

**EFFECT OF GLASS POWDER ON DURABILITY PERFORMANCE OF  
HARDENED CONCRETE IN AGGRESSIVE ENVIRONMENT**

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**Thesis submitted in partial fulfilment of the requirements for the Award of the  
Degree of Master of Science in Structural Engineering of Masinde Muliro University  
of Science and Technology**

**OCTOBER, 2025**

## DECLARATION

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

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## **DEDICATION**

I dedicate this thesis to my late father Mr. Edwine Jobondo Otero for his unwavering support and encouragement to further my studies.

## **ACKNOWLEDGEMENT**

I am eternally grateful to the Almighty God for the gift of life and enabling me undertake my studies. My sincere gratitude to my supervisors Dr. Benard Omondi and Dr. Chrispinus Wamalwa for their continued advice, guidance and contribution throughout this research. My sisters, Miss Nelly Odera and Miss Caroline Odera for their continued encouragement and support. Special gratitude to Prof. David Koteng', Mr. Leonard Simiyu, Mr. Joseph Odari, Mr. Keithy Kamau, Miss Mercy Lovi and Mr. Brian Otieno of the Technical University of Kenya for their assistance and guidance during the course of this research.

## ABSTRACT

Concrete structures exposed to aggressive environment such as sewer water, sea fronts, drains among others are susceptible to abrasion, chemical seepage among other factors that lead to its deterioration. To mitigate deterioration of concrete, various methods have been proposed such as use of supplementary cementitious materials, regular replacement of worn-out sections among other considerations. This research recommends use of glass powder as an additive to concrete mixture to mitigate risks associated with concrete deterioration due to exposure to aggressive environment with the aim of determine its effect on durability parameters. This study was guided by objectives considering concrete water absorptivity, resistance to sulphate attack and its chloride permeability. Crushed waste glass powder was added to the concrete mix at 10%, 20% and 30% by weight of cement. Fresh concrete was subjected to slump test while hardened concrete was subjected to compressive strength, water absorption, sulphate attack and electrical resistivity tests. The data obtained were computed and comparison made with the control samples at maturity and presented in forms of tables and graphs. Best results relative to the control samples were obtained at 30% addition of crushed waste glass powder into the concrete mix, with a notable increase in compressive strength from 32.8 N/mm<sup>2</sup> to 42.8 N/mm<sup>2</sup> representing an increase of 30.5%. Water absorption reduced from 1.7% to 1.6% representing a reduction of 5.9%. Sulphate attack results based on mass and length variation showed that mass and length least increment from 38g to 40g and 5.7 mm to 5.9 mm representing an increase of 5.3% and 3.5% respectively. Electrical resistivity reduced from 13.6 kΩ/cm to 11.6 kΩ/cm representing a reduction of 14.7%. This study proved that addition of crushed waste glass powder to concrete mix at 30% by weight of cement improved its permeability, reduced its susceptibility to sulphate attack although it reduced its surface electrical resistivity. Concrete made with addition of 30% crushed waste glass powder to concrete mix by weight of cement is therefore recommended to be applied in areas prone to moisture ingress, for use as a sacrificial concrete against sulphate attack such as in sewer conduit lining. Further research is recommended to determine the possible causes of the reduction in surface electrical resistivity.

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## LIST OF ABBREVIATIONS AND ACRONYMS

<b>AASHTO</b>	American Association of State Highway and Transportation Officials
<b>ACV</b>	Aggregate Crushing Value
<b>AIV</b>	Aggregate Impact Value
<b>ASAL</b>	Arid and Semi – Arid Lands
<b>ASG</b>	Alkali Silica Gel
<b>ASR</b>	Alkali Silica Reaction
<b>ASTM</b>	American Society for Testing and Materials
<b>BS</b>	British Standards
<b>C-S-H</b>	Calcium Silicate Hydrate
<b>CWG</b>	Crushed Waste Glass
<b>CWGP</b>	Crushed Waste Glass Powder
<b>DMDA</b>	Densified Mixture Design Algorithm
<b>EN</b>	European Norm
<b>NACOSTI</b>	National Commission for Science, Technology and Innovation
<b>NEMA</b>	National Environmental Management Authority
<b>PPC</b>	Portland Pozzolanic Cement
<b>SCM</b>	Supplementary Cementitious Material

## LIST OF SYMBOLS

<b>%</b>	Percent
<b>CaO</b>	Calcium Oxide
<b>H<sub>2</sub>S</b>	Hydrogen sulphide
<b>H<sub>2</sub>SO<sub>4</sub></b>	Sulphuric acid
<b>kN</b>	Kilonewton
<b>mm</b>	Millimetres
<b>MPa</b>	Megapascals
<b>N</b>	Newtons
<b>NaO<sub>2</sub></b>	Sodium superoxide
<b>°C</b>	Degrees Celsius
<b>SiO<sub>2</sub></b>	Silicon Oxide

## CHAPTER ONE: INTRODUCTION

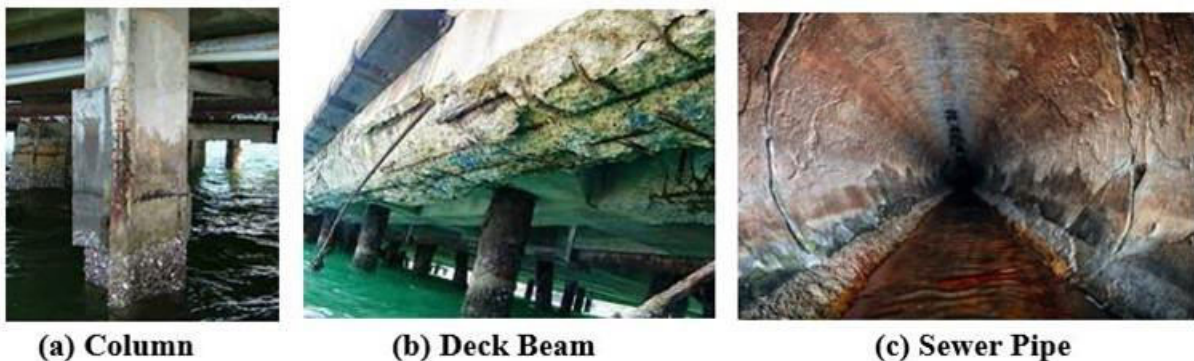
This chapter provides background information on the research area, problem statement, justification and research objectives that contribute to core of the research.

### 1.1 Background Information

Concrete is a widely used building material in construction industry. It is often used with steel reinforcement to strengthen its tensile capacity. It is essential for concrete to sustain its design capacity over the intended design life to successfully fulfil its function. In this regard, quality of concrete aggregates is essential to sustain its durability against intended exposure conditions during its service life, (Eme & Nwaobakata, 2019).

Durability performance of concrete particularly in aggressive environment is significant in that premature deterioration of concrete in environment such as marine water as shown in figure 1.1 (a) and (b) for column and beam respectively, as well as in wastewater systems as indicated in figure 1.1 (c), expose concrete to cracking, spalling, weathering, abrasion among other means. This increases its permeability hence allowing further ingress of harmful compounds into concrete leading to further degradation.

(The Constructor, 2023) and (Nicole, 2017).



**Figure 1.1 : Concrete Deterioration in Marine and Wastewater Environment.**

Increasing demand for durable concrete necessitates demand for sustainable mitigation measures. Traditional methods such as use of chemical additives, protective coatings among other means have been used consistently at greater cost and environmentally taxing. In this regard, alternative means such as use of glass powder has gained interest as potential additive to improve concrete's resistance to aggressive environmental conditions. Glass powder contains silica and has pozzolanic properties that can refine concrete microstructure thereby reducing its permeability. Use of glass powder has potential to improve concrete's durability as well as promote sustainable practices through the recycling of waste materials.

Research on enhancement of concrete performance in aggressive environments by use of admixtures and Supplementary Cementitious Materials (SCM) such as Sugarcane Bagasse Ash (SBA), Rice Husks Ash (RHA), Silica Fumes, Fly Ash, Waste Glass Powder (WGP) among others as supported by research done by (Verma & Varshney, 2018), (Eme & Nwaobakata, 2019), (Rerkpiboon, Tangchirapat, & Jaturapitakkul, 2015) among others. These researches have significantly contributed to understanding the variation in performance of concrete in terms of physical, mechanical and chemical properties as well as clarifying and cautioning on the limits of their applications.

Glass is a translucent material made from sand, soda ash and limestone melted at high temperature. Waste glass powder from different sources when ground to different sizes has been used in concrete production. Particle size less than 0.75  $\mu\text{m}$  when used as powder, induced pozzolanic reaction, had micro filling effect and resulted into increased density, strength and durability at optimum of between 10% to 20%. Particle size of between 0.75  $\mu\text{m}$  to 4.75 mm used as fine Aggregate at an optimum of 40% with micro filling effect resulting into decreased workability but with increased density, strength and durability and particle size of between 4.75mm to 25 mm used as coarse aggregate at an

optimum of between 10% to 20% were noted to cause a decrease in workability, strength, durability and increased risk of Alkali Silica Reaction (ASR), (Ahmad, Zhou, Usanova, Vatin, & El-Shorbagy, 2022).

Glass powder when used as partial replacement of cement resulted in an increase in workability, compressive strength and improved durability at an optimum of 4% by weight of cement. Glass powder could also be used as a substitute of SCM in concrete such as silica fume where it was noted to increase in workability and reduce heat flow at 30% replacement of silica fume, (Eme & Nwaobakata, 2019) and (Soliman & Tagnit-Hamou, 2017). Chemical analysis between clear and coloured glass was found to be similar as per requirements of American Society for Testing and Materials (ASTM) hence classification as a pozzolanic material, (Islam, Rahman, & Kazi, 2017). This finding is critical as it shows similarity in the variation of type of glass that can be used in concrete production.

Research on use of glass in concrete showed that optimal results were obtained with a range of between 20% to 30 % replacement of fine aggregate, coarse aggregate and cement with glass or glass powder under different conditions, (Jani & Hogland, 2014). Chemical shrinkage and heat assessment indicated that high glass powder content in replacement of cement paste resulted into increased rate of hydration leading to decreased compressive strength and dynamic young's and shear moduli, (Nasry, et al., 2021). In research evaluating high volume glass powder concrete, it was noted that beyond 30% partial replacement, amount of calcium hydroxide decreased at 45% and 60%, indicating depletion of formed calcium hydroxide in pozzolanic reaction. Despite this it was noted that the concrete retained resistance against water and chloride ingress, (Du & Tan, 2016).

Through the reviewed research, glass powder has been shown to have potential of improving concrete durability, although there remains lack of comprehensive research on long-term effects when exposed to aggressive environmental conditions. This study aims to bridge that gap by investigating the effectiveness of glass powder as an additive in enhancing the durability of hardened concrete. This was investigated by subjecting hardened concrete samples to water absorption, sulphate attack and chloride permeability tests respectively at predetermined age as per standard guidelines. The obtained data was then analysed and findings on the performance of the samples recorded relative to control samples.

## **1.2 Problem Statement**

Concrete structures exposed to aggressive environment are vulnerable to deterioration caused by harmful compounds such as sulphates, chlorides, and carbonic acids. This exposure leads to physical and mechanical degradation ultimately compromising the durability and structural integrity of concrete. Such deterioration poses a significant risk to the performance and longevity of concrete structures, especially when design constraints are no longer met. Therefore, there is a critical need to explore effective mitigation strategies to enhance concrete durability in such aggressive conditions. This study evaluated effectiveness of using glass powder as an additive to concrete in improving the durability performance of hardened concrete exposed to aggressive environmental conditions.

## **1.3 Objectives**

### **1.3.1 Main Objective**

To determine the effect of glass powder on durability performance of hardened concrete in aggressive environment.

### **1.3.2 Specific Objectives**

1. To determine the rate of water absorption of concrete when glass powder is incorporated in varying proportions.
2. To evaluate the effect of sulphate attack on concrete when glass powder is incorporated in varying proportions.
3. To determine chloride permeability of the concrete when glass powder is incorporated in varying proportions.

## **1.4 Research Questions**

This research was guided by following research questions;

1. What is the effect of adding crushed waste glass powder in concrete on water absorption?
2. What is the effect of adding crushed waste glass powder in concrete on sulphate attack?
3. What is the effect of adding crushed waste glass powder in concrete on chloride permeability?

### **1.5 Justification**

Findings of this research helps in understanding impact of adding waste glass powder to concrete mix by guiding on the degree it influences its durability performance against water absorptivity, sulphate aggression and chloride permeability. Additionally, it identifies potential areas for further research and proposes an alternative avenue for recycling waste glass. Application of the findings can result to improving sulphate resistance, water permeability and compressive strength.

### **1.6 Scope and Limitations of the Study**

This research scope was limited to specific durability parameters namely water absorptivity, sulphate attack and chloride permeability. Research parameters were limited to use of Portland Pozzolanic Cement (PPC) CEM IV/ B(P) 32.5N, Densified Mixture Design Algorithm (DMDA), laboratory tests at standard room temperature during the research period as control measure to reduce possible variables that could affect the outcome.

## **1.7 Outline of the thesis**

This thesis is divided into five chapters namely chapter one, two, three, four and five respectively.

Chapter one: Introduction, provides background relating to the topic of study entailing how aggressive environment deteriorates concretes design capacity, remedies taken to reduce the effects and proposing alternative means of reducing effect of the aggressive environment on concrete. This chapter also covers justification of the study, objectives, scope and research questions that guided the research.

Chapter two: Literature review, details research conducted by various scholars, publications made and articles relating to the topic of research broken down to guide the research. It reviews literature relating to use of glass powder in concrete, finding of the researches and their applications.

Chapter three: Methodology, covers details on materials used in the research, preliminary tests conducted when profiling research materials and test methods used in the research as per guidelines of the standards of practice as referenced.

Chapter four: Results and discussion, contains the research findings represented in forms of graphs and tables. It includes discussions based on the findings of the research in comparison to findings of other researchers, publications and articles.

Chapter five: Conclusions and recommendations, indicates the conclusions drawn from the research findings and makes recommendations based on the research findings.

## CHAPTER TWO: LITERATURE REVIEW

This chapter entails a review of published researches on glass powder as an additive in concrete, its properties, application in concrete production and performance when exposed to aggressive environmental conditions.

### 2.1 Aggressive Environment for Concrete

Aggressive environment refers to exposure with hazardous substances that can degrade concrete reducing its design capacity. Concrete in such environment is exposed to chemicals such as acids, bases and abrasion through agent medium such as water, (Sunday, D., & A., 2020). Concrete durability can be affected based on the environmental conditions its exposed to such as water, salts, temperature variation among other factors. Coastal regions of Kenya weather variations affected by temperature variation of between 20°C to 54°C as well as humidity of between 80% to 90%.

Dissolved salts in the marine water such as chloride permeate through concrete via diffusion in combination to temperature variation and high humidity leading to corrosion of steel reinforcement. Temperature variation such as in Arid and Semi – Arid Lands (ASAL) in Kenya affects plastic shrinkage, compressive strength and pulse velocity of concrete. Research noted a decrease in compressive strength in concrete cast at elevated temperatures and higher pulse velocity. Thaw and freeze conditions contribute to expansion of fissures hence during thawing creates a channel for ingress of aggressive substances.

Concrete resting on natural soil may be exposed to soil water that contain dissolved salts that can permeate through concrete. Substances such as sulphate compounds can lead to swelling, cracking and reduction in strength of the concrete, (Rambabu & Mahindrakar,

2017). To overcome the negative effects of aggressive environment on concrete durability, various solutions have been adopted in concrete design.

Addition of pozzolana materials such as silica fumes, fly ash among others have been found to increase concrete durability. Use of appropriate chemical and mineral admixtures have been found to improve plastic properties of concrete such as workability, cohesion, adhesion and reduced bleeding thereby reducing the void ratio.

Research into nanomodified concrete for harsh environments by (B., et al., 2025) tested concrete against seawater, acidic conditions and household water. The research established that conventional concrete had a degrade of 25% in compressive strength when subjected to seawater at 56 days and 35% increase in water absorption triggered by sulphate/chloride induced microcracking and portlandite dissolution. By integrating polycarboxylate ether superplasticizer for improved capillary porosity, vinsol resin air entrainers for continuous micro bubble barrier and glutonic acid retarders to for homogeneous C-S-H nucleation, it was found that strength degradation was limited to 15% in seawater and absorption increased to 15% out performing ordinary concrete by 40% in key durability parameters. This research clearly indicates significance of modification of concrete microstructure by use admixtures (superplasticizers, air entrainers and retarders) in concrete which contributes to overall improvement of durability against harsh environmental conditions.

Study by (Otieno, Sylvester, Siphila, & Muthomi, 2023) on influence of corn cob ash – silica fume blend on mechanical and durability properties of concrete established that at 10% CCA-SF blend, durability indicators water absorption reduced from 2.6% to 1.6% and electrical resistivity improved from 11 k $\Omega$ -cm to 29.5 k $\Omega$ -cm based on the control samples.

Study on Evaluating Superplasticizer Compatibility in the Production of High Performance Concrete using Portland Pozzolana Cement CEM II/B-P by (Thomas, David, & John, 2020) brought out significance of using chemical and mineral admixture in concrete and found that silica fumes improved densification of the concrete when used within the recommended dosage, improved workability and durability indicators of water absorption being lower than the reference sample by 24% while electrical resistivity improved by 26%.

## **2.2. Glass Powder in Concrete**

Glass powder is a compound obtained by crushing of glass and sieving via sieve size 75µm. Crushing of glass powder increases its surface area making it finer for use in concrete where it contributes to micro filling effect and provides additional pozzolana for cement hydration.

### **2.2.1 Particle Size of Glass Powder**

Particle size of crushed glass directly affects physical, mechanical and chemical properties of concrete thereby affecting durability of the concrete. Incorporating glass in concrete has been noted to have side effects such as deterioration due to Alkali Silica Reaction (ASR) resulting from reaction between cement paste and reactive siliceous aggregates leading to formation of Alkali Silica Gel (ASG) that has ability to absorb water and increase in volume hence increase in pressure causing internal stresses that lead to development of microcracks weakening the cement paste, (Jani & Hogland, 2014).

To help mitigate effect of ASR, it was found that milled glass of particle size less than 75 µm can be used. Finer particle size was noted to increase pozzolanic properties of glass powder. Use of glass in fine particle size as partial replacement of cement in

concrete improves microstructure of the concrete through the pozzolanic reactions. The fine particle size of milled glass also has filling effect effectively parking the paste making it denser and hence less permeable, improving its durability, (Serpa, Silva, De Brito, Pontes, & Soares, 2013).

Table 2.1 represents a summary of research review for use of glass powder as partial replacement of cement indicating the optimum particle size used against optimum quantity of various glass powder the sources used, (Jani & Hogland, 2014).

**Table 2.1: Glass Powder as Partial Replacement of Cement, (Jani & Hogland, 2014).**

Type of Waste Glass	Optimum Particle Size ( $\mu\text{m}$ )	Optimum Composition (%)
Fluorescent Lamps Glass (Soda – Lime)	38	30
Glass Beads (Soda – Lime)	30 – 100	20
Window Plate Glass (Soda - Lime)	1 – 100	10
Bottle (Soda – Lime Glass)	13 – 25	20
Container (Soda – Lime Glass)	20 – 100	20
Recycled Waste Glass (Soda – Lime)	0.1 – 100	20

Research into different mixing methods for glass powder replacement of cement, conventional mixing method where glass powder is added with the cement and aggregates verses new method where glass is first dissolved in water before adding cement and aggregates, it was found that new mixing method gave the best results attributed to hydrolysis of glass powder in water. Soaking of glass powder in water for 8 hours before adding to concrete aggregates, dissolved  $\text{SiO}_2$ ,  $\text{CaO}$  and  $\text{NaO}_2$  ions in the glass powder, that will play key role in formation of C – S – H gel, (Elaqra, Abou Haloub, & Rustom, 2019).

## 2.2.2 Properties of Glass Powder

Understanding chemical properties of glass powder used in this research helped clarify its composition hence its contribution to the hydration process. Chemical properties of Crushed Waste Glass Powder and Cement are as indicated in Table 2.2. based on the laboratory tests finding in appendix A.8 and A.9.

**Table 2.2: Chemical Properties of Glass Powder and Cement, (Appendix A.8 and A.9).**

Compound	Composition (%)	
	Cement	CWGP
Magnesium Oxide (MgO)	0	4.583
Aluminium Oxide (Al <sub>2</sub> O <sub>3</sub> )	7.419	0.703
Silicon Oxide (SiO <sub>2</sub> )	43.662	83.383
Phosphorous Pentoxide (P <sub>2</sub> O <sub>5</sub> )	0.191	0.116
Potassium Oxide (K <sub>2</sub> O)	2.64	0.272
Calcium Oxide (CaO)	40.585	10.553

## 2.3 Durability Performance of Concrete Made with Glass Powder

Incorporating glass into concrete plays a critical role as a partial replacement of aggregate or cement or as an admixture in the concrete mix. This research reviewed findings researches based on use of glass powder in concrete relative to its performance in compressive strength development, water absorptivity, chloride permeability and sulphate attack resistance.

### 2.3.1 Compressive Strength of Concrete Made with Glass Powder

Performance of glass powder in concrete based on compressive strength and workability showed appreciable improvement. At 20% replacement of cement with glass powder ( $\leq 600 \mu\text{m}$ ), an appreciable increment in compressive strength of 27% was noted, this was attributed to the pozzolanic reaction of the glass powder, with a slump value of 70 – 72

mm, (Bhat & Rao, 2014). Similarly, compressive strength increased with increase in replacement of cement with glass powder at 10% based on new mixing method from 27.5 MPa for control sample to 38 Mpa at 90 days representing an increase of 38.18%. A similar trend was noted up to 10% replacement beyond which a decreasing trend was noted, (Elaqra, Abou Haloub, & Rustom, 2019). At 4% replacement of cement with glass powder it was noted that there was an increase in compressive strength compared to the control sample recording an increase of 11%, (Eme & Nwaobakata, 2019).

In research on the use of glass aggregate as partial replacement of fine aggregate in structural concrete, it was noted that compressive strength increased by 6% with 30% replacement of fine aggregate at 28 days, (Adaway & Wang, 2015). These findings attributes to critical contribution of glass aggregate in strength development of concrete via the pozzolanic and micro filling capabilities.

Mathematical method for analysing activity of any addition or replacement material known as Relative Index (RI) or Activity Index (AI) was proposed as per equation 2.1. This help in determining significance of the admixture to the concrete relative to strength development, (Elaqra, Abou Haloub, & Rustom, 2019).

$$\text{RI or AI} = 1 - \frac{\text{Compressive Strength of Control Mix} * \text{Glass Powder Percentage}}{\text{Compressive Strength of Glass Powder Mix} * 100} \quad \text{Equation 2.1}$$

Positive values show that glass powder is reactive and has a positive impact on compressive strength, negative values show inactivity and a loss in compressive strength while zero value show no change in glass powder reactivity and compressive strength.

### **2.3.2 Water Absorption of Concrete Made with Glass Powder**

The most common medium for hazardous substances to ingress into concrete is water. Water ingress into concrete via capillary suction due to capillary action in cement paste and permeation due to pressure gradients factors affect durability of concrete, (Pratiwi, et al., 2021). Water absorption of concrete when cement is replaced with glass powder was noted to decrease with increase in content of glass powder, this was noted through research findings as follows. An optimum of 0.516% at 20% replacement of cement compared to 1.204% of the control sample, representing a decrease of 0.688%, (Bhat & Rao, 2014). A decreasing trend was noted in water absorption when glass powder was used to replace cement over time. This trend was correlated to density during the hydration process resulting into decreased porosity. At 30% replacement of cement water absorption decreased from 4.8% at day 7 to 3% at day 28 representing a decrease of 1.8%, (Elaqra, Abou Haloub, & Rustom, 2019). Concrete made with 20% replacement of cement with glass powder showed a 57% reduction in moisture sorption at age 300 days in field conditions, (Nassar, Soroushian, & Sufyan-Ud-Din, 2021). These findings depict performance of partial replacement of cement with glass powder against water absorption indicating its durability against moisture aggression.

### **2.3.3 Sulphate Attack on Concrete Made with Glass Powder**

Concrete in aggressive environment is as well exposed to sulphate salts from dissolved minerals containing aqueous sulphate, bacterial action causing decay in water environment producing hydrogen sulphide ( $H_2S$ ) which is converted to sulphuric acid ( $H_2SO_4$ ), fertilisers in agricultural soils giving rise to ammonium sulphate, (Nadir & Ahmed, 2022). Sulphate attack is a long – term process involving chemical reaction between sulphate ions and components of hardened concrete that may result in cracking, spalling or strength loss. When moisture and sulphate ions from internal or external

sources react, ettringite or secondary ettringite forms in hardened cement paste resulting in expansion and cracking of concrete structure, (Tittelboom, Belie, & Hooton, 2012).

Magnesium sulphate is known to have adverse effects as compared to other sulphates by decomposing hydrated calcium silicates, aluminates and hydroxide. Magnesium hydroxide reacts with silica gel very slowly forming crumbly fibrous hydrated magnesium silicate which is a weaker binder compared to silica gel, the reaction effects can be observed over long period of time. Reaction of magnesium sulphate with calcium aluminate form calcium sulphoaluminate and magnesium hydroxide. Calcium sulphoaluminate decomposes in presence of magnesium sulphate solution to form gypsum, hydrated alumina and magnesium hydroxide attributed to the lower pH of saturated magnesium hydroxide solution that is below required pH to stabilise calcium sulphoaluminate.

Attack by magnesium sulphate solution on concrete results into hard dense granular particles due to deposition of magnesium hydroxide in the pores that hinder further ingress of the solution, (Eglinton, 2003). Accelerated methods for determining effect of sulphate attack on concrete include test method in ASTM C1012, Wittekindt method among others however, they still require several months. Qualifying degree of degradation can be done via measurement of expansion as per Wittekindt method and ASTM C1012 methods. Other research such as Jain, Sancheti, & Gupta, 2020, proposed use of decrease in compressive strength as a means to determine degradation, (Tittelboom, Belie, & Hooton, 2012).

Previous research findings on sulphate attack on concrete were as mentioned. Blended concrete was noted to have better sulphuric acid and sodium sulphate attack resistance in comparison to the control samples, this was attributed to the better packing of concrete

by finer particle of glass and granite particles and mineral admixture, (Jain, Sancheti, & Gupta, 2020).

Research on effect of 5% Magnesium Sulphate ( $MgSO_4$ ) on concrete strength of concrete when cement was partially replaced with glass powder noted an optimal result at 20% had better sulphate resistance. Compressive strength recorded at day 28 was 33.5 MPa for the mix with 20% glass powder and 31.85 MPa when the mix is subjected to sulphate attack representing a reduction of 4.92%. Similar reduction trend was noted was noted at days 7 and 90 with reduction of 2.01% and 14.76% respectively, (Bajad, Modhera, & Desal, 2011).

#### **2.3.4 Chloride Permeability of Concrete Made with Glass Powder**

Chloride penetration refers to gradual intrusion of chloride ions into concrete weakening its long-term durability and accelerates steel reinforcement corrosion through capillary absorption, hydrostatic pressure, and diffusion. The main factors affecting rate of chloride ion penetration are pore structure of the concrete, building methods, exposure conditions and concrete mix proportions, (Construction Materials Consultants, 2023). Conductive property of concrete microstructure is determined via electrical resistivity test by determining the ability of concrete to withstand transfer of ions subject to an electrical current thereby determining size and extent of interconnectivity of pores. Determination of electrical resistivity is dependent upon degree of saturation of pores, temperature where a variation in temperature affects ionic movement hence reducing or increasing concrete resistivity and signal frequency among other factors, (Layssi, Ghods, Alizadeh, & Salehi, 2015). Presence of soluble salts particularly chlorides increase probability of corrosion in concrete, this occurs by reducing resistance of concrete and efficiency of corrosion is increased, (Eglinton, 2003).

Methods for determining chloride permeability in concrete include the Nordtest NT Build 443, Bulk Diffusion Test, AASHTO T277 Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (Rapid Chloride Permeability Test) and ASTM C1202 Standard Test Method for Electrical Induction of Concrete's ability to Resist Chloride Ion Penetration. The most widely used test technique is ASTM C1202, which evaluates the relationship between the resistance to chloride permeability and the quantity of electric current traveling through concrete summarised as shown in table 2.3, (Construction Materials Consultants, 2023).

**Table 2.3: Chloride Permeability Classification, (ASTM C1202 & AASHTO TP 95).**

<b>Resistivity (kΩ/cm) (AASHTO TP 95)</b>	<b>Charge Passed (Coulombs) (ASTM C1202)</b>	<b>Chloride Ion Permeability</b>
< 12	> 4000	High
12 – 21	2000 – 4000	Moderate
21 – 37	1000 – 2000	Low
37 – 254	100 – 1000	Very Low
> 254	< 100	Negligible

Research on effect of glass powder on concrete permeability to chloride ions noted that increase in water binder ratio from 0.35 to 0.65 resulted to increase in chloride permeability by three times for control sample as opposed to when incorporating 30% of glass powder. At 56 days, control sample having water binder ratio of 0.35 had a chloride permeability higher than that of samples with water binder ratio of 0.65 containing glass powder. Based on these findings its feasible that concrete with low chloride permeability can be obtained with water binder ratio as high as those of conventional concrete, thereby limiting problems caused by low water binder ratio such as autogenous shrinkage,

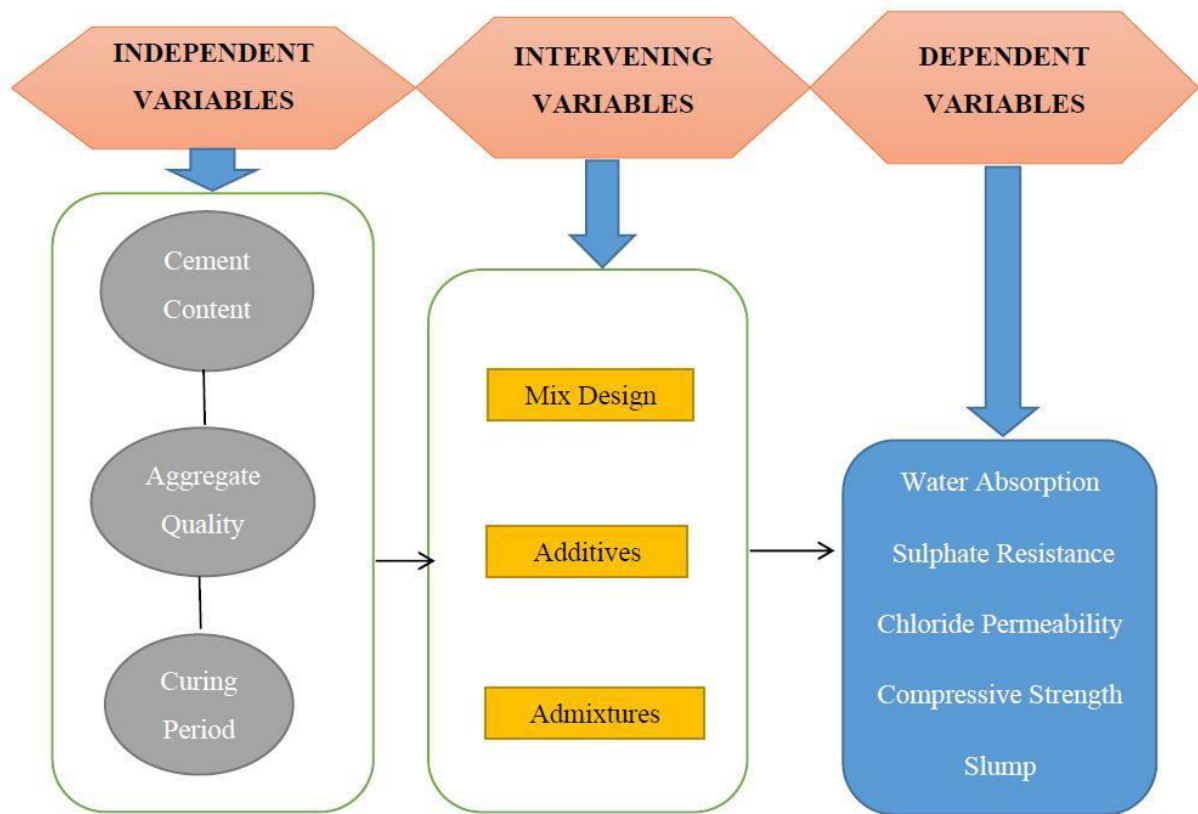
cracking, increase of the cement content and chemical admixtures and subsequently the cost of concrete, (Zidol, Pavoine, & Tagnit - Hamou, 2012).

#### **2.4 Research Gap**

Reviewed literature and data have shown that glass powder use is primarily limited to partial replacement of cement and subject to majorly mechanical tests. Use of glass powder as an additive to concrete mixture as a measure to mitigate effects of aggressive environment on concrete and as mitigation compound to improve durability of concrete is still limited especially with respect to parameters such as water absorptivity, chloride permeability and sulphate attack resistance. Hence the goal of this research to add to the knowledge base on use of waste glass powder as an additive to concrete mix and asses its durability performance in aggressive environment.

#### **2.5 Conceptual Framework**

The research independent, intervening and dependent variables were summarized as shown in figure 2.1.



**Figure 2.1: Conceptual Framework**

## **CHAPTER THREE: METHODOLOGY**

This chapter outlines materials used in this research, preparation processes and methodology used to obtain laboratory data with aim of meeting the research objectives as guided by the relevant standards of practice.

### **3.1 Material Sourcing and Preparation**

Materials were sourced from different geographical regions that influence their compositions.

#### **3.1.1 Water**

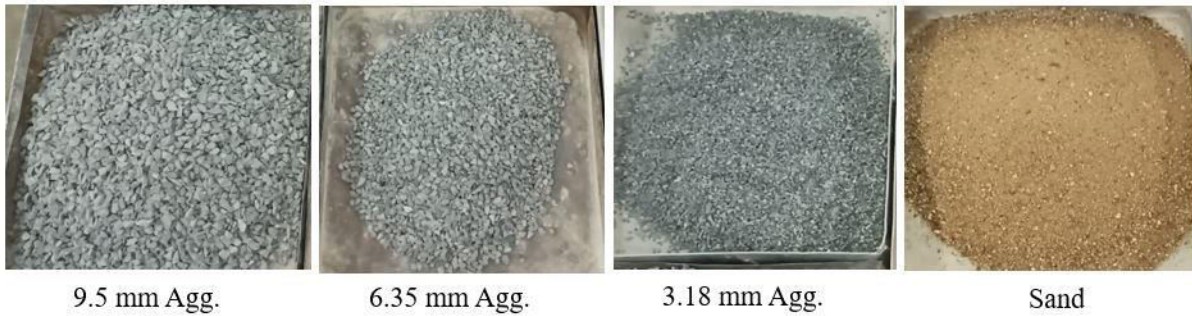
Mixing water was sourced from the Nairobi City County supply mains to the research laboratory at the Technical University of Kenya, which was used in cleaning aggregates and in mix design for making concrete with a constant water – cement ratio for all mixes.

#### **3.1.2 Cement**

Portland Pozzolanic Cement (PPC) CEM IV/ B(P) 32.5N cement conforming to (Kenya Bureau of Standards (KEBS), 2017) sourced from a local supply hardware in Nairobi was used.

#### **3.1.3 Fine and Coarse Aggregates**

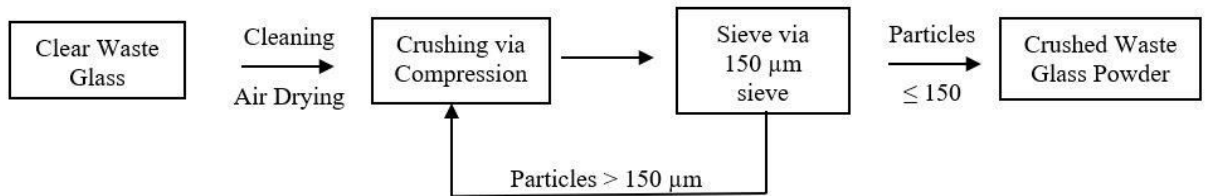
Coarse and fine aggregates were locally sourced, cleaned to reduce silt content and oven-dried to reduce moisture content. Coarse aggregates used were of sizes 3.18 mm, 6.35 mm and 9.5 mm while fine aggregate was sieved through 4.75 mm and retained on 150  $\mu\text{m}$  sieves as shown in figure 3.1.



**Figure 3.1: Sieved Concrete Aggregate.**

### 3.1.4 Glass Powder

Crushed Waste Glass Powder was made from locally sourced waste clear glass, crushed and sieved through 150  $\mu\text{m}$  sieve through the process shown in figure 3.2.



**Figure 3.2: Crushed Waste Glass Powder Preparation Process.**

## 3.2 Concreting

### 3.2.1 Mix Design and Batching

Concrete mix design for this research was done as per guidelines of Densified Mixture Design Algorithm (DMDA) method that proposed maximum packing of larger aggregate size with smaller aggregate size successively until maximum dry density is achieved. Based on maximum dry density, the quantities of paste contents were determined based on prescribed procedure to obtain concrete aggregate quantities per unit volume of concrete. The target strength of the mix design was to achieve concrete class 30. Batched proportions were determined for the respective mixes as in table 3.1, (Techman & Skibicki, 2018). The glass powder was added to the concrete mix in the proportion of 10%, 20% and 30% by weight of cement. Super plasticizer was also added at a constant rate of 2.1% by weight of cement to help in dispersion of cement and waste glass powder particles when added to mixing water and enhance workability of the concrete mix under constant water cement ratio of 0.35.

**Table 3.1: Mix Design Proportions, (Appendix B).**

S/No.	Mix Type	Water (kg/m <sup>3</sup> )	Super plasticizer (kg/m <sup>3</sup> )	Cement (kg/m <sup>3</sup> )	CWGP (kg/m <sup>3</sup> )	Sand (kg/m <sup>3</sup> )	3.18 mm (kg/m <sup>3</sup> )	6.35 mm (kg/m <sup>3</sup> )	9.5 mm (kg/m <sup>3</sup> )
1	Mix 1	170	10	486	0	425	191	163	922
2	Mix 2	170	10	486	48.6	425	191	163	922
3	Mix 3	170	10	486	97.2	425	191	163	922
4	Mix 4	170	10	486	145.8	425	191	163	922

### 3.2.2 Concrete Mixing and Casting

Batched aggregates, cement, crushed waste glass powder and water were mixed in a concrete paddle mixing machine by placing the materials in an ascending order, at a constant mixing rate until uniformity was achieved and slump determined as illustrated in figure 3.3. Fresh concrete was then cast into 100 mm X 100 mm X 100 mm moulds in 3 layers tamping 25 times using standard tamping rod after each layer then levelled. The casted concrete was then be left in the mould covered with moist covering under shade for a period of 24 hours after which they were demoulded and placed in curing tank as shown in figure 3.4.



**Figure 3.3: Concrete Mixing and Slump Test.**



**Figure 3.4: Fresh Concrete in Moulds and Hardened Demoulded Samples.**

Test samples for sulphate resistance test were prepared from fresh mortar paste with equivalent mix ratios as of the concrete mixes and then subjected to curing in 5% Magnesium Sulphate solution for 28 days, samples were as shown in figure 3.5.



**Figure 3.5: Fresh and Hardened Mortar Samples.**

### **3.2.3 Curing of Hardened Concrete**

Demoulded concrete was placed in specifically marked curing tanks containing saturated lime water at room temperature for period of 7, 14 and 28 days respectively to allow for the hydration processes. Saturated lime water helps reduce leaching of hydration salts during curing. Hardened concrete on maturity was then be subjected to compressive strength, water absorption, electrical resistivity and sulphate attack tests.

## **3.3 Laboratory Tests**

Laboratory tests conducted were specific to meet research objectives that guided the data collected. Tests were carried out on constitute aggregates and the concrete.

### **3.3.1 Tests on Aggregates**

Tests on aggregates help determine properties of the individual aggregates.

#### **3.3.1.1 Sieve Analysis**

Sieve analysis was carried out on sand and ballast to determine the grading of the aggregates.

#### **3.3.1.2 Aggregate Impact and Crushing Value**

The coarse aggregates were subjected to Aggregate Impact and Crushing Value tests in accordance to specifications of (BS 812 - 110, 1990) and (BS 812 - 112, 1990) respectively.

#### **3.3.1.3 Water Absorption**

The fine and coarse aggregates were subjected to water absorption in accordance to specifications of (BS ISO 20290 - 1, 2021).

### **3.3.2 Tests on Fresh Concrete**

Laboratory tests on fresh concrete helped understand the physical properties and performance of freshly prepared concrete.

### **3.3.2.1 Slump Test**

Fresh concrete was tested for slump to determine the ease of placement of fresh concrete in accordance to guidelines of (BS 12350 - 2, 2019).

### **3.3.3 Tests on Hardened Concrete**

Laboratory tests on hardened concrete helped understand the physical and chemical properties and performance of the hardened concrete.

#### **3.3.3.1 Compressive Strength Test**

Hardened concrete was subjected to compressive strength test at days 7, 14 and 28. Concrete samples were removed from the curing tank, wiped to remove excess surface water and air-dried under shade for at least an hour. The dimensions and weight of the samples were recorded, then subjected to gradual axial compressive force in a compressive testing machine. The load at failure was recorded and used to determine the compressive strength by computing the load per unit area at failure, the result was reported for each specimen per testing age, (BS EN 12390 - 3, 2019).

#### **3.3.3.2 Water Absorption Test**

Hardened concrete samples were removed from the curing tanks after 28 days of curing, cleaned with fresh running water, wiped dry and oven-dried for a period of 72 hours at temperature of  $105 \pm 5$  °C. The oven-dried samples were then removed from the oven and allowed to cool for a period of 24 hours in a moisture-free environment. Initial weight after cooling was recorded and the samples immersed in clean water at room temperature at an interval of 30 minutes removing and reweighing for up to 2 hours. Water absorption was then computed as the difference between mass after immersion and mass of the oven-dried sample, (BS 1881 - 122, 2011).

### **3.3.3.3 Sulphate Attack Test**

A solution of 5% Magnesium Sulphate ( $\text{MgSO}_4$ ) was prepared and allowed to settle for 24 hours. Mortar samples were then immersed into the solution for a period of 28 days at constant concentration with pH of between 6 to 8. The samples were then removed from the solution, wiped dry and allowed to dry under shade. The samples were then be weighed and length measurement recorded.

### **3.3.3.4 Electrical Resistivity Test**

Electrical resistivity test was carried out to determine resistivity of the concrete to electrical current as an indication of its permeability to chloride ions at age of 28 days. Hardened concrete was removed from curing tank, cleaned, wiped dry and airdried under shade. The sample dimensions and weight were recorded, two holes 20 mm deep, 10 mm wide was drilled into the samples, filled with sodium chloride. Resistivity meter electrodes were then placed into the holes and used to trigger the electrolysis process, current flowing through the concrete was then be recorded for each sample, (AASHTO T358, 2015).

## **3.4 Data Analysis**

To achieve the objectives of the research, descriptive data analysis method was used to analyse laboratory collected data and presented inform of tables and graphs. Compressive strength, water absorption and sulphate attack data were obtained by determining the mean value of three samples per data set considered and average values determined. The data was then presented in graph as shown in figures 4.3, 4.4, 4.5, 4.6 and 4.7.

## CHAPTER FOUR: RESULTS AND DISCUSSION

This chapter discusses the analysed results of the research in relation to findings of other previous researches.

### 4.1 Concrete Material Properties

#### 4.1.1 Water Absorption, ACV and AIV

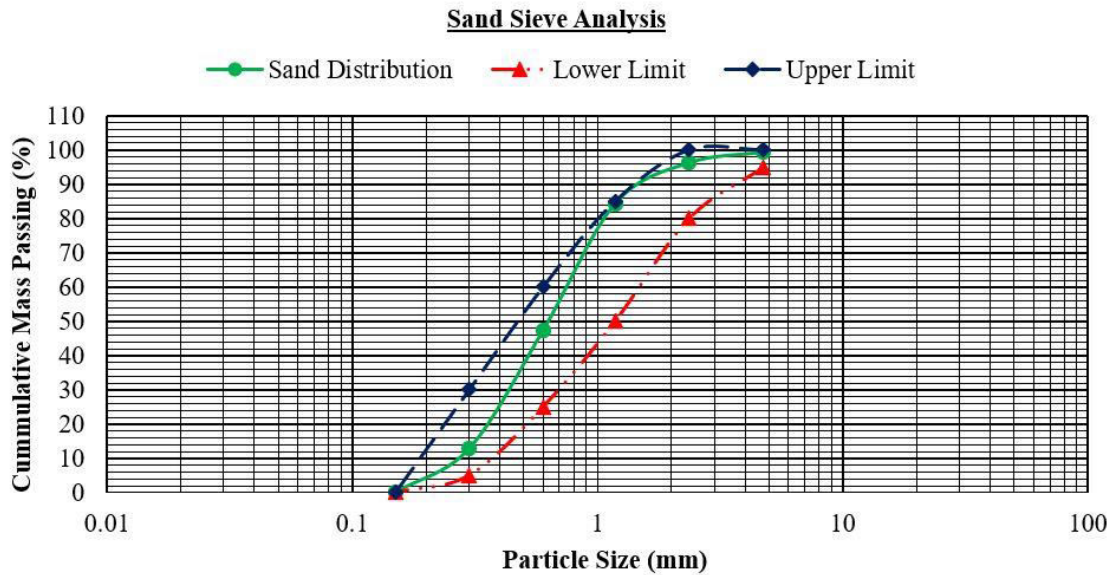
Ballast was subjected to ACV, AIV and Water Absorption tests while sand was subjected to water absorption and silt tests prior to batching as part of material profiling as indicated in table 4.1. The test results were below the maximum allowable limits hence the materials were suitable for use in concreting.

**Table 4.1: Properties of Concrete Aggregates, (Appendix A.1, A.2, A.3, A.4 & A.5).**

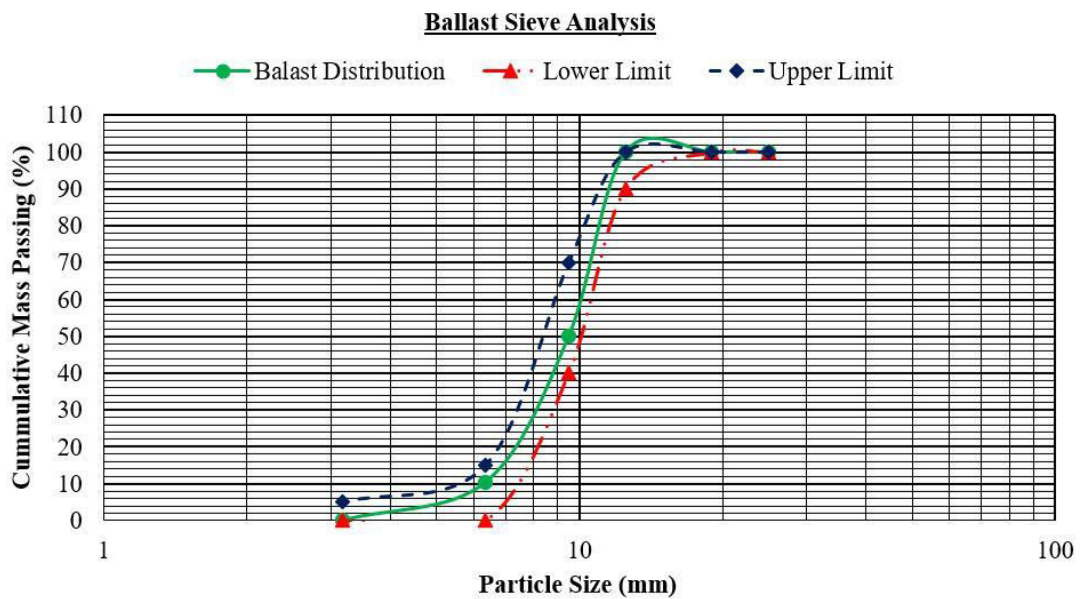
	<b>Water Absorption (%)</b>	<b>ACV (%)</b>	<b>AIV (%)</b>	<b>Silt Content (%)</b>
Maximum limit	3	30	45	7
Coarse Aggregate	2.6	18.4	13.4	-
Fine Aggregate	2.4	-	-	6.9

#### 4.1.2 Sieve Analysis

Sieve analysis was used to determine grading of the fine and coarse aggregates, the results were illustrated in figure 4.1 and figure 4.2.



**Figure 4.1: Sand Sieve Analysis.**



**Figure 4.2: Ballast Sieve Analysis.**

Sieve analysis determined distribution of particles in the aggregates. The particle distribution within the aggregates were found to be within the lower and upper limits as per requirements of ASTM C33/C33M, (ASTM International, 2018) indicating they were well graded.

## 4.2 Fresh Concrete Property

Fresh concrete was subjected to slump test to determine the ease of workability of the concrete. The results are as shown in table 4.2. An increase in slump was noted across the mixes compared to the control sample, this was similar to findings of (Soliman & Tagnit-Hamou, 2017), (Eme & Nwaobakata, 2019). This performance can be attributed to the use of superplasticizer which causes dispersion of cement and crushed waste glass powder particles coupled with the crystalline non-porous micro structure nature of the crushed waste glass powder with lower water absorptivity hence free flow of the particles.

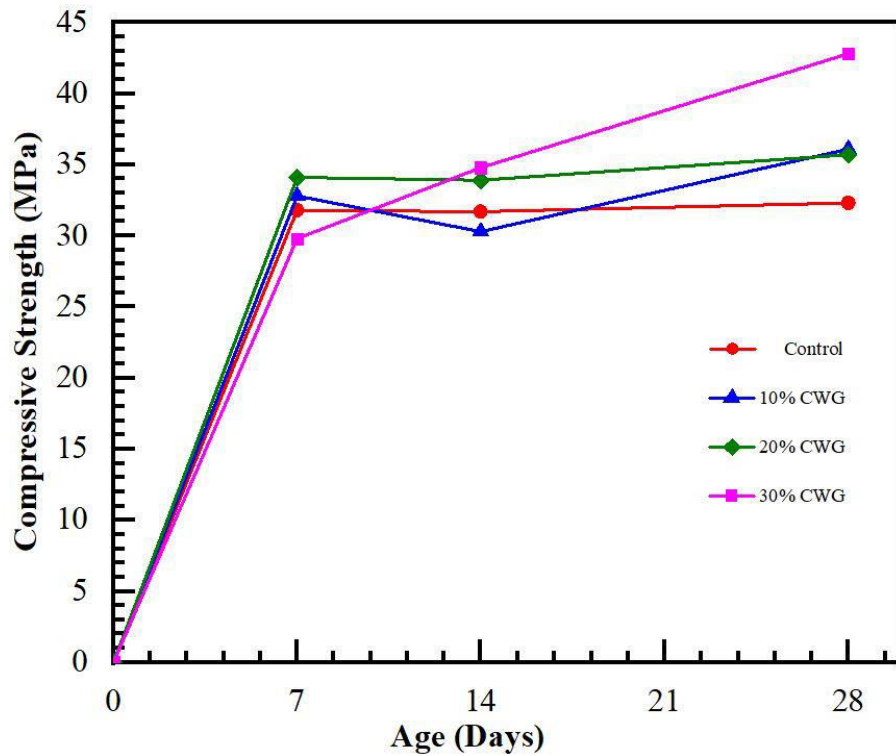
**Table 4.2: Slump Test Results.**

<b>Mix ID</b>	<b>Mix 1: Control</b>	<b>Mix 2: 10% CWG</b>	<b>Mix 3: 20% CWG</b>	<b>Mix 4: 30% CWG</b>
<b>Slump (mm)</b>	135	200	-	-
<b>Flow Diameter (mm)</b>	-	-	555	655

## 4.3 Hardened Concrete Properties

### 4.3.1 Compressive Strength

Hardened concrete was subjected to compressive strength test at 7, 14 and 28 days respectively in accordance to guidelines of BS EN 12390 – 3, the results were as shown in figure 4.3.



**Figure 4.3: Compressive Strength.**

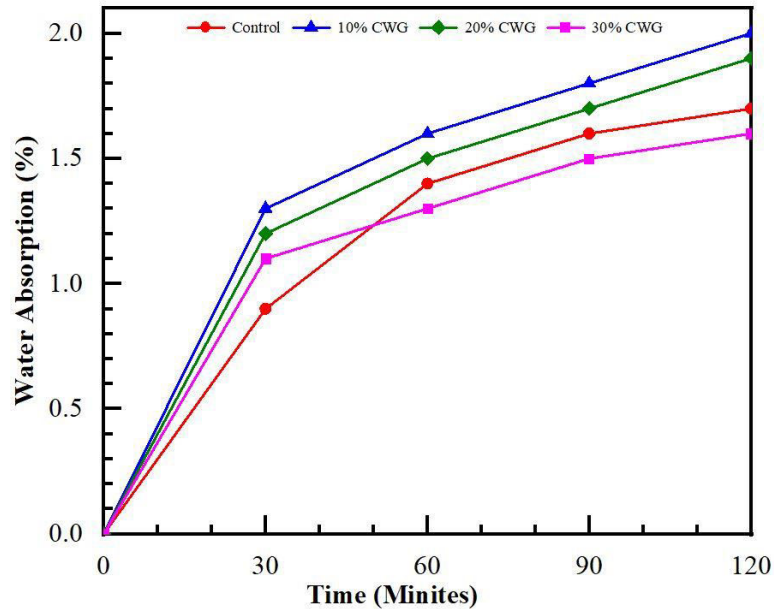
Compressive strength increased by 10.1%, 8.8% and 30.5% for mix 2, 3 and 4 respectively at day 28 relative to mix 1. This performance indicated an increase in compressive strength with an increase in the amount of crushed waste glass powder across all the mix proportions. The trend can be attributed to pozzolanic reaction of crushed waste glass powder and cement during the hydration process where silica in glass powder dissolves under an alkaline environment reacting with calcium ions to form C – S – H gel similar to findings of (Elaqra, Abou Haloub, & Rustom, 2019), (Du & Tan, 2016) and (Bhat & Rao, 2014). Relative Index (RI) was determined based on equation 2.1 giving a value of 0.77 a positive value noting that the addition of glass powder had positive effect on the compressive strength.

$$RI = 1 - \frac{32.8 \times 30}{42.8 \times 100} = 0.77 \dots\dots\dots \text{Equation 1.1}$$

### 4.3.2 Water Absorption

Hardened concrete was subjected to water absorption test after 28 days of curing in accordance with guidelines of BS 1881 – 122: 2011. The results were as shown in figure

4.4.



**Figure 4.4: Rate of Water Absorption.**

An increase of 17.6% and 11.7% for mix 2 and 3 and a decrease of 5.9% in mix 4 respectively were noted after 120 minutes immersion in water compared to mix 1. Rapid absorption is noted within the first 30 minutes due capillary suction by pores caused by deprivation of moisture during oven drying leaving voids within the concrete matrix. The rate of absorption later on gradually decreases across all mixes as the voids get filled and aggregates start absorbing water. Mix 4 sustained a lower rate of water absorption among all the mixes. This performance can be attributed to the densification effect of the crushed waste glass powder as the quantity is increased providing finer particles for densification of the concrete mix. (Du & Tan, 2016) observation of similar reduction in water absorption relative to increase of amount of glass powder in concrete mix attributed the performance to contribution of glass powder to production of additional hydration products that lead to the formation of C – S – H gel that densify the pore structure of concrete.

### 4.3.3 Sulphate Attack

Sulphate Attack test was conducted as per the guidelines of ASTM C1012 – 04. The test results were as shown in figure 4.5 and figure 4.6.

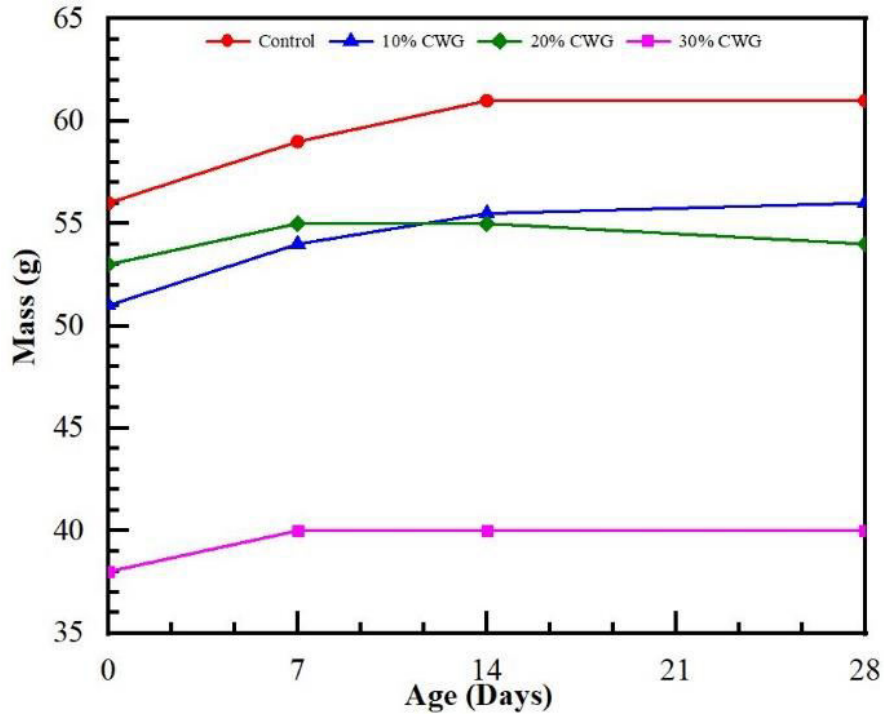


Figure 4.5: Mass Variation after Sulphate Attack.

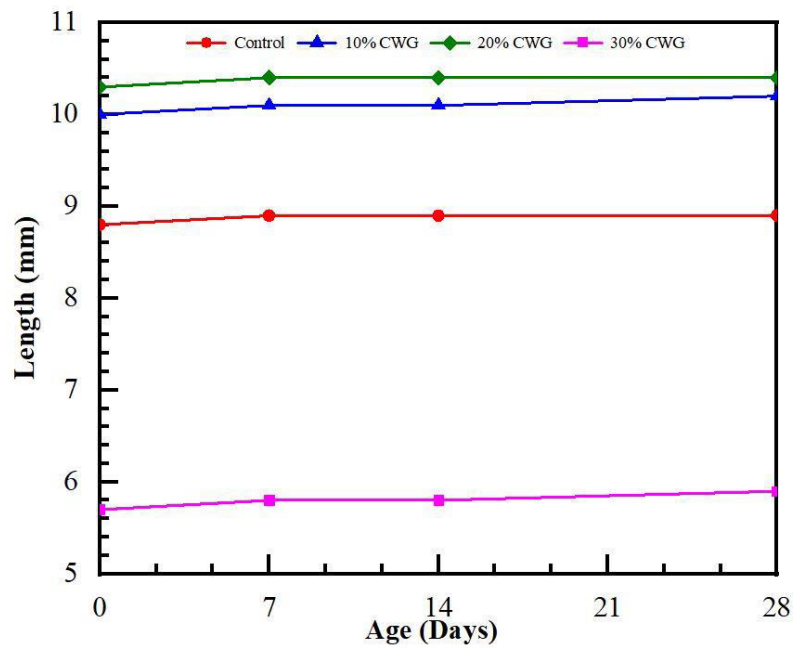


Figure 4.6: Length Variation after Sulphate Attack.

Mass increase of 8.9%, 9.8%, 5.3% and a decrease of 1.8% for mix 1, 2, 4 and 3 was noted respectively relative to day 0. Similarly, length increase of 1.1%, 2%, 1% and 3.5% respectively was noted for mix 1, 2, 3 and 4 respectively relative to day 0. Increase in mass and increase in length across the mixes relative to control mix could be attributed to ingress of sulphate ion which react with gypsum in cement forming ettringite that is subsequently transformed into a thin mono-sulphate aluminate hydrate. Further attack on mono-sulphate aluminate hydrate leads to expansion and cracking through conversion into ettringite crystals. Additionally, increase in mass can be explained by magnesium sulphate attack that results in hard dense granular particles deposition of magnesium hydroxide in concrete pores, (Tittelboom, Belie, & Hooton, 2012) and (Du & Tan, 2016).

#### 4.3.4 Chloride Permeability

Chloride Permeability was determined by inferring to the electrical resistivity performance of hardened concrete as per guidelines of ASTM C1202 – 12. The results were as shown in figure 4.7.

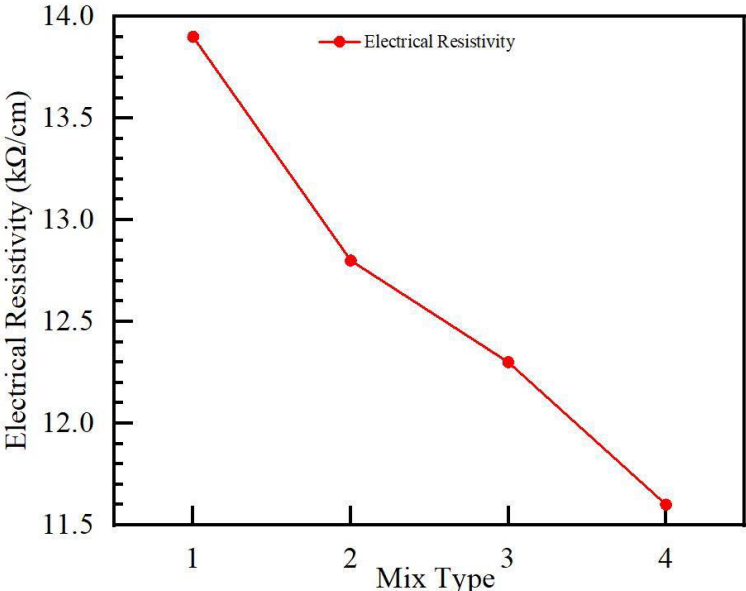


Figure 4.7: Electrical Resistivity.

A decrease of 5.9%, 9.6% and 14.7% was noted for mix 2, 3 and 4 respectively relative to mix 1 at day 28 with an increase in the quantity of crushed waste glass powder yet within moderate classification in terms of chloride permeability, (AASHTO T358, 2015) and as indicated in table 2.1. This performance could be attributed to the level of porosity, pore structure and pore solution temperature among other varying factors that affect the movement of ions within the concrete microstructure as explained by (Du & Tan, 2016), (Eglinton, 2003) and (Layssi, Ghods, Alizadeh, & Salehi, 2015).

## **CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS**

This chapter presents the conclusions drawn from the findings of the study in relation to the overall objective and specific objectives. The main objective of the research was to determine the effect of incorporating crushed waste glass powder on the durability performance of hardened concrete in aggressive environments. The specific objectives were: (1) To determine the rate of water absorption of concrete when glass powder is incorporated in varying proportions; (2) To evaluate the effect of sulphate attack on concrete when glass powder is incorporated in varying proportions; and (3) To determine the chloride permeability of concrete when glass powder is incorporated in varying proportions. The chapter also provides recommendations for practice and further research.

### **5.1 Conclusions**

Based on the results obtained, the following conclusions are made:

#### **1. Water absorption and permeability**

Incorporation of glass powder reduced the permeability of concrete to water. The maximum reduction of 5.9% was observed at 30% replacement by weight of cement, indicating enhanced resistance to ingress of moisture and potentially aggressive agents.

#### **2. Sulphate attack resistance**

Under sulphate exposure, concrete with glass powder showed slight increases in mass by 5.3% and length by 3.5% at 30% replacement. This suggests that while glass powder does not significantly improve sulphate resistance, its performance remains comparable to conventional concrete and may serve as sacrificial protection in sulphate-rich environments.

### 3. Chloride – related durability

The surface electrical resistivity of concrete decreased by 14.7% at 30% replacement, implying a reduction in resistance to chloride ion penetration. This highlights a durability trade-off, where improvements in permeability may be accompanied by reduced chloride-related performance.

Overall, the study demonstrates that glass powder has potential as a supplementary cementitious material for enhancing certain durability parameters, particularly moisture permeability, while also pointing to the need for careful optimization to balance performance under different aggressive conditions.

## **5.2 Recommendations**

### **5.2.1 Recommendation from the Research**

- 1 Moderate incorporation of glass powder at 30% addition may be considered in concrete applications where improved resistance to water permeability is required, such as water-retaining structures, foundations, or moisture-prone environments.
- 2 Given the mixed performance in sulphate and chloride resistance, large-scale application in highly aggressive environments such as offshore structures and sewer systems should be preceded by extended field validation.

### **5.2.2 Recommendations for Further Research**

During the research period, some limitations were noted and are recommended for further investigations. The main recommendations for further investigations are as follows:

1. Investigate the mechanisms responsible for the observed reduction in electrical resistivity, including microstructural and pore structure analyses.
2. Conduct long-term field studies to validate laboratory findings under real environmental exposure conditions.
3. Explore the influence of different particle sizes and fineness of glass powder on durability performance.
4. Assess combined exposure conditions such as simultaneous chloride and sulphate attack to better simulate real service environments.
5. Evaluate the environmental and economic benefits of largescale adoption of waste glass powder in cementitious systems.

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## APPENDIX

### Appendix A: Material Properties

#### A.1 Ballast Aggregate Impact Value Results

Sample No.	Mass of Crushed Aggregates (g)	Mass of Aggregates Passing 2.4 mm Sieve (g)	Aggregate Impact Value (%)
1	545	71	13
2	534	74	13.9
3	535	72	13.5
<b>Average</b>	<b>538</b>	<b>72.3</b>	<b>13.4</b>

#### A.2 Ballast Aggregate Crushing Value Results

Sample No.	Mass of Crushed Aggregates (g)	Mass of Aggregates Passing 2.4 mm Sieve (g)	Aggregate Crushing Value (%)
1	3455	640	18.5
2	3458	632	18.3
3	3456	635	18.4
<b>Average</b>	<b>3456.3</b>	<b>635.7</b>	<b>18.4</b>

#### A.3 Ballast Water Absorption

Sample No.	Initial Mass (g)	Saturated Mass (g)	Absorbed Water (g)	Water Absorption (%)
1	1000	1027	27	2.7
2	1000	1024	24	2.4
3	1000	1026	26	2.6

<b>Average</b>	<b>1000</b>	<b>1025.7</b>	<b>25.7</b>	<b>2.6</b>
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#### A.4 Sand Water Absorption

<b>Sample No.</b>	<b>Initial Mass (g)</b>	<b>Saturated Mass (g)</b>	<b>Absorbed Water (g)</b>	<b>Water Absorption (%)</b>
1	1000	1026	26	2.6
2	1000	1023	23	2.3
3	1000	1024	24	2.4
<b>Average</b>	<b>1000</b>	<b>1024.3</b>	<b>24.3</b>	<b>2.4</b>

#### A.5 Sand Silt Content Test

<b>Sample No.</b>	<b>Overall Height, H (mm)</b>	<b>Sand Height (mm)</b>	<b>Silt Height (mm)</b>	<b>Silt Content (%)</b>
1	6.4	6.0	0.4	6.3
2	6.3	5.9	0.4	6.3
3	6.2	5.7	0.5	8.1
<b>Average</b>	<b>6.3</b>	<b>5.9</b>	<b>0.4</b>	<b>6.9</b>

#### A.6 Sand Sieve Analysis

<b>Sieve Size (mm)</b>	<b>Mass Retained (g)</b>			
	<b>Sample ID</b>			<b>Average</b>
	<b>1</b>	<b>2</b>	<b>3</b>	
4.75	16	2	0	<b>6</b>
2.4	34	32	24	<b>30</b>
1.2	104	126	110	<b>113</b>
0.6	308	382	362	<b>351</b>
0.3	358	306	316	<b>327</b>
0.15	148	108	110	<b>122</b>
Pan	30	38	30	<b>33</b>
<b>Total</b>	<b>998</b>	<b>994</b>	<b>952</b>	<b>981</b>

**A. 6.1**

<b>Sieve Size (mm)</b>	<b>Mass Retained (g)</b>	<b>Cumulative Mass Retained (g)</b>	<b>Cumulative Mass Retained (%)</b>	<b>Cumulative Mass Passing (%)</b>	<b>Lower Limit (%)</b>	<b>Upper Limit (%)</b>
4.75	6	6	0.61	99.39	95	100
2.36	30	36	3.67	96.33	80	100
1.18	113	149	15.17	84.83	50	85
0.6	351	500	50.92	49.08	25	60
0.3	327	827	84.22	15.78	5	30
0.15	122	949	96.64	3.36	0	10
Pan	33	982	100	0	0	0
<b>Total</b>	<b>982</b>					

**A.7 Ballast Sieve Analysis**

<b>Sieve Size (mm)</b>	<b>Mass Retained (g)</b>			
	<b>Sample ID</b>			<b>Average</b>
	<b>1</b>	<b>2</b>	<b>3</b>	
25	0	0	0	<b>0</b>
19	0	0	0	<b>0</b>
12.5	0	0	0	<b>0</b>
9.5	489	480	485	<b>485</b>
6.35	388	385	382	<b>385</b>
3.18	98	105	96	<b>100</b>
Pan	30	27	32	<b>30</b>
<b>Total</b>	<b>1005</b>	<b>997</b>	<b>995</b>	<b>1000</b>

**A. 7.1**

<b>Sieve Size (mm)</b>	<b>Mass Retained (g)</b>	<b>Cumulative Mass Retained (g)</b>	<b>Cumulative Mass Retained (%)</b>	<b>Cumulative Mass Passing (%)</b>	<b>Lower Limit (%)</b>	<b>Upper Limit (%)</b>
<b>25.00</b>	0	0	0	100	100	100
<b>19.00</b>	0	0	0	100	100	100
<b>12.50</b>	0	0	0	100	90	100
<b>9.50</b>	485	485	48.5	52	40	70
<b>6.35</b>	385	870	87	13	0	15
<b>3.18</b>	100	970	97	3	0	5
Pan	30	1000	100	0	0	0
<b>Total</b>	<b>1000</b>					

## A.8 XRF for CEM IV/ B(P) 32.5N Cement



00763-GeoChem.pdz	AssayTime: 9/15/2023 4:17:50	ElapsedTime: 24
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Alloy 1:	Match No:
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Field Info			
Operator	SUPERVISOR	Sender name	WILLIAM ONYANGO
Sample type	CEMENT	Sender ref	CEM 1V/B 32.5N CEMENT
LAB NO			

Element Name	Min	%	Max	+/- [*3]
MgO	0	0.000	0	1.753
Al2O3	0	7.419	0	0.589
SiO2	0	43.662	0	0.795
P2O5	0	0.191	0	0.109
S	0	1.738	0	0.061
Cl	0	0.013	0	0.027
K2O	0	2.640	0	0.049
CaO	0	40.585	0	0.160
Ti	0	0.247	0	0.015
V	0	0.001	0	0.007
Cr	0	0.000	0	0.005
Mn	0	0.108	0	0.015
Fe	0	3.215	0	0.063
Co	0	0.000	0	0.005
Ni	0	0.000	0	0.004
Cu	0	0.024	0	0.005
Zn	0	0.028	0	0.003
As	0	0.001	0	0.001
Se	0	0.000	0	0.001
Rb	0	0.007	0	0.002
Sr	0	0.060	0	0.003
Y	0	0.005	0	0.002
Zr	0	0.041	0	0.002
Nb	0	0.008	0	0.002
Mo	0	0.004	0	0.002



00763-GeoChem.pdz	AssayTime: 9/15/2023 4:17:50	ElapsedTime: 24
Alloy 1:		Match No:

Element Name	Min	%	Max	+/- [*3]
Ag	0	0.000	0	0.003
Cd	0	0.000	0	0.005
Sn	0	0.000	0	0.018
Sb	0	0.000	0	0.007
Ba	0	0.000	0	0.043
La	0	0.000	0	0.093
Ce	0	0.000	0	0.028
Hf	0	0.000	0	0.004
Ta	0	0.000	0	0.003
W	0	0.001	0	0.002
Pt	0	0.000	0	0.002
Au	0	0.000	0	0.003
Hg	0	0.000	0	0.002
Tl	0	0.000	0	0.002
Pb	0	0.000	0	0.003
Bi	0	0.000	0	0.004
Th	0	0.000	0	0.007
U	0	0.000	0	0.011

## A.9 XRF for Crushed Waste Glass Powder



00762-GeoChem.pdz	AssayTime: 9/15/2023 4:16:09	ElapsedTime: 26
-------------------	------------------------------	-----------------

Alloy 1:	Match No:
----------	-----------

Field Info			
Operator	SUPERVISOR	Sender name	WILLIAM ONYANGO
Sample type	POWDER	Sender ref	WASTE GLASS POWDE...
LAB NO			

Element Name	Min	%	Max	+/- [*3]
MgO	0	4.583	0	1.531
Al2O3	0	0.703	0	0.332
SiO2	0	83.383	0	1.045
P2O5	0	0.116	0	0.058
S	0	0.148	0	0.025
Cl	0	0.001	0	0.025
K2O	0	0.272	0	0.019
CaO	0	10.553	0	0.078
Ti	0	0.042	0	0.007
V	0	0.002	0	0.003
Cr	0	0.000	0	0.003
Mn	0	0.028	0	0.008
Fe	0	0.147	0	0.011
Co	0	0.000	0	0.000
Ni	0	0.000	0	0.002
Cu	0	0.004	0	0.002
Zn	0	0.002	0	0.001
As	0	0.000	0	0.001
Se	0	0.000	0	0.001
Rb	0	0.003	0	0.001
Sr	0	0.006	0	0.001
Y	0	0.000	0	0.001
Zr	0	0.009	0	0.001
Nb	0	0.000	0	0.001
Mo	0	0.000	0	0.002



00762-GeoChem.pdz	AssayTime: 9/15/2023 4:16:09	ElapsedTime: 26
Alloy 1:		Match No:

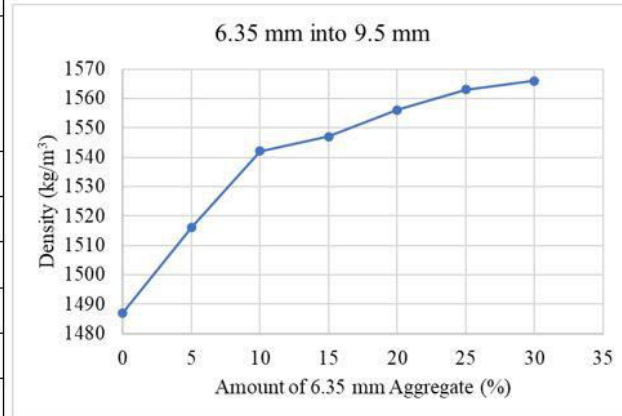
Element Name	Min	%	Max	+/- [*3]
Rh	0	0.000	0	0.003
Pd	0	0.000	0	0.005
Ag	0	0.000	0	0.003
Cd	0	0.000	0	0.005
Sn	0	0.000	0	0.016
Sb	0	0.000	0	0.007
Ba	0	0.000	0	0.029
La	0	0.000	0	0.071
Hf	0	0.000	0	0.005
Ta	0	0.000	0	0.001
W	0	0.000	0	0.001
Pt	0	0.000	0	0.002
Au	0	0.000	0	0.002
Hg	0	0.000	0	0.001
Tl	0	0.000	0	0.001
Pb	0	0.000	0	0.003
Bi	0	0.000	0	0.003
Th	0	0.000	0	0.005
U	0	0.000	0	0.009

## Appendix B: Mix Design

### B.1 6.35 mm Aggregate into 9.5 mm Aggregate

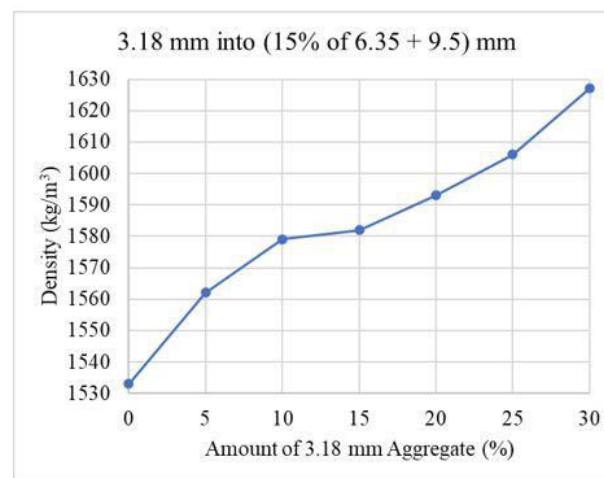
Volume of Mould = 2651

6.35 mm into 9.5 mm			
Mass of 6.35 mm Aggregate (g)	Amount (%)	Compacted Mass (g)	Density (kg/m <sup>3</sup> )
	0	3942	1487
197.1	5	4018	1516
394.2	10	4088	1542
591.3	15	4102	1547
788.4	20	4126	1556
985.5	25	4144	1563
1182.6	30	4152	1566



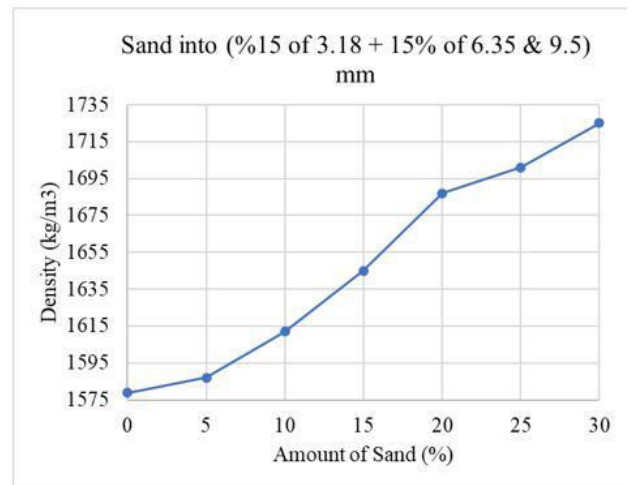
### B.2 3.18 mm Aggregate into (15% of 6.35 + 9.5) mm Aggregate

3.18 mm into (15% of 6.35 + 9.5) mm			
Mass of 3.18 mm Aggregate (g)	Amount (%)	Compacted Mass (g)	Density (kg/m <sup>3</sup> )
	0	4064	1533
207	5	4140	1562
414	10	4186	1579
621	15	4194	1582
828	20	4224	1593
1035	25	4258	1606
1242	30	4312	1627



### B.3 Sand into (15% of 3.18 + 15% of 6.35 + 9.5) mm Aggregate

Sand into (15% of 3.18 + 15% of 6.35 & 9.5) mm			
Mass of 6.35 Aggregate	Amount (%)	Compacted Mass (g)	Density (kg/m <sup>3</sup> )
	0	4186	1579
209.3	5	4206	1587
418.6	10	4274	1612
627.9	15	4360	1645
837.2	20	4472	1687
1046.5	25	4510	1701
1255.8	30	4574	1725



### B.4 Material Proportioning

#### DENSIFIED MIXTURE DESIGN ALGORITHM (DMA)

Material	Density (kg/m <sup>3</sup> )
Water	1000
Cement	2840
CWG	1300
Aggregates	2700
MDD	1701
Superplasticizer	1080

#### Mass of Cement, $M_{Cement}$

$$V_{Rate} = V_{Cement} + V_{Superplasticizer} + V_{Water}$$

$$M_{Cement} = 0.35 / \left\{ \frac{1}{2840} + \frac{0.02}{1080} + \frac{0.35}{1000} \right\}$$

$$M_{Cement} = \frac{0.35}{0.00072052} = 485.76 \text{ kg}$$

#### Mass of Aggregates

$$\text{Sand} = 0.25 * 1701 = 425.25 \text{ kg}$$

$$3.18 \text{ mm Aggregate} = 0.15 * 1275.75 = 191.363 \text{ kg}$$

$$6.35 \text{ mm Aggregate} = 0.15 * 1084.387 = 162.658 \text{ kg}$$

$$9.5 \text{ mm Aggregate} = 1701 - 779.271 = 921.729 \text{ kg}$$

$$V_{Concrete} = V_{Aggregates} + V_{Void} + V_{Rate}$$

#### Assumptions

$$V_{Concrete} = 1 \text{ m}^3$$

$$V_{Rate} = 2\% \text{ of Concrete Volume} = 0.02 \text{ m}^3$$

$$1 = V_{Aggregates} + 0.02 + V_{Rate}$$

$$0.98 = V_{Aggregates} + V_{Rate}$$

$$V_{Aggregates} = \frac{Mass}{Density} = \frac{1701}{2700} = 0.63 \text{ m}^3$$

$$0.98 = 0.63 + V_{Rate}$$

$$V_{Rate} = 0.35 \text{ m}^3$$

From Packing of Aggregates chart (B.1 to B.3), material composition

Material	Ratio
Water/Cement	0.35
Superplasticizer	0.02
Sand	0.25
3.18 mm Aggregate	0.15
6.35 mm Aggregate	0.15

#### Mix Design Proportions per cubic meter of concrete

Material	Quantity (kg/m <sup>3</sup> )
Water	170
Superplasticizer	10
Cement	486
Sand	425
3.18 mm Aggregate	191
6.35 mm Aggregate	163
9.5 mm Aggregate	922

## Appendix C: Test Results

### C.1 Compressive Strength Results.

Mix ID	Mix 1: Control	Mix 2: 10% CWG	Mix 3: 20% CWG	Mix 4: 30% CWG
Age (Days)	Compressive Strength (N/mm <sup>2</sup> )			
7	31.8	32.8	34.1	29.8
14	31.7	30.3	33.9	34.8
28	32.8	36.1	35.7	42.8

### C.2 Water Absorption Results.

Mix ID	Mix 1: Control	Mix 2: 10% CWG	Mix 3: 20% CWG	Mix 4: 30% CWG
Time (Min)	Water Absorption (%)			
0	0	0	0	0
30	0.9	1.3	1.2	1.1
60	1.4	1.6	1.5	1.3
90	1.6	1.8	1.7	1.5
120	1.7	2	1.9	1.6
1440	2.3	2.6	2.4	2.1

### C.3 Sulphate Attack Mass Variation.

Mix ID	Mix 1: Control	Mix 2: 10% CWG	Mix 3: 20% CWG	Mix 4: 30% CWG
Age (Days)	Mass Variation (g)			
0	56	51	55	38
7	59	54	55	40
14	61	55.5	55	40
21	59	54	55	40
28	61	56	54	40




### C.4 Sulphate Attack Length Variation.

Mix ID	Mix 1: Control	Mix 2: 10% CWG	Mix 3: 20% CWG	Mix 4: 30% CWG
Age (Days)	Length Variation (mm)			
0	8.8	10	10.3	5.7
7	8.9	10.1	10.4	5.8
14	8.9	10.1	10.4	5.8
21	8.9	10.1	10.4	5.8
28	8.9	10.2	10.4	5.9

### C.5 Electrical Resistivity Results.

Mix ID	Mix 1: Control	Mix 2: 10% CWG	Mix 3: 20% CWG	Mix 4: 30% CWG
Ohm Meter Reading (kΩ/cm)	13.6	12.8	12.3	11.6

## Appendix D: NACOSTI Research Permit

 <b>REPUBLIC OF KENYA</b>	 <b>NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY &amp; INNOVATION</b>
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<b>This is to Certify that Mr. Frank ONYANGO ODERO of Masinde Muliro University of Science and Technology, has been licensed to conduct research as per the provision of the Science, Technology and Innovation Act, 2013 (Rev.2014) in Nairobi on the topic: EFFECT OF GLASS POWDER ON DURABILITY PERFORMANCE OF HARDENED CONCRETE IN AGGRESSIVE ENVIRONMENT for the period ending : 08/August/2025.</b>	
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## Appendix E: Research Paper Publication

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### Effect of Glass Powder on Durability Performance of Hardened Concrete in Aggressive Environment

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**Abstract** – Supplementary Cementitious Materials have been widely researched for application in concrete works, primarily to reduce dependence on cement as a binding medium. This research sought to add to that knowledge base by determining the effect of crushed waste glass powder on the durability performance of hardened concrete in an aggressive environment. Crushed waste glass powder was added to the concrete mix at 10%, 20% and 30% respectively by weight of cement. Fresh concrete was subjected to slump test while hardened concrete was subjected to compressive strength, water absorption, sulphate attack and electrical resistivity tests. The results were then compared to the control mix as well as previous studies. Optimal results were obtained at 30% addition of crushed waste glass powder into the concrete mix, noting an increase in compressive strength by 32.5%, water absorption reduced by 5.9%, sulphate attack effect was low while electrical resistivity reduced by 14.7%.

**Keywords:** *Absorptivity, Crushed Waste Glass, Durability, Electrical Resistivity, Pozzolanic Activity, Sulphate Attack.*

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#### 1. Introduction

The quality of concrete is primarily affected by the quality of constituent aggregates which ultimately affect its durability [1]. Factors that affect concrete durability period include but are not limited to its constituents, proportioning of the constituents, interaction between the constituents, placing of concrete, curing technique and service environment exposure conditions [2]. Determination of concrete durability is subject to performance parameters such as exposure conditions, permeability and abrasion resistance among other factors as indicators of its properties [3]. Concrete subjected to an aggressive environment tends to deteriorate by spalling, cracking, weathering and abrasion among other means thereby allowing further ingress and exposing concrete to further degradation [4], [5].

Improper packing of concrete microstructure and use of a higher water binder ratio results in development of voids, increased permeability, risk of bleeding and segregation. Supplementary Cementitious Materials (SCM) such as crushed waste glass powder and modification of mix design have been adopted as a measure to mitigate such degrading effects. Proper packing of the microstructure of concrete and enriching of cementing paste reduces the permeability of concrete by minimising the void ratio hence increasing the durability performance of concrete. [6], [1].

Performance of glass powder in concrete has been well documented through various researches. Glass has been used as a Supplementary Cementitious Material (SCM) and as an aggregate in concrete development [7], [8] [9]. Chemical analysis between clear and coloured glass has been noted to have

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