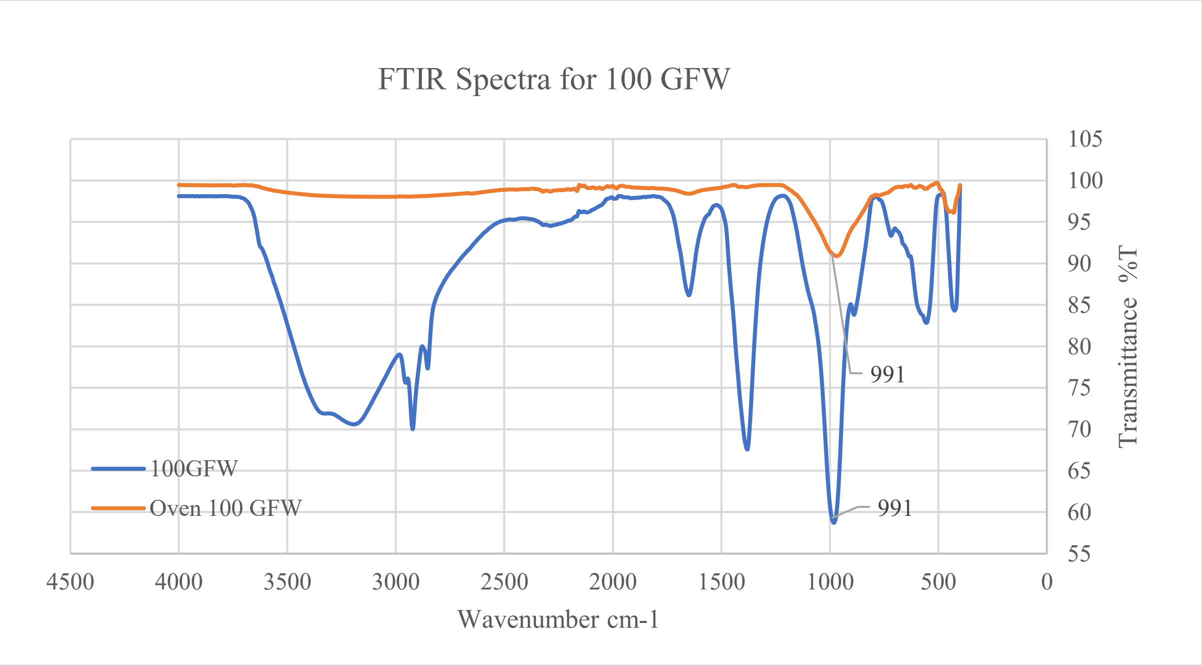


Figure 4.9: FTIR Spectra for Geopolymer Paste with 100GFW (100% glover former waste)

Figure 4.9 illustrates the FTIR spectra of the geopolymer paste made with 100% glove former waste, showing both the uncured and oven-cured samples. Broad bands are visible in the region of 3000–3500 cm⁻¹, corresponding to O–H stretching vibrations from adsorbed water and hydroxyl groups. The intensity of these bands decreases after oven curing at 100 °C, indicating the removal of bound water and further condensation within the aluminosilicate network. This trend reflects the dehydration effect of thermal curing, which promotes structural stabilization of the geopolymer gel.

The key band for geopolymerization is observed at ~991 cm^{-1}, assigned to Si–O–T (T = Si or Al) asymmetric stretching vibrations. The presence of this band confirms the dissolution of precursor material and the subsequent formation of an aluminosilicate gel structure. Compared to raw glove former waste, the shift of this band to lower wavenumbers suggests aluminum incorporation into the silicate framework. The more defined band in the oven-cured spectrum indicates enhanced geopolymer gel formation and a higher degree of reaction after curing.

4.3 Physical property test

4.3.1 Compressive Strength

The compressive strength test was conducted to evaluate the mechanical integrity and load-bearing capacity of the synthesized geopolymer specimens. This property is a critical indicator of the success of the geopolymerization reaction and the potential suitability of the material for construction applications.

Table 4.3: Average Compressive Strength of MIX 50

MIX 50 (Mpa)	RESULT 1	RESULT 2	RESULT 3	Average
7days	0.3	0.5	0.4	0.4
14days	0.5	0.3	0.4	0.4
28days	1.33	1.3	1.33	1.32
oven curing	18.5	24.1	24.21	22.27

Table 4.4: Average Compressive Strength of 100 GW

100GW (Mpa)	RESULT 1	RESULT 2	RESULT 3	Average
7days	0.2	0.2	0.2	0.2
14days	0.2	0.1	0.3	0.2
28days	0.8	1.2	0.85	0.95

oven curing	18	25.5	16.8	20.1

Table 4.5: Average Compressive Strength of 100 GFW

100 GFW (Mpa)	RESULT 1	RESULT 2	RESULT 3	Average
7days	0.3	0.3	0.3	0.3
14days	0.3	0.2	0.4	0.3
28days	0.7	1.5	1.1	1.1
oven curing	24.28	28	27.4	26.56

Table 4.6: Average Compressive Strength of different Geopolymer Specimen

Specimen	**Average Compressive Strength (Mpa)**			
	7 days	14 days	28 days	28days + 24 hours Oven curing (100 °c)
MIX 50	0.4	0.4	1.32	22.27
100GW	0.2	0.2	0.95	20.1
100GFW	0.3	0.3	1.1	26.56

The compressive strength results of geopolymer mortar incorporating glass waste (GW), glove former waste (GFW), and their combination (MIX 50) are presented in table 4.6. At ambient curing for 7 and 14 days, all mixes exhibited very low strength, ranging between 0.2–0.4 MPa, indicating limited geopolymerization at early ages. After 28 days, slight strength improvement was observed, with MIX 50 achieving 1.32 MPa, followed by GFW (1.10 MPa) and GW (0.95 MPa).

The gradual increase in strength from day 7 to day 28 can be attributed to the progressive dissolution of silica and alumina species under alkaline conditions, which continues to supply reactive precursors for geopolymer gel formation. Over time, these precursors undergo polycondensation reactions, leading to the development of a denser aluminosilicate gel network that enhances the mechanical performance of the mortar (Wong et al., 2021). According to *A Comprehensive Review of Synthesis Kinetics and Formation Mechanism of Geopolymers*, this extended reaction process under ambient curing promotes continuous structural reorganization, which explains the observable improvement in strength between early and later curing ages (Ahmer Ali Siyal et al., 2024).

A significant increase in strength was observed after specimens were subjected to oven curing at 100 °C for 24 hours. MIX 50 achieved a compressive strength of 22.27 MPa, while GW and GFW recorded 20.10 MPa and 26.56 MPa, respectively. Among the mixes, GFW exhibited the highest compressive strength, demonstrating the potential of glove former waste as a precursor material for geopolymer mortar.

At ambient temperature, the compressive strength of all mixes remained very low, even after 28 days. This can be attributed to the limited dissolution of silica and alumina species from the glass waste (GW) and glove former waste (GFW) precursors. The slow reaction rate restricted the formation of geopolymeric gel, leaving a large portion of the alkaline solution unreacted. During testing, the specimens appeared wet with excess solution seeping out, indicating that the binder was unable to properly absorb and integrate the alkaline activator. Such incomplete geopolymerization produces a weak and porous matrix, which explains the negligible strength values recorded under room temperature curing conditions. Similar observations have been reported in previous studies, where low-calcium geopolymer systems cured at ambient conditions showed poor strength development due to insufficient reaction (Davidovits, 2020).

A geopolymer develops strength through a chemical process known as geopolymerization. In this process, the aluminosilicate precursors (such as fly ash, slag, glass waste, or glove former waste) dissolve in the alkaline activator, releasing silica (Si) and alumina (Al) species. These species then undergo polycondensation reactions to form a continuous three-dimensional network of geopolymeric gel, commonly N–A–S–H or C–A–S–H gel depending on calcium content (Davidovits, 2020). The formation of this dense and interconnected gel structure binds the particles together, fills the pore spaces, and results in the progressive development of compressive strength. The rate and extent of this reaction are strongly influenced by factors such as curing temperature, activator concentration, precursor reactivity, and curing time

In contrast, specimens subjected to oven curing at 100 °C for 24 hours demonstrated a remarkable increase in compressive strength, reaching values above 20 MPa. Elevated curing temperature significantly enhanced the dissolution of aluminosilicate species, accelerating the polycondensation reaction and promoting the rapid formation of geopolymeric gel. This process consumed the excess alkaline solution observed in ambient specimens, resulting in a denser and more homogeneous matrix. The improved microstructural development led to greater bonding within the binder, which translated into higher compressive strength. Among the mixes, GFW exhibited the highest strength (26.56 MPa), suggesting that glove former waste is highly reactive under thermal curing conditions (Fernández-Jiménez, Palomo and Criado, 2005).

4.3.2 Porosity test

The porosity test was conducted to quantitatively measure the volume fraction of pores within the geopolymer specimens. This property is a fundamental determinant of the material's density, durability, and mechanical performance.

Table 4.7: Porosity of different Geopolymer Specimen

Specimen	Porosity (%)		
	7 days	14 days	28 days
MIX 50	19.35	18.17	13.25
100GW	9.17	8.66	7.17
100GFW	15.85	13.99	13.7

Table 4.7 presents the porosity development of geopolymer mortar containing glass waste (GW), glove former waste (GFW), and their blend (MIX 50) at different curing periods. In general, porosity decreased with curing age for all mixes, indicating progressive densification of the geopolymer matrix. At 7 days, MIX 50 recorded the highest porosity (19.35%), followed by GFW (15.85%) and GW (9.17%). A slight reduction was observed at 14 days, with values ranging from 18.17% for MIX 50 to 8.66% for GW. By 28 days, porosity further declined, reaching 13.25% (MIX 50), 13.70% (GFW), and 7.17% (GW).

The reduction in porosity with curing time can be attributed to the ongoing geopolymerization process, in which additional silica and alumina species dissolve and react to form gel products that fill voids within the matrix. This leads to gradual refinement of pore structure and improved compactness. However, the persistence of relatively high porosity in MIX 50 and GFW compared to GW suggests that the reactivity of glove former waste is lower at room temperature curing, resulting in less effective gel formation and pore filling. Conversely, GW exhibited the lowest porosity across all curing ages, which is consistent with its finer particle size and higher glassy content that favor faster dissolution and densification of the microstructure.

These findings are consistent with previous studies, which reported that the reduction in porosity with curing time corresponds to strength development, as a denser geopolymer matrix contributes to higher compressive strength (Fernández-Jiménez, Palomo and Criado, 2005). The correlation between porosity and compressive strength is evident in the present study, where specimens with lower porosity demonstrated improved structural integrity compared to highly porous specimens.

4.3.3 Water absorption test

Table 4.8: Water absorption rate of different Geopolymer Specimen

Specimen	Water absorption rate (%)		
	7 days	14 days	28 days
MIX 50	12.11	11.24	8.11
100GW	4.96	4.92	4.13
100GFW	10.29	9.04	9.09

Table 4.8 shows the water absorption rate of geopolymer mortar mixes over curing periods of 7, 14, and 28 days. Overall, water absorption decreased with curing age for all specimens, reflecting progressive densification of the matrix. At 7 days, MIX 50 exhibited the highest water absorption (12.11%), followed by GFW (10.29%) and GW (4.96%). A gradual reduction was recorded at 14 days, and by 28 days, the values had decreased to 8.11% (MIX 50), 9.09% (GFW), and 4.13% (GW).

The decreasing trend in water absorption with curing age can be attributed to ongoing geopolymerization, where gel products gradually fill voids and refine the pore structure. This reduces the connectivity of pores and limits the ingress of water. The relatively high-water absorption in MIX 50 and GFW compared to GW suggests that glove former waste is less reactive under ambient curing, resulting in incomplete gel formation and a more open pore network. Conversely, GW consistently exhibited the lowest water absorption rate, which aligns with its lower porosity values and indicates the formation of a denser matrix with fewer accessible capillary pores.

4.4 Carbon Dioxide Estimation

Table 4.9: Carbon Dioxide Emission for different Specimen of Geopolymer paste

Specimens	**Material (kg CO_2)**				
	Glass waste	Glove former Waste	NaOH	Na_2SiO_3	Total
(50+50) GW/GFW	0.067	0.105	0.179	0.109	0.461
100% GFW	—	0.211	0.179	0.109	0.498
100% GW	0.135	—	0.179	0.109	0.423

*Cement CO_2 for **1.162 kg**: 1.162 kg × 0.9 kg CO_2/ kg = **1.046 kg CO_2**

Table 4.10 Comparison between Carbon Dioxide Emission for OPC paste and Geopolymer Paste

Specimens	**Total carbon emission (kg CO_2)**	**Reduction vs cement (%)**
(50+50) GW/GFW	0.461	55.93
100% GFW	0.498	52.39
100% GW	0.423	59.56
OPC	1.046	-

Table 4.10 presents the comparison of carbon dioxide (CO_2) emissions for ordinary Portland cement (OPC) paste and geopolymer paste specimens made from glass waste (GW), glove former waste (GFW), and their combination (MIX 50). The OPC paste exhibited the highest carbon footprint, with emissions of **1.046 kg CO_2** per unit mix. In contrast, the geopolymer pastes produced significantly lower emissions, ranging from **0.423 to 0.498 kg CO_2**, corresponding to reductions of **52.39–59.56%** compared to OPC. Among the mixes, the 100% GW specimen achieved the lowest CO_2 emission (0.423 kg), representing the greatest reduction (59.56%).

4.5 Comparative Analysis of Different Mix Design

Table 4.11: Comparison for different Geopolymer Paste Specimens with Standard Requirements.

Parameter	**Standard requirement**	**Geopolymer design**			**Oven Curing Method**
		100 GW	100 GFW	50 MIX	
Compressive strength	13.76 - 16.56 (MPa) (ASTM C 150)	0.95	1.1	1.32	>20.0
Porosity	<3% = good quality 3% - 5% = moderate quality >5% = bad quality (CEB-FIP)	7.17	13.7	13.25	-
Water absorption	-	4.13	9.09	8.11	-

Table 4.11 show the performance of geopolymer paste specimens in comparison with standard requirements for compressive strength, porosity, and water absorption. According to ASTM C150, the minimum compressive strength for cement paste is 13.76–16.56 MPa (Astm.org, 2024). Under ambient curing, all geopolymer mixes (GW, GFW, MIX 50) recorded strengths below this requirement, with values between 0.95–1.32 MPa, indicating insufficient geopolymerization at room temperature. However, when subjected to oven curing at 100 °C, the specimens achieved compressive strengths above 20 MPa, which exceeded the ASTM minimum requirement, confirming the effectiveness of heat curing in promoting strength development.

For porosity, the CEB-FIP classification defines values of <3% as good quality, 3–5% as moderate quality, and >5% as poor quality (Du, 1993). Based on this classification, all the geopolymer mixes fall into the poor-quality category, with porosity values of 7.17% for GW, 13.70% for GFW, and 13.25% for MIX 50. The relatively high porosity values indicate that the matrix was insufficiently densified under ambient curing conditions, leaving a significant volume of interconnected pores. This explains the weak compressive strength observed for all mixes, as high porosity reduces load-bearing capacity and hinders the development of a strong geopolymeric gel network. Among the specimens, the GW mix showed the lowest porosity, suggesting comparatively better densification, while GFW and MIX 50 exhibited very high porosity levels, which directly correlates with their poor mechanical performance.

The trend in water absorption aligned with the findings of porosity. While GFW (9.09%) and MIX 50 (8.11%) showed higher absorption rates, indicating a more porous matrix with better permeability, the 100% GW mix had the lowest absorption (4.13%), suggesting a denser microstructure. This implies that GW-based geopolymer paste has a higher potential for endurance than mixed systems or GFW.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study set out to investigate the potential of glove former waste (GFW) and glass waste (GW) as alternative raw materials for geopolymer development with the aim of reducing dependency on ordinary Portland cement (OPC) and lowering carbon emissions. The chemical composition analysis confirmed that both GFW and GW are rich in silica (SiO_2) and alumina (Al_2O_3), which are essential for geopolymerization. The physical and microstructural analyses further supported their suitability as precursors in alkali-activated systems.

Three mix designs were developed and tested: (1) 50% GFW + 50% GW, (2) 100% GW, and (3) 100% GFW. Results from compressive strength testing showed that the blended mix (50% GFW + 50% GW) achieved relatively better strength performance compared to the single-material systems, indicating a synergistic effect between the two waste materials. Strength development from 7 to 28 days demonstrated that the geopolymerization process continues with time, resulting in improved mechanical performance. Furthermore, the incorporation of oven curing enhanced early strength gain, confirming the influence of thermal activation on geopolymer properties.

In terms of environmental impact, the use of GFW and GW in geopolymer production presents a significant advantage over OPC by reducing CO_2 emissions associated with cement manufacture. This aligns with global efforts to mitigate climate change while simultaneously addressing waste management challenges. By utilizing industrial waste streams that are otherwise discarded, the study demonstrates that geopolymer technology can serve as a sustainable alternative binder with dual benefits of resource efficiency and carbon footprint reduction.

Overall, the research concludes that glove former waste and glass waste are feasible precursors for geopolymer development, offering a promising pathway toward sustainable construction materials. While the study was limited to small-scale laboratory tests, the findings provide a foundation for further exploration of waste-based geopolymers for broader structural and environmental applications.

5.2 Recommendations

Based on the outcomes of this study on geopolymer paste, several recommendations and potential improvements are proposed for future research and development:

1. Future studies should investigate a broader range of mix proportions and activator concentrations to achieve higher mechanical strength and improved geopolymerization efficiency.

2. Additional curing methods, such as steam curing or extended elevated temperature curing, should be explored to enhance strength development while minimizing energy usage and carbon emissions.

3. The potential of combining GFW and GW with supplementary precursors should be explored to determine an optimum mix design that balances mechanical performance and sustainability.

4. A detailed life cycle assessment (LCA) should be carried out to quantify the overall environmental benefits, particularly in terms of CO_2 emission reduction and waste utilization.

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