ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

ADDIS ABABA INSTITUTE OF TECHNOLOGY

DEPARTMENT OF CIVIL ENGINEERING

A study on strength and water permeability of concrete containing glass powder as supplementary cementitious material

SAMUEL MEKONEN

ADVISOR: PROF. DR. - ING. ABEBE DINKU

A Thesis Submitted to School of Graduate Studies in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering

(Construction Technology and Management)

August, 2021

UNDERTAKING

I certify that research work titled "A Study on Strength and Water Permeability of Concrete Containing Glass Powder as Supplementary Cementitious Material" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

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Samuel Mekonen

The undersigned have examined the thesis entitled "**A Study on Strength and Water Permeability of Concrete Containing Glass Powder as Supplementary Cementitious Material**" presented by **Samuel Mekonen**, a candidate for the degree of Master **of Science** and hereby certify that it is worthy of acceptance.

Professor Abebe Dinku (Dr.-Ing)	________________	______________
ADVISOR	Signature	Date
____________________________	________________	______________
INTERNAL EXAMINER	Signature	Date
____________________________	________________	______________
EXTERNAL EXAMINER	Signature	Date
____________________________	________________	______________
CHAIRPERSON	Signature	Date

ACKNOWLEDGEMENTS

First of all, I praise to the Almighty God for giving me endurance, patience and grace to cope all the ups and downs throughout the studying and thesis work period.

I would like to pass my honest gratitude to my advisor and instructor Prof. Dr. -Ing. Abebe Dinku for his interesting teaching methodologies, punctuality during the whole studying period, helpful comments, sincere uphold, and counseling, wonderful conversations, creative and worthily suggestions during the various phases of my thesis work.

I would also like to thank Ethiopian Roads Authority for financing my postgraduate studies and thesis budget in collaboration with Addis Ababa University, Addis Ababa bottle and glass Share Company for giving me the information I required and for providing me sample waste glass free of charge for the research work.

My respectful thank goes to Ato Demessew Melaku, Fikru Bedada, Ato Biniam Fantahun and and W/ro Wubet Gebreyes, construction materials laboratory technical assistances, at Addis Ababa Institute of Technology, in School of Civil and Environmental Engineering. They have always given me their heartfelt cooperation and assistance during research work period.

I am thankful to all my friends, especially Solomon Tibebu, Leyouwork Sertse and Michael Wondimu for their material and moral support.

Finally, I greatly appreciate all the help from my family members who have always been supporting and encouraging me throughout the postgraduate study and during the thesis work.

Samuel Mekonen

Addis Ababa, Ethiopia

August, 2021

ABSTRACT

In today's boom of urbanization, construction of civil infrastructure is very important for any developing country. Particularly, in countries like Ethiopia, cement production is the most useful process for construction purpose despite its carbon emission to the atmosphere. Therefore, efforts are being done to develop some alternative material for concrete production using waste materials. Waste glass powder is one of such alternative materials.

This study focuses on strength development and water permeability of concrete containing waste glass powder (WGP) as supplementary cementitious material. Waste glasses were collected from Addis Ababa bottle and glass Share Company, washed, dried and ground to powder. The glass powder was sieved to a particle size of less than 75 micron and its chemical and physical properties were investigated. The setting time and normal consistency of the pastes with OPC, the compressive strength of mortars with OPC and PPC cement, the compressive and flexural strength of OPC concrete shaving a characteristic strength of 30 MPa concrete and finally water permeability of concrete with OPC cement partially replaced by waste glass powder from 5% to 20% cement replacement were studied and compared.

The water to cement ratio and amount of cement used for one cubic meter of control concrete mix was 0.55 and 335 kg/m^3 respectively. The mix design was carried out based on ACI 211, 2002. The compressive strength of concrete with glass powder at the 28 days for 5% and 10% replacement increased by 5.4% and 0.8% respectively; and keeps on decreasing by 4.5% and 7.3% for 15% and 20% replacement respectively. And the water penetration depth of concrete with glass powder at the 28 days for 5% and 10% replacement decreased by 9.3% and 5.1% respectively; and keep on increasing by 3.5% and 8.9% for 15% and 20% replacement respectively.

Key words: Glass powder, Cement replacement.

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LIST OF ABBREVIATIONS

%: Percent

Al_2O_3: Alumina

B_2O_3: Boron Oxide

C_2S: Dicalcium Silicate

C_3A: Ticalcium Aluminate

C_3S: Tricalcium Silicate

C_4AF: Tetra Calcium Alumino Ferrite

K_2O_3: PotassiumOxide

$\frac{Kg}{M^3}$: Kilogram per meter cube

Na_2O: Sodium Oxide

ASR: Alkali silica reaction

℃: Degree Centigrade

$Ca(OH)_2$: Calcium Hydroxide

CaO: Calcium Oxide

CM: Centimeter

C-S-H: Calcium Silicate Hydrate

GDP: Gross Domestic Product

MSW: Municipal Solid Waste

OPC: Ordinary Portland cement

PPC: Portland Pozzolana Cement

SCMs: Supplementary cementitious material

SiO_2: Silicon Dioxide

SSD: Saturated Surface Dry

W/(C + G): Water to cement and glassr ratio

W/C: Water to Cement Ratio

CHAPTER ONE

1. INTRODUCTION

1.1 General

Concrete is the most commonly used construction material in the world. It is formed by mixing cement, sand, coarse aggregate and water at a certain proportion. Generally, it can also be said that it is a blend of two ingredients: aggregate and paste. The aggregate contains fine aggregate (sand) and crushed stone (gravel) whereas the paste consists of cement and water with or without Cementitious materials and chemical admixtures. The main purpose of the paste is to bind the fine and coarse aggregates together. Comparatively, aggregates are inert filler materials which take up 70% to 80% of the volume of concrete [1]. Therefore, the proportions of these ingredients depend on workability, strength, durability and cost of the concrete.

Cement is one of the major ingredients of concrete. However, its production process makes it very expensive and environmentally unfriendly material. This is due to the carbon emission during mass production which results in global warming and environmental devastation. Therefore, the need for economic and environmentally friendly binding supplementary cementitious materials is increasing recently. Thus, wastes of industries need to be tested for use in concrete production. One of the solid wastes in industries such as beverage (during loading and unloading) and construction industries (during construction, rehabilitation, repair, installation and removal) of structures is waste glass [4].

There are different types of glass types depending up on the chemicals they are composed of such as: alkali-silicate glass, soda-lime silicate glass and boron-silicate glass. Currently these types of glasses are being used to produce concrete, brick and ceramic ingredients. Waste glass powder in cement increases the alkali content of the cement as glass contains sodium oxide and potassium oxide as clearly shown in the chemical composition and is usually used in concrete production as partial replacement of cement without adverse effect in durability.

Recently, glasses and its powder have been used as a construction material to minimize environmental problems. Glass can partially replace fine and coarse aggregate in concrete.

However, when it is used as partial replacement of fine and coarse aggregate it could cause ASR (alkali-silica reaction) in concrete, but the glass powder could suppress the ASR tendency, an effect similar to supplementary cementations materials (SCMs). Therefore, the glass in this paper is used as a supplementary cementitious material [2].

1.2 Statement of the Problem

Concrete is the most used material in the construction industry. The high flexibility of form, lower cost and good physical and mechanical properties of concrete made it very suitable for construction purpose. However, the increasing environmental pollution due to excessive emission of carbon dioxide over the last decades has attracted the attention of recycled or waste materials as concrete ingredients [4].

Introducing waste glass powder as partial replacement of cement or aggregate should be considered as an alternative material for concrete production. Glass can also be melted and recycled repeatedly without changing its properties. Dirt and other pieces of materials that are attached to the surface of the glass cullet having sizes below 8 mm are usually land filled or stockpiled by recycling companies. Therefore, making use of glass in concrete may improve its property rather than land filling. Moreover, urbanization in developing countries like Ethiopia has increased the demand for cement production which highly contributes for environmental carbon dioxide emission. Thus, the need for environmentally friendly alternative cementitious materials is very crucial. Therefore, collecting, cleaning and recycling waste glass ground to powder as supplementary cementitious material may improve the compressive strength of concrete, may reduce the cost of concrete production and may minimize environmental pollution.

Generally, the main reason for the need to replace cement by glass powder encompasses the following areas: -

1. Environmental friendliness of glass powder concrete.
2. The increase in price of cement in the Ethiopian industry.
3. Poor awareness of using glass powder as an alternative cementitious material.

1.3 Objective of the thesis project

1.3.1 General Objective

The main objective of the thesis project is:

- To investigate the possibility of improving the compressive strength and water permeability of concrete by replacing OPC cement partially with glass powder over a range of glass percentages.
- To compare the strength of glass concrete against conventional concrete.

1.3.2 Specific Objective

The specific objectives of the project are: -

- To study the chemical composition of waste glass powder.
- To study the influence of blending waste glass powder with OPC on the fresh properties of concrete mixes such as workability (using slump measures.)
- To study the influence of blending waste glass powder with OPC on hardened properties of concrete (density, compressive strength, flexural strength and water permeability.)
- To study the optimum content of waste glass powder to be added as a partial replacement of cement.
- To make cost comparison between concrete with and without glass powder.

1.4 Scope of the project

This project covers the study of physical and chemical properties of waste glass powder (container glass) powder, studying the properties of concrete ingredients, investigating fresh (workability) and hardened (compressive strength, flexural strength and water permeability) properties of conventional concrete and glass powder concrete at various ranges of cement replacement. And finally making cost comparison between concrete produced using waste glass powder as a partial replacement of cement and concrete produced without using glass powder as a partial replacement of cement.

1.5 Limitation

This research is intended to investigate the possibility of improving the compressive strength of concrete by replacing as much of the cement as possible by bottle glass powder (flint glass) over a range of glass powder percentages and compare its compressive strength against the conventional concrete. There was no access to study the chemical properties of flat glasses manufactured by the Chinese hansom glass manufacturing company located in Jemo. Since there was no crushing and screening machine for recycled waste glass, it was difficult to obtain glass powder as fine as desired for conducting the laboratory tests, as a result, the study was exposed to laborious works. Thus, other issues such as compressive strength of glass powder concrete at various fineness levels of glass is not included due to time limitation, difficulty to ground glass into powder and lack of finance to cover material, labor and transportation cost.

Moreover, it was difficult to obtain the required current data about the percentage of waste glass disposed in and around Addis Ababa from Addis Ababa City Administration. This has hindered the researcher from using current and updated information in the research paper.

1.6 Methodology

The methodology employed in this research was outlined in such a way that it can address both the general and specific objectives and for the development of concepts, which are fundamental for the formation of the whole research work.

A comprehensive literature review is made to understand the previous efforts made in the area which include the review of research papers, journals, textbooks and seminars. The type and method of data collection, organization, analysis and interpretation is made in order to achieve the main objective of the research work. The data collection methodology of the research work mainly covers observations, experiments and archival records.

Preparations of concrete making ingredients, proportioning, mixing and testing have been carried out as per the mix-design.

Based on the properties of concrete making ingredients, various types of laboratory tests were conducted on pastes, mortars and concrete have been conducted. The properties of cement, glass powder (flint glass) and their blends setting time and normal consistency have been studied intensively. The compressive strength test of mortar at three, seven, twenty-eight and fifty-six days were carried out. The compressive strength test of concrete at the seven, twenty-eight and fifty-six days were conducted. And finally, the flexural tests at the seven and twenty-eight days and water penetration test at twenty-eight days were conducted on the hardened concrete.

Both primary data from the source itself and secondary data from different sources are collected and used for the research analysis. The laboratory test results were presented in tabular and graphical forms and the analysis and discussions were also made on the research findings both qualitatively and quantitatively.

Finally, based on the research findings, conclusions and recommendations are drawn.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The successful utilization of waste materials for concrete production has a long history. Among the many, waste materials have been in use as supplementary cementitious material to minimize cost, environmental pollution and improve the property of concrete [3].

The advantages of using supplementary binding materials for concrete production are briefly discussed by [4], who categorize them into economic, ecological and engineering. The ecological benefits of alternative materials include (1) the diversion of non-recycled waste from landfills for useful applications, (2) the reduction in the negative effects of producing cement powder, namely the consumption of non-renewable natural resources, (3) the reduction in the use of energy for cement production and (4) the corresponding emission of greenhouse gasses.

The economic benefits of using alternative materials are best realized in situations where the cost of the alternative material is less than that of cement powder while providing comparable performance. This cost must consider the source of the alternative material, its transportation, processing, and should consider savings through diversion, such as tipping fees and landfill management costs. The engineering or technical benefits of alternative materials are realized when a specialized use for such material may be developed, such that the use of the alternative material is more desirable than use of concrete made with OPC alone. Hence, there exists an opportunity to realize the potential benefits of alternative cementitious materials such as waste glass as it is thoroughly described in this project [4].

In history, glass is one of the oldest man-made materials produced for different purposes such as: container glass or packaging, bulb glass and flat glass. Since glass made materials have short lifetime, either they are land filled of recycled and used again to minimize environmental pollution. These days, waste materials including waste glass are commonly used in the construction industry as partial replacement of cement. As modern industrialization increases from time to time, the production and disposal of waste glass have also been increasing causing environmental problem and waste of natural resources [5].

Thus, the use of waste glass for concrete production minimizes the environmental pollution, improves concrete property, saves landfill space and minimizes use of virgin materials for cement production.

2.2 Cement

Cement is a hydraulic binder and is defined as a finely ground inorganic material which, when mixed with water, forms a paste which sets and hardens by means of hydration reactions and processes which, after hardening, retains its strength and stability even under water. The cohesive and adhesive property of cement makes it the best material for bonding mineral ingredients of concrete into a compact whole [6].

The history of making cementing material is as old as the history of engineering construction. Some kinds of cementing materials were used by Egyptians, Romans and Indians in their ancient constructions [6]. The early Greeks and Romans used cementing materials obtained by burning limestone. The remarkable hardness of the mortar used in early Roman brickworks, some of which still exist, presents sufficient evidence of the perfection which the art of cementing material had attained in ancient times [7]. The Greek and Romans had known the fact that certain volcanic ash and tuff, when mixed with lime and sand yielded mortar possessing superior strength and better durability in fresh or salt water. Roman builders used volcanic tuff found near Pozzuoli village near Mount Vesuvius in Italy. This volcanic tuff or ash mostly siliceous in nature thus acquired the name Pozzolana. Later on, the name Pozzolana was applied to any other material, natural or artificial, having nearly the same composition as that of volcanic tuff or ash found at Pozzuoli. The Romans, in the absence of natural volcanic ash, used powered tiles or pottery as pozzolana [7]. The most important advancement in the knowledge of cements, the forerunner to the discoveries and manufacture of all modern cements is undoubtedly the investigations carried out by John Smeaton. When he was called upon to rebuild the Eddy Stone Light House in 1756, he made extensive enquiries into the state of art existing in those days and also conducted experiments with a view to find out the best material to withstand the sever action of sea water. Finally, he concluded that limestone which contained considerable proportion of clayey material yielded better lime possessing superior hydraulic properties. In spite of the success of Smeaton's experiments, the use of hydraulic lime made little progress, and the old practice of mixture of lime and pozzolana remained popular for a long period. In 1976 hydraulic cement was made by calcining nodules of argillaceous limestone. In about 1800 the product thus obtained was called Roman cement. This type of cement was in use till about 1850 after which this was outdated by Portland cement [7].

The current cement clinker production throughout the world has now become 1.6 billion tons per year. Concrete is the second most consumable material on earth next to water [8]. The annual consumption of cement depends on the economic developmental stage of the country. Cement production of mainly increases in developing countries than those developed countries.

2.1.1 Types of cement

The type of cement varies depending on method of manufacturing (grinding, burning, etc.), chemical composition and proportion of the different compounds. Among the different types of cements, which are: Ordinary Portland cement (OPC), "Portland pozzolana cement (PPC), Rapid hardening cement, Quick setting cement, Low heat cement, Sulfate resisting cement, Blast furnace slug cement, High alumina cement, white cement, colored cement, Air entraining cement, Expansive cement and Hydrographic cement", the most commonly known one is ordinary portland cement, which is also divided into different types. The second common type of cement is Portland pozzolana cement which is composed of some siliceous pozzolanic minerals [9].

2.1.1.1 Portland cement

Portland cement was developed from natural cements made in Britain within the early part of the nineteenth century, and its name springs from its similarity to Portland stone, a kind of building stone that was quarried on the Isle of Portland in Dorset, England [9].

Portland cement is one among the foremost widely used cement and is that the most significant cement. It may also be used for mortar & plaster production. It's utilized in all kinds of structural concrete like walls, floors, bridges, tunnels, etc. It's further employed in all sorts of masonry works like foundations, footings, dams, retaining walls, and pavements.

When cement is mixed with sand and lime, it is mortar for laying brick and stone; And when it's mixed with coarse aggregate and fine aggregate (sand) along with enough water, to confirm an honest consistency, we get concrete. The origin of the name portland cement is sometimes attributed to Joseph Aspdin, a brick mason in England who in 1824 took out a patent for creating a powder made up of mixed and ground hard limestone and finely divided clay. This forms into slurry so are calcined during a furnace till the CO_2 was expelled. He called the resulting material hydraulic Portland cement because when the mortar made with it hardened it produced a fabric resembling the stone which was quarried near Portland, England [10]. Chemically, however, Portland cement could be a complex substance whose mechanisms and interactions have yet to be fully defined [11].

The Portland cement Association provides the subsequent precise definitions: Hydraulic cement: Hydraulic binder, i.e., a finely ground inorganic material, which, when mixed with water, forms a paste which sets and hardens by means of hydration reactions and processes and which, after hardening, retains its strength and stability even under water. Portland cement: Portland cement composed primarily of hydraulic calcium silicates [11]. The strategy of creating cement has been improved since the time it had been discovered but the essential process has remained the identical.

i. Manufacturing Process of Portland cement

Portland cement is produced by grinding cement clinker in association with gypsum to specified fineness counting on the wants of the cement consumers. Cement clinker is produced on large scale by heating finely ground raw materials (Calcareous and Argillaceous materials) at very warmth up to 1,450 ℃ in rotary kilns [11]. Raw mixture preparation and raw mix blending, formation and grinding of clinker are the basic stages within the production of cement [9].

ii. Raw mix preparation and blending

The raw materials for cement production are a combination (as fine powder within the dry process or within the type of slurry within the wet process) of minerals containing calcium oxide, silicon oxide, aluminum oxide, ferric oxide and magnesium oxide. The raw materials are usually quarried from local rock, which in some places has already practically the specified composition and in other places requires the addition of clay and limestone, likewise iron ore, bauxite or recycled materials. The individual raw materials are first crushed, typically to below 50 mm. In many plants, some or all of the raw materials are then roughly blended in a "pre-homogenization pile". The raw materials are next ground together in a raw mill silo of individual raw materials are arranged over the feed conveyor belt. Accurately controlled proportions of each material are delivered onto the belt by weigh feeders. Passing into the raw mill, the mixture is ground to raw mix. The fineness of raw mix is per terms of the dimensions of the most important particles and is sometimes controlled in order that there are but 5%-15% by mass of particles exceeding 90 m in diameter. The raw mix contains no large particles so as to finish the chemical reactions within the kiln, and to confirm the combo is chemically homogenous. In the case of a dry process, the raw mill also dries the raw materials, usually by-passing hot exhaust gases from the kiln through the mill, in order that the raw mix emerges as a fine powder. This can be conveyed to the blending system by belt or by a powder pump. In the case of wet process, water is added to the raw mill feed, and therefore the mill product is slurry with moisture content of 25-45% by mass. This slurry is conveyed to the blending system by conventional liquid pumps [9].

The raw mix is formulated to a tight chemical specification. Typically, the content of individual components within the raw mix must be controlled within 0.1% or better. Calcium and silicon are present so as to create the strength producing calcium silicates.

Aluminum and iron are utilized in order to supply liquid (flux) within the kiln burning zone. The liquid acts as a solvent for the silicate forming reactions and allows these to occur at an economically reduced temperature. Insufficient aluminum and iron cause difficult burning of the clinker, while excessive amounts cause low strength because of dilution of the silicates by aluminates and ferrites.

Very small changes in calcium content cause large changes within the ratio of alite to belite in the clinker, and to corresponding changes within the cement's strength development characteristics.

The relative amounts of every oxide are therefore kept constant so as to keep up steady conditions within the kiln, and to keep up constant product properties. In practice, the raw mix is controlled by frequent qualitative analysis (hourly by x-ray fluorescence analysis, or every three minutes by prompt gamma neutron activation analysis). The analysis data is employed to create automatic adjustments to raw material feed rates. The remaining chemical variation is minimized by passing the raw mix through a blending system that homogenizes up to a day's supply of raw mix [9].

iii. Formation and grinding of clinker

The raw mixture is heated in a cement kiln throughout the cylinder progressively up to a temperature of 1400-1450 °C. As the temperature rises, complex successions of chemical reactions take place. The highest temperature is balanced so as to produce sintered lumps instead of fused lumps and consists of the melting of 25-30% of the mass of the raw mixture. The formation of molten liquid bonds the remaining solid particles together by surface tension, and acts as a solvent so that the final chemical reaction for the formation of a lite shall take place. If the temperature is very slow, it results in insufficient sintering and incomplete reaction on the other hand a very high a temperature results in a liquid (molten mass or glass), wastage of fuel and damage to the kiln lining. However, if carried out properly, then the resulting material is clinker. It is conveyed to storage after cooling. Blending of the clinker should be carried out carefully in order to alleviate the problems that might occur during raw material proportioning and heating resulting in chemical variability. The clinker obtained can be kept in store for many years before use. The exposure of cement produced to water (weights environment) reduces the reactivity of cement produced from the weathered clinker [9].

Standardized quality of cement which satisfies the require setting time is obtained by adding 2-8%, usually 5% of calcium sulfate (Anhydride Gypsum) to the clinker and the mixture is finally ground to form the finished cement powder. The particle size of cement varies depending on the grinding process, typically 15% by mass of particles contains less than 5 μm diameter, 5% of the cement particles greater than 45 μm. The finesse of cement is measured in specific surface (total particle surface area of a unit mass of cement.) The initial rate of reaction of cement after adding water for 24 hours is directly proportional to its surface. The specific surface area for general purpose cements ranges from 320–380 $\frac{m^2}{Kg}$ and rapid hardening cements it ranges from 450–650 $\frac{m^2}{Kg}$ for "rapid hardening" cements [9].

The production of Modern Portland cement generally requires the proper composition of is lime (CaO), silica (SiO_2), alumina (Al_2O_3), Ferrite (Fe_2O_3) with minor addition of magnesia and sulfur trioxide. The following Table 2.1 blow demonstrates the typical composition of general-purpose Ordinary Portland cement.

Table 2.1 Composition of typical ordinary Portland cement [1].

Chemical Name	Chemical formula	Shorthand Nation	Weight percentage
Tricalcium silicate	$3CaO.SiO_2$	C_3S	55
Dicalcium silicate	$2CaO.SiO_2$	C_2S	18
Tricalcium aluminate	$3CaO.Al_2O_3$	C_3A	10
Tetracalcium aluminoferrite	$4CaO.Al_2O_3.FeO_3$	C_4AF	8
Calcium sulfate dehydrate (gypsum)	$CaSO_4.2H_2O$	CSH_2	6

Among the above compounds, tri-calcium-silicate and tri-calcium-aluminate or C_3S and C_3A respectively are mainly responsible for early strength development of concrete. High amount of C_3S and low amount of C_2S causes high early strength resulting in heat generation as the concrete sets. Low amount of C_3S and high C_2S results in slow strength development and reduced heat evolution. The addition of C_3A (Tri calcium aluminate) causes excessive heat and fast hydration reaction, and this is alleviated by adding $CaSO_4$ (Gypsum) to the final product. Portland cement is usually classified using ASTM classification of cement. ASTM classifies Portland cement majorly into five groups except that non-air entrained cement differing only on the degree of fineness and relative amount of compounds.

- ASTM type I cement: is a general-purpose Portland cement used when there is no special property required by the concrete.

- ASTM type II cement: is Moderate Portland cement. It is also a general-purpose cement to be used when moderate sulphate resistance or moderate heat of hydration is desired.
- ASTM type III cement: is High early strength Portland cement which is used when high early strength is desired, usually less than one week, it is usually used when a structure must be put into service as quickly as possible.
- ASTM type IV cement: is Low-Heat of Hydration Portland cement, which is used when a low heat of hydration is required, like in mass concrete.
- ASTM type V cement: is Sulphate resisting Portland cement which is used when high sulphate resistance is desired.

iv. Environmental Concerns in Cement Production

The production process of cement damages the environment as it is an energy intensive project [12]. The formation of cement clinker from calcium carbonate and clay minerals require an enthalpy ranging from 1500 to 1700 kJ/kg. However, the actual values could be even higher. The release of high amount of Carbon dioxide during the calcination phase of cement production is becoming a concern for global warming [9]. About 1 ton CO_2 is released to the atmosphere in order to make 1 ton of clinker [9].

2.1.1.2 Portland pozzolana cement

Portland pozzolana cement (PPC) is produced by inter-grinding 15 to 35 % of pozzolanic materials with ordinary portland cement clinker [10]. Pozzolanic materials are siliceous or aluminous materials which by themselves possess little or no cementitious properties. However, it reacts with calcium hydroxide liberated from the hydration of cement to make a mixture possessing cementitious property in the presence of water.

The hydration reaction of pozzolanic materials with calcium hydroxide brings about prons of PPC over OPC. If these pozzolanic materials do not react with the calcium hydroxide free calcium hydroxide will be produced in the concrete making it susceptibility to permeability and chemical attacks. The process of pozzonaic reaction produces cementitious compound and helps in minimizing the porosity of the concrete and heat of hydration as its reaction is slower than that of OPC. It is suitable for mass concrete construction due to its slow rate of hydration reaction resulting in slower rate of strength.

There are also other types of cement which could be produced by forming other type of compounds during the burning process or by adding other types of materials to the clinker. And these are collectively called modified portland cements.

Some of such types of cements are calcium sulfo-aluminate cement, Expansive cement, masonry cement, oil well cement, white cement etc. There are also other types of inorganic non-Portland cements which are applied for special type of construction works.

2.3 Concrete

The word concrete comes from a Latin word concretus meaning to grow together [1], which indicates that it is composite of different materials. Concrete is composed of coarse granular material called aggregate or filler which is embedded in a hard matrix of material (cement or binder with water) binding the aggregates together and filling the space formed between them. When the ingredients are mixed with water the concrete solidifies and hardens due to a chemical reaction between the water and the cement called hydration reaction, which finally forms a stone like strong material.

Cementitious materials, pozzolanic materials, filler materials, chemical admixtures, and some other additives may also be the ingredients of concrete based on the need and their availability. All the ingredients used have their own unique purpose in the production of concrete. The aggregates which account 70% to 80% by volume of the concrete are bound together by cement paste (cement plus water), which acts as binding material to form concrete. The main reasons behind using aggregates in concrete are dimensional stability, wear resistance and economy. Various types of admixtures can be used to improve the properties of concrete.

Properties such as: workability, strength and durability make concrete to be the most versatile and widely used manmade construction materials even in the 21^{st} century [19]. Therefore, the selection of ingredients of concrete depends on the ease of work, the quality and economy of the concrete required.

2.4 Pozzolans

The term Pozzolana is described as a natural volcanic material with pozzolanic properties. The ability of a material to react and combine with lime at ambient temperature in the presence of water in order to produce compounds that set and harden with the formation of hydrated phases is called pozzolanic property [29].

The silica from the pozzolana reacts and combines with the free lime released during the hydration of the cement and this process is known as pozzolanic activity. Amorphous Silica reacts with lime more readily than crystalline form of silica. This is the major reason for the difference between active pozzolanas and inactive Pozzolanic materials of similar chemical composition resulting in high or little pozzolanic activity.

The commonly known natural pozzolanic materials are: opaline, cherts, diatomites, and some shales. Other volcanic materials such as: tuffs and pumicites are known for their less reactivity; on the other hand, materials such as clay require calcination before they become reactive [31].

Admixtures of mineral are also one of these admixtures used in concrete for various purposes and they may be found naturally or artificially. They are divided into three main categories, which are cementitious, Pozzolanic and non-reactive materials out of which the first two are added to the mixer as supplementary cementing materials. And these materials react with hydrated Portland cement to form a modified microstructure paste.

On the other hand, the non-reactive admixtures are finely divided materials such as: hydrated lime, limestone, silica flour, etc. which reacts very slowly with cement and is usually blended with Portland cement to improve workability [30].

2.4.1 Pozzolanic materials

Pozzolanic materials are siliceous or siliceous and aluminous materials which alone possess little or no cementitious value but will, in finely divided form and in the presence of moisture, react chemically with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties [31].

Their recognition dates back long ago to the ancient Greeks and Romans. The Greeks used volcanic ash and the Romans adopted and extended the Greeks technology using ash from varieties of sources from around their empire. Pozzolanic materials can be divided into two groups: natural pozzolana and artificial pozzolana. Clay and shales, opalinc chert, diatomaceous earth, and volcanic ash are an example of natural pozzolans while fly ash, blast furnace slag, silica fume, rice husk ash, and metakaoline are example of artificial pozzolans. Most of the pozzolans in use today are mainly byproduct materials that are widely available [31].

Because of the diversity of pozzolans their chemical composition also varies. Therefore, classifying pozzolans only depending on their chemical composition would be difficult. For this reason, ASTM C 618 classifies pozzolans depending on performance basis. ASTM C 618 chemical composition for pozzolans is as shown in Table 2.2.

Table 2.2 ASTM C 618 chemical requirement for Pozzolans [32].

Chemicals	Pozzolans Class		
	N	F	S
$SiO_2 + Al_2O_3 + Fe_2O_3$ (min %)	70.0	70.0	70.0
MgO (max %)	5.0	…	5.0
SO_3 (max %)	4.0	5.0	4.0
Moisture content (max %)	3.0	3.0	3.0
Loss on ignition (max %)	10.0	12.0	10.0
Available alkalis as Na_2O (max %)	…	1.5	1.5

The reason behind using pozzolans is the improvement found on both the fresh and hard concrete. Lowering of the heat of hydration and thermal shrinkage, increase in water tightness, reduction in the alkali aggregate reaction, resistance to sulfate attack, better workability, and cost efficiency are some of the improvements achieved by using pozzolans blended with Portland cement.

2.4.2 Pozzolanic reaction

The hydration reaction of tri-calcium silicate and di-calcium silicate with water produces calcium silicate hydrate and calcium hydroxide. The first compound has very low solubility in water on the other hand the later one is highly soluble in water and has no cementitious property and is just found as a free lime in the concrete, causing porosity of the concrete, which in turn leads to weak durability of concrete. The siliceous and aluminous compounds found in Pozzolanic materials react with calcium hydroxide of cement to form very stable cementitious substances of complex composition involving water, silica and calcium. Generally, amorphous silicates result a better pozzolanic reaction. The following Equation 2.9 shows the principal pozolanic reactions taking place [1].

Pozzolan + Calcium Hydroxide + water $\longrightarrow$ Calcium Silicate Hydrate (gel)

S + CH + H $\longrightarrow$ C-S-H ………………………………………………… [2.9]

The above reaction is known as pozzolanic reaction. The calcium hydroxide produced by the hydration of portland cement is consumed by the silica from the pozolana resulting in a decrease in calcium hydroxide content in the concrete. The C-S-H produced in this reaction is similar to the one formed in the regular reaction, with the exception that C/S ratio is slightly lower. The usual ratio of C/S is about 2 [6].

The pozzolanic reaction shown Equation 2.9 above and its kinetics resembles the slow rate of hydration of C_2S [1]. Therefore, the increase in the amount of C_2S has similar effect as the increase in pozzolana. And hence, this leads to reduced rate of strength development and heat of hydration making it advantageous for mass concrete construction.

As the rate of hydration of portland cement is measured by measuring the amount of calcium hydroxide in the cement paste, the rate of pozzolanic reaction can be measured by controlling the decrease in amount of calcium hydroxide over a period of time. Prolonged moist curing of the concrete is required in order to observe the effect of pozzolanic materials due to their slow hydration reaction; else they just act as a filler material.

2.5 Glass

2.5.1 General

Glass is one of the oldest materials used in different industries. It is broadly utilized in building industry and architecture. It is manufactured in different colors and chemical compositions. Generally, glass is an amorphous transparent solid material produced by cooling molten glass. The composition of glass is similar to that of igneous rocks where the hollow volcanic space acts as a furnace and the eruption as a source of energy to produce a naturally made glass material [33].

Waste glass is a non-decomposable material that has to be land filled or recycled up to 100%. It is an inert, inorganic, and chemical resistant material and hence has good resistance to external influences and also used as heat insulating material.

There are different types of glasses depending up on the type of chemicals they are composed of such as: silicate glass, borosilicate glass, sodium borosilicate glass, soda-lime glass, alumino silicate glass, lead oxide glass, germanium oxide glass. Moreover, ZnO and MgO are added in order to produce special types of glasses. Generally, glasses are categorized depending on the use, the purpose and the method of manufacture [33].

The quantity of waste glass have been rising rapidly during the recent decades due to the high increase in industrialization and the considerable improvement in the standards of living, but unfortunately, the majority of these waste quantities are not being recycled but rather abandoned causing certain serious Due to the increase in industrialization and improvement in standard of living the quantity of waste glass disposed has been increasing at an alarming rate creating problems such as environmental pollution and wastage of natural resources [34].

Therefore, recycling this waste material by converting it to concrete ingredient could save landfill space and also reduce the demand for extraction of natural raw materials for construction activities.

A. Types of glass

Depending on chemical composition, almost all commercial glasses fall into one of the following six basic types [49]. These are:

1. Soda-lime glass

Soda lime glass is the most commonly used and least expensive glass type that covers ninety percent of the glass made in the industry. It is resistant against corrosive chemicals and high temperature and is used to make bottles, light bulbs, jars and windows.

It is also light permeable and has a smooth fine pored surface making it easy to clean the surface. However, it expands very quickly due to the influence of heat so that proper care has to be taken while putting hot water into a soda lime glass bottle or container. It withstands up to a temperature of 200 ℃ but have very little thermal shock resistance. The following Table 2.3 below shows the chemical composition of soda lime silica glass.

Table 2.3 Composition of soda lime silica glass.

Type of Glass	Composition (by weight)
Soda Lime Silica	73% Silica – 14% Soda – 9% Lime – 4% Magnesia – 0.1% Alumina

2. Lead glass

This type of glass is composed of high percentage of lead oxide; a minimum of twenty percent. It is relatively soft, preferable for electrical applications due to its excellent electrical insulating properties and is more expensive than that of soda lime glass. Lead glass is usually used to produce art glass, thermometer tubing and lead crystal tableware. However, it does not withstand sudden change in temperature. The following Table 2.4 given below shows the chemical composition of lead glass.

Table 2.4 Chemical compositions of lead glass.

Type of glass	Composition (by weight)
Lead (Crystal)	57% Silica – 31% lead Oxide – 12% Potassium Oxide

3. Boro silicate glass (Pyrex)

This type of glass is highly resistant against temperature fluctuation and chemical attack. Therefore, it is primarily used for laboratory equipment's, heat resistant kitchenware and durable lamp covers. It withstands up to a temperature of 170 ℃. The following Table 2.5 shows the chemical compositions of borosilicate glass.

Table 2.5 Chemical composition of boro silicate glass.

Types of Glass	Composition (by weight)
Boro-Silicate	81% Silica – 13% Boron Oxide – 4% Soda – 2% Alumina

4. Alumino-silicate glass

This type of glass is composed of aluminum oxide. It withstands high temperature and thermal shock and is usually used in combustion tubes, gauge glass for high pressure steam boilers and in halogen tungsten lamps which is capable of operating up to a temperature of 750 °C. The following Table 2.6 shows the Chemical compositions of alumino silicate glass.

Table 2.6 Chemical compositions of alumino silicate glass.

Type of Glass	Composition (by weight)
Alumino Silicate	64.5% Silica – 24.5% Alumina – 10.5% Magnesia – 0.5% Soda

5. Ninety six percent silica glass

It is a borosilicate glass that is melted to remove nearly all the non-silicate elements by conventional means to form a heat shock resistant glass up to 900 °C. The resulting pores of this glass are consolidated by reheating up to a temperature of 1200 °C.

6. Fused silica glass

Fused silica glass in the non-crystalline state is pure silicon dioxide. This glass is very difficult to produce, and this makes it the most expensive of all the types of glass. It can withstand an operating temperature up to 1200 °C for short period of time. These six glass types are the widely used glasses for different purposes [2].

B. Glass production

The properties and compositions of glass were first studied scientifically in the 18^{th} century by Lomonosov which includes the dissolution of glass in water studied by Griffiths and various researches conducted by Michael Faraday, who introduced the earliest technologies of glass. Moreover, different scientific studies of glass have been carried out in the early 18^{th} and 19^{th} century by William E.S. Turner, Otto Schott, George W and F. W. Preston Morey. Advancements in glass science technology have served as essential ingredients for modern day society especially in the area of transportation, energy, architecture, medicine, scientific exploration and communication.

Generally, glass is formed from its ingredients in a carefully controlled two-step process and is then molded to form either bottles or sheet glass [35].

Step 1 - Batch mixing

Depending on the desired purpose of the material the minor components of glass are weighed first in a special weighing hopper and is then added to the major raw materials in the presence of some amount of water to protect clogging up of furnace due to dry fines. The 2tone batch is then mixed between 2 and 3 minutes in a rotary mixer, before transporting to the batch hopper, which then be slowly fed into the furnace.

The proportioning of raw materials I depend on the desired type of glass; for instance, window glass is produced from 72 percent SiO_2, 13 percent Na_2CO_3 and 12 percent $CaCO_3$, on the other hand bottle glass requires more quantity of silica (SiO_2) and less quantity of limestone ($CaCO_3$). Crystal glass is produced from 45 percent SiO_2 and 44 percent PbO with 9 percent K_2CO_3, on the other hand pyrex, which is used to produce laboratory equipment's and oven wear is formed from 80 percent SiO_2 and 12 percent B_2O_3. The remaining raw materials in the above mixtures are covered by different minor ingredients.

Glass color

The final minor ingredient also determines the color of the required glass. The color of the glass can be determined either by the oxidation state of the glass or by using specific colorant additives. Oxidation of glass is carried out by the addition of carbon, and the degree of oxidation is measured by the carbon number; for instance: amber glass has a carbon number of 52, dark green 28 and clear glass zero.

Variations of color could be achieved due to the action of colored raw materials which act as dyes, for instance: the iron (II) ions that is naturally present in sand causes a green tinge seen in clear glass, and this can be masked by adding selenium. The amber and green colors of glass bottles are also caused by the addition of iron chromite and iron sand respectively rather than the degree of oxidation. It takes about twelve to forty-eight hours to produce glass of the required acceptable standard after the raw materials have been fed into the furnace continuously.

Step 2 – Batch melting

The ingredients are fed into the furnace continuously and is fired by a natural gas or electricity initially at a temperature of 1,400 ℃ and then raised to 1,540 ℃ until the mixture melts. The molten glass is ready to be formed into the desired end product when the evolution of gasses stops. To minimize heat loss and promote heat distribution in the molten glass, the furnaces are kept at this temperature by a cross fired system. Figure 2.1 demonstrates the process of glass production.

Shaping plate glass

The cooled liquid glass from the furnace flows into drawing canal and is cooled to 1,000 ℃ before being drawn up into a tower and is then the 2.5 meter wide glass sheet is drawn up into the tower by rollers, which in turn cools it down as it rises.

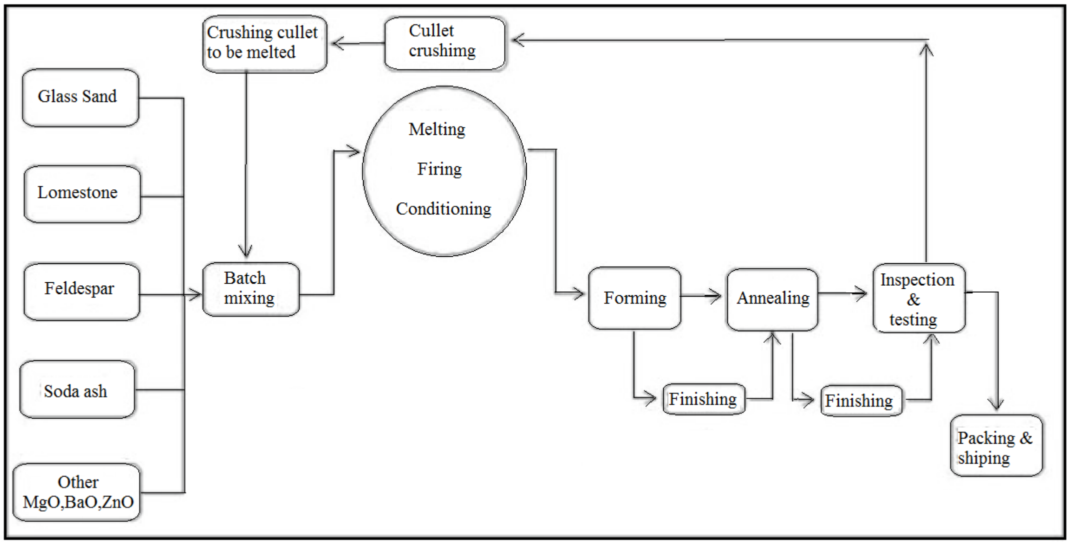

Fig. 2.1 A flow chart of glass production process [35].

Sheet glasses can be made as thin as 2 millimeter (or as thicker as required) and moves up at a speed of 170 meter per hour (the average speed is about 40 meters per hour).

The individual glasses sheet weigh about 22 kg are then lifted up and are placed in the warehouse before it is transported for use.

Molding glass containers

After molten glass is removed from the furnace between 1,100 and 1,150℃, it is then fed into a forming machine and are molded in sections held in the air for a short period of time to protect them from losing their shape quickly and is transported to the annealing lehrs.

The bottles are further reheated up to 600 ℃ to prevent glass from becoming brittle known as annealing lehrs stage. The bottles are finally coated with a shiny, slippery spray-on coating that protects them from becoming scratched temporarily, and then they are packed transported to clients for use.

The role of the laboratory

The proportion of each batch of glass is determined in the laboratory. The type of elements and their proportions is determined by taking a small sample from each batch and dissolving in hydrofluoric acid and then analyzing it in an atomic absorption spectrophotometer. Based on the test results obtained the mass of each ingredients are calculated and the required mix is produced [35].

C. Waste glass in concrete production

Waste glass has been in use as concrete ingredient over the last years and comparatively the recycled glass has been in use in much larger scale than the waste glass. This is due to the presence of pollution on the surface of the waste glass which latter on affects the quality of concrete.

Waste glass can be utilized in concrete as: coarse aggregate, fine aggregate and as a mineral additive or supplementary Cementitious material; out of which it is mostly used as partial replacement of aggregates in concrete. The waste glass used in concrete substituting aggregates should guarantee for workability, strength and durability of concrete. Waste glass can also be used as a replacement of sand in concrete pavement, asphalt additive or road filler. In concrete pavement, there was a five percent reduction of the compressive strength for five percent replacement of sand with waste glass, and the reduction increased to twenty seven percent for a replacement of thirty percent of sand with waste glass material. The optimum replacement percentage of waste glass for asphalt pavement is ten percent. However, some researches also indicate that waste glass can replace up to fifteen percent in asphalt keeping good mechanical properties of concrete. The following Figure 2.2 shows some of the applications of waste glass in structural concrete [38].

Fig. 2.2 Application of glass in concrete in structural concrete [39].

Glass cullet can also be applied in concrete for the development of aesthetics and to produce decorated material as shown in Figure 2.3 and 2.4 below. It is also possible to create attractive and shiny surfaces due to the irregular shape of glass particles.

Fig. 2.3 Application of glass for surface finish in concrete [39].

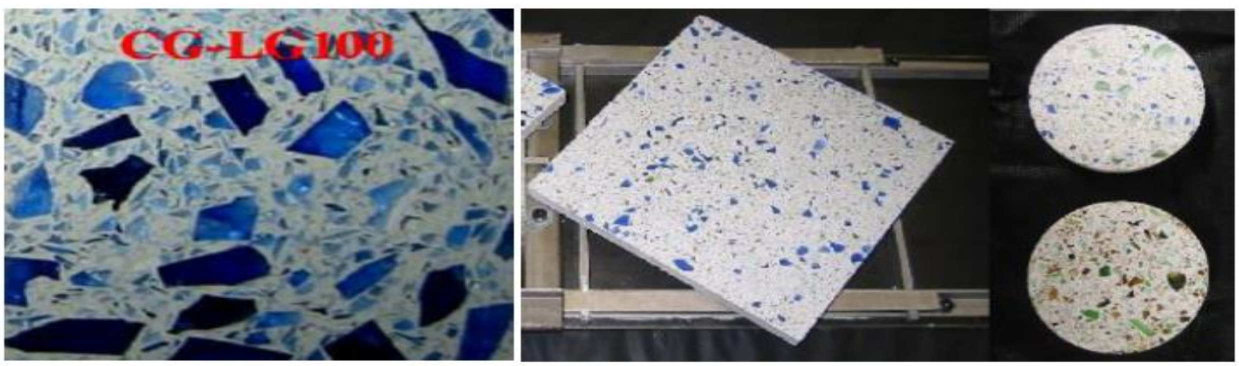

Fig. 2.4 Application of glass cullet to produce decorative mortar [39].

Recently, translucent and self-cleaning concrete has been investigated by using titanium dioxide [38]. Even though the discovered material has low translucency (that is 0.01%), a lot has to be done to improve its property.

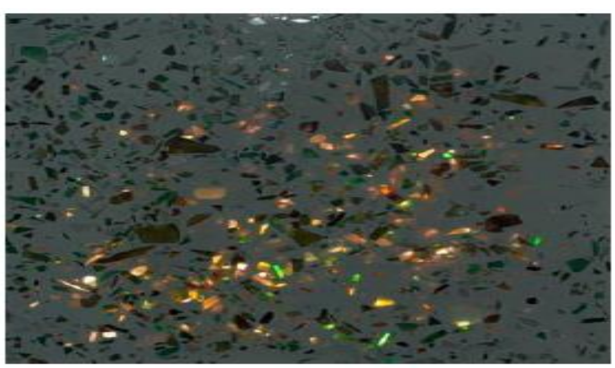

Fig. 2.5 Translucent concrete plate [39].

1. Glass as cement replacement material

Glass is mostly used as supplementary cementitious material in concrete rather than aggregates. Different literatures indicate that glass powder exhibits pozzolanic reactivity when the size of the particle is below 100 microns. The pozzolanic reactivity of waste glass powder is identified by checking whether there is an increase in calcium silicate hydrate (C-S-H) and decrease in calcium hydroxide or $Ca(OH)_2$ in the concrete.

The use of waste glass powder in reactive aggregates has a potential to mitigate ASR; and moreover, improves the workability and durability when used as SCM in concrete. The compressive strength of concrete containing waste glass powder is lower than OPC at the early ages but continues developing strength and can also exceed the strength of OPC in the addition of up to 30 percent of waste glass. The compressive strength of concrete containing waste glass as SCM is higher than that of the same volume and size of fly ash used as SCM in concrete [31].

The Pozzolanic reaction of waste glass powder with cement produces more amount calcium silicate hydrate or CSH gel, resulting in a reduced pore size, increased strength, reduced permeability, and improved durability [40].

According to the research conducted by Jitendra B. (2014), the cement in concrete was partially replaced with different percentages of waste glass powder ranging from 10 percent to 40 percent by mass and after all the tests, the study revealed that compressive strength with 10 percent waste glass powder was best when compared to other mixes with higher replacement.

Similar studies have been conducted by Vijayakumar G. (2013), indicating that waste glass powder could replace cement up to 20 percent in addition to improved workability. Waste glass powder replacing cement by 20%, 30% and 40% increased the compressive strength by 19.6%, 25.3% and 33.7% after 60 days respectively, when the particle size of the waste glass powder is below 75 micron.

Table 2.7 Chemical composition of cement & glass powder.

Contents	Cement	Glass powder
SiO_2	21.0	71.4
Al_2O_3	5.9	1.4
Fe_2O_3	3.4	0.2
CaO	64.7	10.6
MgO	0.9	2.5
Na_2O	-	12.7
K_2O	-	0.5
Ti_2O	-	-
SO_3	2.6	0.1
Loss on ignition	1.2	0.4

(a) (b)

Fig. 2.6 Waste glass before (a) and after it is ground to powder (b).

According to a research conducted by Bezawit W. (2015), undergraduate students at Addis Ababa institute of Technology (AAiT), for the partial fulfillment of Bachelor of science in civil engineering, replacement of cement by waste glass powder at 5% and 10% replacement indicated higher compressive strength than the control concrete mix. However, these research focuses on mortar production using glass powder as partial replacement of cement rather than concrete production.

i. Glass production in Ethiopia

The major glass production sites in Ethiopia are CGCCOC Ethiopia LTD and Addis Ababa bottle and glass Share Company. CGCCOC Ethiopia LTD is Located at Jemo. They are currently working on sheet glasses. The other widely known company, Addis Ababa bottle and glass share company, majorly works on container glass. The production process is similar to the process described above.

Addis Ababa bottle and glass share company

The production process carried out in this company has three phases:

I. Raw material preparation

In this stage basic raw materials needed for the preparation of glass are carefully selected, screened and tested. These are:

- Marble as a flux
- Limestone
- Silica sand
- Soda ash (Na_2CO_3) and
- Recycled glass

The minor raw materials are additives, both colorful and colorless. These are pyrite and coke undergoing reduction reaction and selenium and cobalt oxide undergoing oxidation reaction.

II. Batching process /Measuring process/

The main focus in this area is accurate mass measurement.
One batch is considered to have:

- 215 kg of cullet
- 218 kg of silica sand
- 63 kg Marble and
- 78 kg of soda ash

Magnetic selector device is installed in this section so that impurities invisible to human eye and having magnetic property will be isolated from the raw materials.

The raw materials taken to this stage will be stored in the silo. Each raw material possesses its own room in the silo. Then a web balancer automatically measures the raw materials to their appropriate qualities and then mixing process takes place. The materials will be mixed for 15 minutes and using water from 10 to 15 liter per batch. The process is aided using mixer. The company usually prepares 53 to 60 batches per day. The batching plant is shown under figure 2.7.

Fig. 2.7 Batching plant.

After the materials are well mixed, they will be transferred to the furnace room. This room undergoes **Melting Process.** Here the mix is melted at a temperature between 12,000 ^{0}C-15,000 ^{0}C. If impurities present in the process, the high temperature will ignite the particle so that they don't pose any detrimental effect.

Here, three operations take place:

a. Melting
b. Refining
c. Conditioning

In the refining stage, unwanted particles will be removed that homogenization of the product will be achieved. Next on the conditioning step preparation for desired product will be carried on.

Forming /Molding/ section: in this room, shaping to the required shape take place. The process is assisted by blowing process in which compressed air will be introduced and required shape will be made. Annealing layer is incorporated in this stage. If there is a stress on the glass, molecules definitely break. To avoid such event from happening, annealing layer compressing seven zones is added in the production process. The temperature in each zone decreases as one goes from zone I to VII. Higher energy loss is noted on the first zone. Finally, molecules will get uniform distribution.

III. Quality Control Inspection

The following three stages are carried out under quality control phase:

a. Visual inspection
b. Physical analysis test and
c. Chemical analysis test

For all the three tests the bottle glasses are randomly selected.

2.5.2 Waste glass in Ethiopia

According to the data obtained from the world bank (in 2016), Ethiopia is the second most populous landlocked country in the world with an estimated population of 97.1 million with growth rate of 2.5 percent and a GDP per capita of $550. Although Ethiopia is one of the poorest countries in the world, there has been a great economic growth of about 10.8% per year between 2004 and 2014. The regional annual average economic growth in the horn of Africa is 5 percent. The continuous economic growth of the country reduces poverty from 38.7 percent to 29.6 percent since 2005. Currently, the government has also planned to reduce this figure to a single digit by 2030.

According to Nigatu R. (2011), some of the emerging cities in Ethiopia need to give special attention to waste disposal management. Particularly, the waste management system in Addis Ababa is different from other emerging cities of Ethiopia. Until very recently, there has been no system of waste management in emerging cities. Some of these new municipalities, were designed to develop environmentally degrading practices and minimize human exposure to unsanitary conditions. However, the collection and waste management system of most municipalities is not as efficient as required.

Even though most emerging cities have not experienced systematic waste management system like the city of Addis Ababa, it is crucial to lay the foundation and sustain before things have become very complicated.

Different literatures pointed out different figures regarding the compositions of waste disposed in Addis Ababa. Waste management in Addis Ababa is still becoming a challenge due to the fast-growing population migrating from rural areas with a current population estimate of 5 million and projection estimate of 12 million in 2024 [5].

A study conducted on the history of solid waste disposal in Addis Ababa concluded that waste disposal has been increasing by 3.79 percent annually since 1993 [5].

More than 200,000 metric tons of waste collected each year, the average waste generated in Addis Ababa was estimated to be 0.4 kg per capita per day. Recent studies investigated that 60 percent of the waste generated in Addis Ababa is organic, while 15 percent is regarded as recyclable [5]. The following Figure 2.8 shows the composition of waste generated in Addis Ababa.

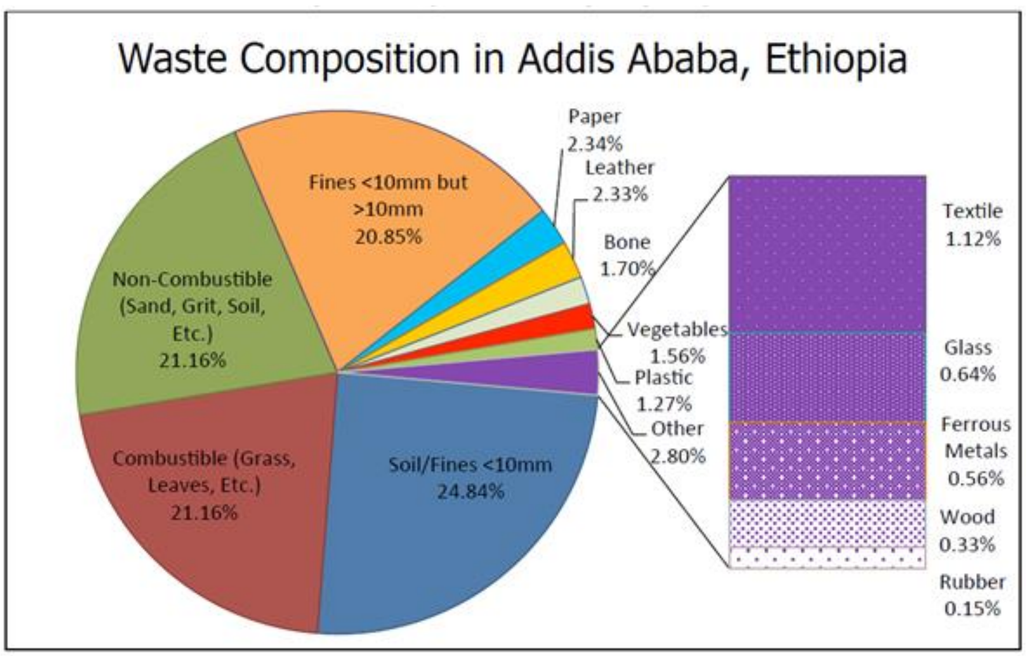

Fig. 2.8 Waste composition in Addis Ababa, 2010 [5].

The daily waste production in A/A is around 0.4 kg/capita/day and from this much amount of waste only 550 tons/day is collected.

Based on different studies conducted so far, the amount of the solid waste generation rate in Addis Ababa city per day, month and year has been estimated based on the 1993/94 population census of Addis Ababa shows constant growth rate of 3.79% (including both natural and net migration).

Table 2.8 Physical composition of solid waste in Addis Ababa, 2010 [5].

Constituents	Percent (%)
Vegetables	1.93
Paper	2.90
Rubber	0.19
Leather	0.41
Wood	2.89
Plastic	1.58
Textile	1.39
Ferrous metals	0.69
Aluminum	0.0
Glass	0.79
Combustible (leaves, grass)	26.26
Non-Combustible (Sand, grit, soil, etc.)	26.26
Soil/Dines 10 mm	30.82
Fines	25.87
Total	100%

The percentage of waste generated from domestic is 76%, commercial waste 9%, hotels 3%, industrial waste 5%, street sweeping 6%, and hospitals 1%.

The following pictures were taken during a visit to Addis Ababa bottle and glass Share

Company (Birchiko fabrica) which is found in Asco area, Addis Ababa.

Fig. 2.9 A photograph captured when sample waste glass is taken from Addis Ababa bottle and glass Share Company, by the researcher (2018).

2.5.3 Beneficiaries of the research

a) Minimizes improper disposal of waste glass which makes the city look unfavorable.
b) Reduced cost of concrete production due to partial replacement of cement with glass powder.
c) Improved compressive strength of concrete for optimal partial replacement of glass powder
d) Improved surface finish (aesthetics) of concrete.
e) Reduced environmental devastation due to excessive carbon emission during cement production.
f) Encourage stakeholders to conduct researches on other alternative cementitious materials.
g) Utilization of waste glasses to such type of work reduces the cost required for dumping.
h) Reduces dead loads to the concrete works.
i) Solid waste collectors shall benefit from selling the waste broken glasses per kilogram.

2.5.4 Summary of literature review

The literature review was carried out through previous studies, browsing related research topics from internet, construction technology & management thesis and engineering journals. By referring to the previous literature, the percentage of waste glass disposal in developed countries is more than the developing countries. It can be seen above that replacing cement with alternative cementitious material is environmentally friendly, as it reduces the percentage of carbon emission during the production of cement by cement factories. Concrete produced with proportions of glass powder are aesthetically beautiful and at certain proportion even a better compressive strength was attained compared to control mix concrete. Thus better quality (Strength and Aesthetics) of concrete can be achieved with cheaper cost by using glass powder as supplementary material.

Although different literatures show different figures for the composition of waste glass in Ethiopia, particularly in Addis Ababa, as can be seen in the literature review an average of about 1,000 tons/year of waste glass is disposed, which is about 1% of the total waste disposed in Addis Ababa.

According to researchers, the mass of raw materials needed to manufacture Portland cement is assumed to be 1.6 times as much as the mass of finished Portland cement. Therefore, this can cause environmental problems like global warming due to depletion of natural resources, dust and noise, gas emissions, such as carbon dioxide emission from clinker production, which is estimated that 1 tone of clinker production releases 1 tone of CO_2. Mixing of clinker to supplementary materials called blending is considered as a very effective way to reduce CO_2 emission. Thus, the use of waste glass powder as a cement replacement material will save a great deal of virgin materials.

From the bottle glass industries in and around Addis Ababa, with an average of 250,000 tons of bottle glasses annual production, considering about 5% waste glass to be used as partial replacement of cement, results in reduction of about 12,500 ton of CO_2 to the atmosphere annually. Moreover, about 1,000 ton of waste glass is disposed in Addis Ababa annually, accounting for a reduction of additional 1,000 ton of CO_2 emission. Thus, a total of 13,500 ton of $C0_2$ emission to the atmosphere can be reduced annually.

Therefore, by taking the above figure and the increase in waste glass disposal in the future into consideration, the potential for the use of waste glasses disposed in Addis Ababa as an alternative cementitious material is encouraging.

The literatures reviewed on concrete produced from waste glass powder as partial replacement of cement show different findings which do not much each other. For instance: the study conducted by Khatib J. (2012) shows that concrete containing 10% glass powder replacing OPC revealed better compressive strength than with replacement of more than 10%. on the other hand the study conducted by Vijayakumar G. (2013) indicates it is possible to replace OPC cement by glass powder up to 40% and obtain better compressive strength than the control mix; provided that the finenness of glass powder is below 75 micron. According to Jitendra B. (2014) it is possible to replace OPC cement in concrete up to 20% and obtain a compressive strength better than the control mix on the other hand the research conducted by Bezawit W. (2015) shows the optimum replacement of OPC cement in concrete by glass powder is 10%.

Moreover, according to Shayan A. (2018) the compressive strength of concrete containing glass powder at the early age is lower than that of the control mix; on the other hand the study made by Jitendra B. (2014) indicates ccompressive strength of concrete containing glass powder has no effect on the early strength of concrete.

In order to fill the gaps observed from different literatures, the researcher has carried out a study on comressive strength of concrete containing glass powder as partial replacemet of cement.

CHAPTER THREE

PROPERTIES OF MATERIALS UTILIZED IN THE PROJECT

3.1 Introduction

The experimental program of this research is primarily concerned with investigating the compressive strength development of concrete using waste glass powder as partial replacement of cement in the concrete mixes. Waste glass is usually produced from empty bottle glass containers and different construction and reconstruction remains and waste materials.

To produce acceptable quality of concrete, it's important to make physical and chemical characteristic tests on materials used for the research before concrete tests have been carried out. Therefore, this chapter elaborates concrete making materials used for the research and their physical and chemical test results conducted from the experiment, mix design and proportion, and concrete production process.

The laboratory tests on the aggregates, fineness of cement and glass powder, pastes, mortars and concrete are carried out in Addis Ababa Institute of Technology, Civil and Environmental Engineering Department, material laboratory, whereas the chemical composition and specific gravity of the glass powder are carried out in Geological Survey of Ethiopia.

3.2 Waste glass powder

Glass is a fused mixture of silicates of alkalis, alkaline earths, and of more common metals or minor constituents. The raw materials of glass are heated up to a temperature of 1500 °C in order to melt them and obtain chemical reaction. The glass is then cooled down in a controlled condition, where it becomes viscous at 1000 °C and hardens at about 500 °C temperature. Usually, a transparent and amorphous solid glass is produced by cooling molten glass. Glass is very similar to igneous rock in its composition, which makes it a natural material and can also be produced in different colors and chemical compositions. Glass is rich in silica and if finely grounded and mixed with OPC cement in the presence of water exhibits pozzolanic properties [33].

The waste glass used for this research is clear bottle glass (Flint glass) and was obtained from Addis Ababa bottle glass Share Company located around Asco in Addis Ababa, Ethiopia. The waste glass obtained from the company was oven dried and reduced to a sieve size of 75 micrometer using Los Angeles abrasion testing machine and manually (see Fig. 3.1).

Fig. 3.1 Waste glass after oven dried (left) and waste glass after ground to powder (right).

The glass powder is sieved (under five sieves of size 150 μm, 125 μm, 75 μm, 63 μm and 32 μm) to determine the average size of the powder and the result is shown in Table 3.1 below.

Table 3.1 Gradation of glass powder (75 μm sieve) and OPC cement.

Sieve size	Percentage passing (Glass powder)	Percentage passing (Cement)
150 μm	100	99.5
125 μm	100	99.1
75 μm	100	94.9
63 μm	62	83.9
32 μm	0.7	1.4

The gradation curve of glass powder and OPC cement is shown in Figure 3.2.

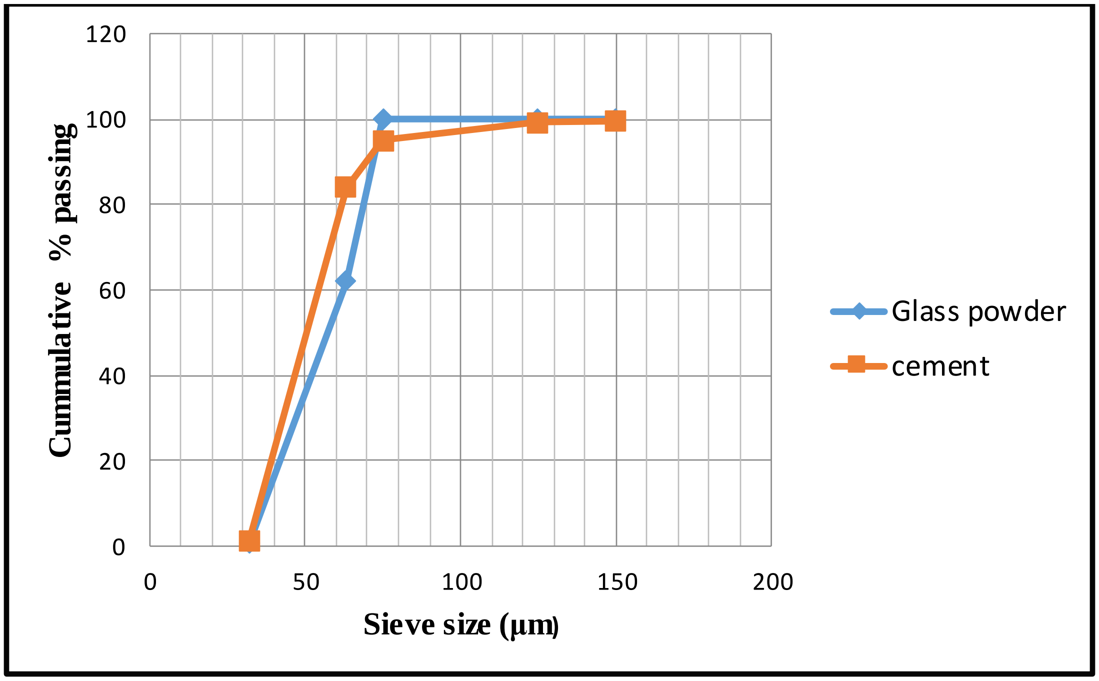

Fig. 3.2 Gradation of glass powder and cement.

The glass powder sample is then taken to the Geological Survey of Ethiopia for silicate analysis and specific gravity tests. The chemical composition of the glass powder is shown in Table 3.3.

3.3 Cement

To study the effect of waste glass powder on the strength development of concrete, initially it was proposed to use Messebo OPC; however, it was difficult to obtain Messebo OPC in and around Addis Ababa during the studying period. Therefore, it was a must to search and use comparable cement which is Dangote OPC was used for the experiment. That is, for all concrete and mortar specimens casted for the investigation, cement of Dangote Ordinary Portland, which complies with the standard set by ES 1176-6: 2005 (2005) for OPC cements. The standard specifies the content of the compositional range of oxides that need to be in a portland cement. All portland cements that are produced within the country, need to comply with the chemical composition shown in the Table 3.2 below. Any OPC product whose constituent deviates from the specified range cannot join the market as a certified product [50].

Table 3.2 Oxide composition of OPC as per ES 1176-6:2005 (2005).

Oxides of OPC	Range of percentage
SiO_2	18-24
Al_2O_3	2.6-8
Fe_2O_3	1.5-7
CaO	61-69
MgO	0.5-4
SO_3	0.2-4
K_2O	0.2-1

The chemical and physical properties of Dangote OPC and waste glass powder were tested in the Geological survey of Ethiopia and the results are shown in the Table 3.3 below.

Table 3.3 Chemical and physical properties of cement and glass powder (Appendix G).

Chemical Composition	Cement %	Glass powder %
SiO_2	22.82	74.20
Al_2O_3	5.41	2.93
Fe_2O_3	3.37	0.08
CaO	66.32	10.64
MgO	1.46	0.4
Na_2O	-	11.64
K_2O	-	0.36
MnO	-	<0.01
P_2O_5	-	0.06
TiO_2	-	0.03
H_2O	-	0.15
LOI	-	0.23
SO_3	2.16	-
$SiO_2 + Al_2O_3 + Fe_2O_3$	31.60	77.21
Specific gravity	3.15	2.46
Blaine fineness (m^2/kg)	316	264
Average size (µm)	50.19	57.09
Physical form	Fine powder	Fine powder
Color	Grey	Light grey

Note: In the above table, the average size of the particle is the sieve size at which 50% of the particles pass and is determined by linear interpolation.

The total composition of silica, alumina and ferrite of the glass powder is 77.21% (which is greater than 70%) as can be seen in the above table. Therefore, the waste glass powder used in this research is categorized as class N pozzolans according to ASTM C 618-02, and hence it can be used as partial replacement of cement in concrete production.

3.4 Aggregates

Aggregates are inert minerals primarily used as fillers with binding material in the production of concrete. Aggregates form the body of the concrete, reduce the shrinkage and affect economy. Therefore, it is significantly important to obtain right type and quality of aggregates to produce concrete. It should be clean, strong, hard and durable, so that it is graded in the required size to achieve utmost economy from the paste. Soft, porous rock can limit strength and wear resistance; it may also break down during mixing and adversely affect workability by increasing the amount of fines. Aggregates should also be free from impurities such as: silt, clay, dirt or organic matter. Therefore, to determine the quality of the aggregate physical characteristic tests should be carried out.

3.4.1 Properties of fine aggregate

The fine aggregate used in this research is natural sand extracted from Langano River. Since, the fine aggregate is extracted from the river side; it's full of dust film on their surface. Due to this reason, the fine aggregate was washed thoroughly and is then air dried before any test was carried out. In addition to this, all fine aggregate which retain on 9.5 mm sieve size were removed, and all the passing fine aggregate were used for experimentation. So, in this research the following physical tests were conducted on the properties of fine aggregate.

3.4.1.1 Silt content

Fine aggregate which is finer than 75 micron is generally categorized as silt. This silt on the surfaces of the sand has a severe effect on the quality of the concrete. It primarily affects the workability of the concrete, the bond between the sand and cement paste, and also results in a reduced strength.

According to the Ethiopian Standard (ESC.D3. 201) it is recommended to wash the sand or reject if the silt content exceeds 6 percent [16]. From the test result obtained, the silt content of the sand used for this experiment before washing was 8.2 percent, which is above the maximum requirement of Ethiopian standard. For this reason, it was washed thoroughly until its silt content becomes 2.4 percent.

3.4.1.2 Sieve Analysis

Sieve analysis is a procedure for the determination of the particle size distribution of the aggregate, the fineness modulus, an index to the fineness, coarseness and uniformity of aggregates. These properties of the aggregate greatly affect the property of the concrete under study. According to ES C.D3.201 [16], the gradation result of the original sand sample taken from Langano River was too coarse to meet the grading requirement and therefore it was blended with Alemtena finer sand available in the market in a proportion of 75%: 25%. The grading requirements for fine aggregates according to ES C.D3.201 and, the particle size distribution of both the original and blended aggregate used for the experiment is shown in Table 3.4 below.

Table 3.4 The particle size distribution of original and blended fine aggregates.

Sieve size	Percentage passing (ES C.D3.201)	Percentage passing (Original sand)	Percentage passing (Blended sand)
9.50 mm	100	100	100
4.75 mm	95-100	98.7	99.6
2.36 mm	80-100	88.2	89.4
1.18 mm	50-85	51.4	60.2
600 µm	25-60	22.8	32.1
300 µm	10-30	4.6	22.3
150 µm	2-10	0.5	2.2

Fineness Modules = $\frac{\sum(\text{cumulative coarser (\%)})}{100}$ = 2.94

Depending up on their size, sand can be classified as coarse sand when a fineness modulus is between 2.90 to 3.20; medium size sand with a fineness modulus of 2.60 to 2.90 and fine sand with a fineness Modulus of 2.20 to 2.60. Hence, the blended sand sample used for concrete and mortar was classified as coarse sand.

The sieve analysis of the original sand, the blend sand and the standard (ES C.D3.201) is shown in Figure 3.3 below.

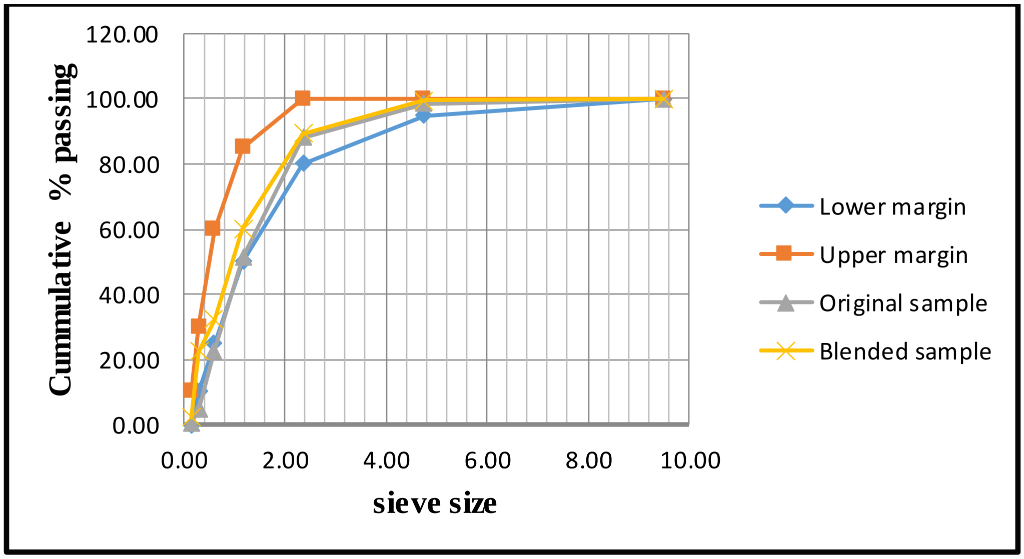

Fig. 3.3 Gradation of fine aggregate.

3.4.1.3 Specific gravity and absorption capacity

Aggregates contain pores on their surfaces, both permeable and impermeable, and hence the specific gravity depends on whether the pores are included in the measurement or not. There are different types of specific gravity such as: apparent specific gravity and bulk specific gravity. Apparent specific gravity of an aggregate refers to the solid materials excluding the pores and bulk specific gravity refers to total volume i.e., including pores of the aggregate. The following results are obtained from the laboratory experiment for the fine aggregate:

Bulk specific gravity = 2.13

Bulk specific gravity (SSD basis) = 2.42

Apparent specific gravity = 2.51

Absorption capacity = 1.15%

3.4.1.4 Moisture content

The aggregates in concrete are assumed to be inert mineral materials. However, most of the aggregates don't meet this assumption by either absorbing water (dry aggregates) or by releasing it (wet aggregates) to the mix. Therefore, moisture content of the aggregate affects the water to cement ratio of a concrete; and hence, this affects the strength and the workability of the concrete. As a result of this property of aggregates, the design of water to cement ratio of the mix changes. Therefore, it is important to workout both the absorption capacity and the moisture content of the aggregate.

The moisture content of fine aggregate was determined by oven drying 500 grams of fine aggregate (sand) for about 24 hours with a temperature of 105 °C to 110 °C and cooling it down for an hour. Then, dividing the weight difference by oven dry weight and multiplying the quotient by hundred gives the moisture content. The moisture content of the sample fine aggregate was found 2.89%.

3.4.1.5 Unit weight (Bulk density)

Unit weight is determined by filling a container of known volume and weighing it and then dividing the aggregate weight by the volume of the container. However, the degree of compaction should be carried out according to the standard; else will change the amount of void space, and hence the value of the unit weight. Constant moisture content of aggregate is required for concrete production as weight of aggregate depends on its moisture content. Oven dried aggregate sample expressed in Kg/m^3 is used to determine its unit weight and this parameter defines the volume of fine aggregate to be used in concrete [16]. The unit weight of the fine aggregate sample used in the experiment was found to be 1.49 g/cm^3. Table 3.5 shows the summarized test results of the fine aggregates.

3.4.2 Properties of the coarse aggregate

The coarse aggregate utilized in this research was basaltic crushed rock obtained from Yerer Aggregate manufacturing plant. Since the aggregates have been stored in the laboratory for ages, visual observation reveals that there was a dust film on their surface and thus, the aggregates were washed thoroughly and dried in open air outside the laboratory.

Table 3.5 Summarized test results of fine aggregate.

No	Test Description		Test Result
1	Silt Content	Before washing	8.2%
		After washing	2.4
2	Fineness Modulus		2.94
3	Moisture content		1.97%
4	Unit weight		1.49g/cm^3
5	Absorption		1.15%
6	Specific gravity	Bulk specific gravity	2.13
		Bulk specific gravity (SSD)	2.42
		Apparent specific gravity	2.51

The size of coarse aggregate used for experimental investigation was a mixture of 20 mm and 10 mm diameter aggregate sizes and it was sieved and stored in various grades for blending. During this study a nominal maximum size of 19 mm diameter aggregate was utilized throughout the concrete mix design.

In the same way similar to that of the fine aggregate, laboratory tests were carried out to determine the physical properties of the coarse aggregate and the results are shown in Table 3.6.

Table 3.6 Summarized test results for coarse aggregate.

No.	Test description		Test result
1.	Nominal maximum size		19 mm
2.	Moisture content		1.98%
3.	Unit weight		1.60g/cm^3
4.	Absorption capacity		1.02%
5.	Specific gravity	Bulk specific gravity	2.52
		Bulk specific gravity (SSD)	2.61
		Apparent specific gravity	2.69

Table 3.7 Sieve analysis of coarse aggregate.

Sieve size (mm)	Percent passing ASTM C 33	Percent passing (Original coarse agg.)	Percent passing (Blended coarse agg.)
25	100	100	100
19	95-100	98.70	98.70
12.5	-	34.60	48.92
9.5	25-55	18.22	26.72
4.75	0-10	0.18	0.18

Figure 3.4 demonstrates the sieve analysis of coarse aggregate utilized and the standard (ES C.D3.201).

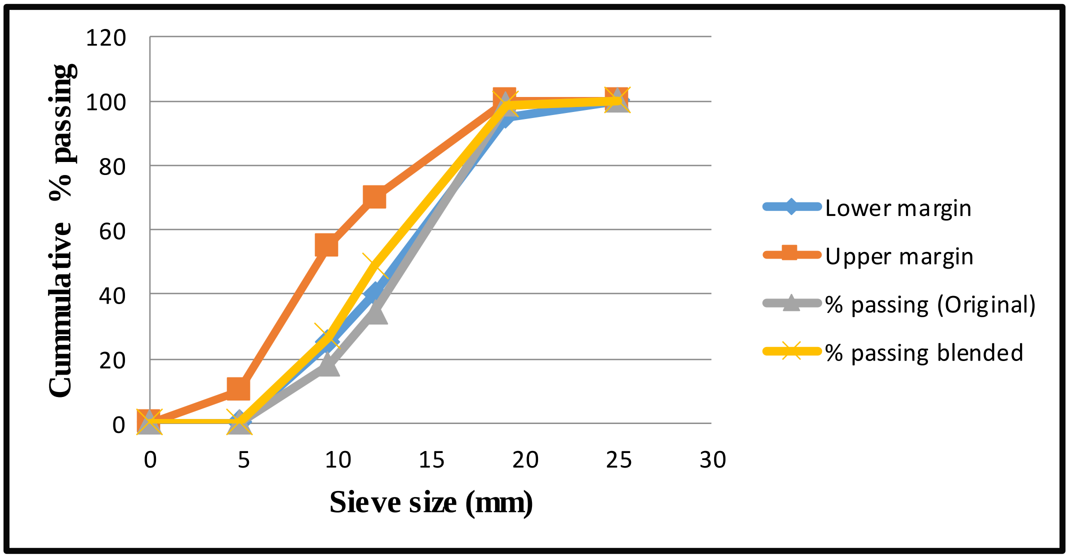

Fig. 3.4 Gradation of coarse aggregate.

3.5 Water used in the experiment

The mixing water utilized in this research work was drinkable pure water supplied by Addis Ababa Water and Sewerage Authority found in the material laboratory of Addis Ababa Institute of Technology.

CHAPTER FOUR

EXPERIMENTAL PROGRAM

4.1 Introduction

The main objective of this research is to study the use of waste glass powder as a cement replacing material in strength development of concrete. All the experimental programs were carried out at the Construction Material Laboratory in Addis Ababa Institute of technology. These include studying properties of paste, mortar and concrete by replacing the cement partially with glass powder at different level of percentages.

In order to realize these objectives, three major laboratory tests were conducted. The first experiment was conducted on blended powders and pastes within which part of the cement was replaced by glass powder so as to determine the fineness of the blended powder, the water requirement (normal consistency) and setting time of the blended paste. The second experiment was conducted on mortar within which part of the cement was replaced by glass powder. This test was used to investigate the pozzolanic property, fresh and hardened properties of the glass powder. Finally, the third experiment was conducted on the fresh and hardened properties of concrete (workability, strength and permeability) during which part of the cement was replaced by glass powder.

4.2 Experiment One

Under this experiment, the fineness of blended powders, normal consistency test and setting time of the blended pastes of Dangote cement and glass powder are carried out.

4.2.1 Fineness test

Blaine air permeability test is employed for determining the fineness of portland cement. It measures the specific surface area of fine materials in square centimeters per gram of test sample. By using this apparatus, a quantity of air is drawn through a bed of definite porosity. The blain air method of determining the specific surface area is based on the relationship between the surface area of the particles in a porous bed and the rate of fluid flow through the bed. Therefore, the fineness of the glass powder, the cement and the blended powders at different percentages were determined by the blain air permeability method. The different mixes are as shown in Table 4.1. The cement was partially replaced from 5% to 20% at 5% increment.

Moreover, volume of blended of mixes are converted into weight measurements. Therefore 1 Kg of cement is replaced by 0.79 Kg of glass powder because volume replacement needs to account for the lower density of glass powder (2.48g/cm^3) to keep the paste volume constant.

Table 4.1 Blending proportion of cement and glass powder.

No	Code	Blending proportion by volume	
		Dangote OPC (%)	**Glass powder (%)**
1.	GP0	100	0
2.	GP5	95	5
3.	GP10	90	10
4.	GP15	85	15
5.	GP20	80	20

4.2.2 Normal consistency test

The normal consistency of hydraulic cement refers to the amount of water required to make a neat paste of satisfactory workability [16]. According to ASTM C 187 (which is recommended by ASTM C 595), the normal consistency measures the resistance of the paste to the penetration of a plunger or needle of 300gm released at the surface of the paste using vicat apparatus. The control (OPC cement without glass powder) and blended pastes were prepared by replacing part of the cement by glass powder. During the experiment different quantity of water was used until the required normal consistent paste is obtained. This test is carried out to determine the amount of water required to prepare a standard cement paste.

4.2.3 Setting time test

Generally, there are two types of setting time to be determined in the laboratory, initial and final setting time. The initial setting time of the paste was determined by the duration of 25 mm penetration of vicat needle into the paste in 30 seconds after it has been released. By recording the results of all penetration tests and, by interpolation, it was possible to determine the time when a penetration of 25 mm is obtained. Whereas the final setting time was determined by measuring the time related to zero penetration of the needle into the paste according to ASTM C 191 method of measuring setting time, which is used for that of hydraulic cements.

4.3 Experiment Two

The second experimental program focuses on preparing different mortar mixes with different percentage of glass powder as partial replacement of cement. In this research, two types of cements were used during the experiment: Ordinary Portland cement and Portland pozzolana cement. Therefore, four types of mortar cubes were produced; mortar cube made of OPC, mortar cube made of OPC partially replaced by glass powder, mortar cube made of PPC, and mortar cube made of PPC partially replaced by glass powder. In addition to cement, sand and water were also used to produce mortar.

4.3.1 Mix proportion of OPC-GP blended mortar

OPC-GP mortar specimens were prepared for destructive tests and compressive strength tests were conducted at the age of 3, 7, 28 and 56. For each substitution ratio, 4 sets (4 x 3 = 12) of mortar specimens were prepared. The mix proportions used in the preparation of OPC-GP mortar specimens are shown in Table 4.2.

Table 4.2 OPC-GP blended mortar mix proportion for nine molds.

Mix code	OPC Cement (g)	Glass powder (g)	W/(C+G)	Water (g)	Sand (g)
GPM 0	650	0	0.500	325	1400
GPM 5	617.5	25.68	0.505	325	1400
GPM 10	585	51.35	0.511	325	1400
GPM 15	552.5	77.03	0.516	325	1400
GPM 20	520	102.7	0.522	325	1400

4.3.2 Mix proportion of PPC-GP blended mortars

The mix proportions used in the preparation of PPC-GP mortar specimens are shown in the Table 4.3 below. For each of the substitution ratios, 4 sets (4 x 3 = 12) of mortar specimens were prepared for destructive test (compressive strength) conducted at the age of 3, 7,28 and 56 days.

Table 4.3 PPC-GP blended mortar mix proportion for nine molds.

Mix code	PPC Cement (g)	Glass powder (g)	W/(C+G)	Water (g)	Sand (g)
GPMP 0	650	0	0.500	325	1400
GPMP 5	617.5	25.51	0.505	325	1400
GPMP 10	585	51.03	0.511	325	1400
GPMP 15	552.5	76.54	0.517	325	1400
GPMP 20	520	102.05	0.522	325	1400

4.3.3 Batching of mortar specimen and mixing procedure

Batching is a process of measuring and preparing the materials used for one mix. In this research the batching was carried out according to ASTM C 270 – 10. Cement, glass powder and sand were weighted and dry mixed for about one minute. After the addition of water all of the materials were mixed for another two minutes. Immediately after wet mixing, the flow table test was conducted to check the workability of the mix. The test specimens were then casted in a steel mold with 50 mm x 50 mm x 50 mm cube in two layers and each layer were compacted using a tamping rod [16]. The specimens were then demolded in the next day after 24 hours and were placed in a curing pond prepared for the cubes until the test day.

4.4 Experiment Three

The third experimental program focuses on preparing different concrete mixes with different percentage of glass powder in order to study the fresh and hardened properties of concrete such as workability, compressive and flexural strength and durability aspects by using water permeability test. For each of the substitution ratios, 3 sets (3 x 3 = 9) of concrete cubes of size 15 cm x 15 cm x 15 cm were prepared. The compressive strength tests were conducted at 7, 28 and 56 days, flexural strength at 7 and 28 days, whereas the water permeability tests were carried out at 28 and 56days.

4.4.1 Mix design and trial mix preparation

Mix design is the process of proportioning the ingredients of concrete in order to get a suitable workability, specified strength, durability, minimum cost and other required characteristics of concrete. Although there are many papers and standards for determining mix design, the perfect mix design can only be achieved through repetition of trial mixes and following the correct path which results in a continuous error reduction and a more precise result. The major cause for multiple iteration of mix design could be due to the difference in material property across different places. The mix designs, as well as glass powder replacements, were done volumetrically.

During mix proportioning, it is necessary to know how much water the aggregate will absorb from the mix water or how much extra water the aggregate might contribute to the mix. In this research, ACI 211.1 - 91 mix design method is used for material proportioning of C-30 class of concrete.

A trial mix was prepared for characteristics strength of 30 MPa with water to cement ratio of 0.56 and a cement content of 335 kg/m^3. The trial mix resulted in a slump of 77 mm and a 28 day compressive strength of 29.97 MPa at a loading rate of 28 Mp/s. The slump of the concrete was above the targeted slump which is 25-75 mm and the compressive strength was slightly lower than the targeted strength.

For the purpose of preparing a final mix the water to cement ratio of the mix was decreased to 0.55 from 0.56 by keeping the cement content constant i.e., water decreased from 189 kg/m^3 to 185 kg/m^3, in order to adjust the slump. Sidney Mindess (2003) suggested that an increase or decrease of the water content by 6 kg/m^3 will increase or decrease the slump by approximately 25 mm. The final mix proportions for 1m^3 of the different control and OPC-GP concrete are as shown in Table 4.4.

Table 4.4 Concrete mix proportions.

Code	**Cement quantity (kg/m^3)**	**Glass powder (kg/m^3)**	$\frac{W}{(C+G)}$	**Water (kg/m^3)**	**FA (kg/m^3)**	**CA (kg/m^3)**	**FA (%)**	**CA (%)**
GPC 0	335	0	0.55	185	712	1256	36	64
GPC 5	318.25	13.23	0.558	185	712	1256	36	64
GPC 10	301.50	26.47	0.564	185	712	1256	36	64
GPC 15	284.75	39.70	0.570	185	712	1256	36	64
GPC 20	268.00	52.93	0.576	185	712	1256	36	64

4.4.2 Specimen preparation

All the concrete specimens were mixed in the material laboratory at Addis Ababa Institute of technology. The coarse aggregate was added to the mixer first followed by cement and fine aggregate, and then it was dry blended for about one minute. Two-thirds of water was added, and the mixing was continued for an additional one minute. The remaining water is then added, and the total mixing time was three minutes. Slump tests of fresh concrete were done immediately after mixing to check workability and consistency using a slump cone. Regarding placing and compaction, placing was started immediately and was done in two layers and compacted on a table vibrator for 30 seconds for single (150 mm x 150 mm x 150 mm) cube mold and for 45 seconds for couple of (150 mm x 150 mm x 150 mm) cube molds. After vibration has been completed, the top surface was finished using a trowel.

4.4.3 Curing

After 24 hours of placing and compaction, samples were removed from their molds and placed in a water pond at room temperature until the intended days for testing concrete compressive strengths, that is, 3^{rd}, 7^{th} and 28^{th} days. Then after, the concrete cubes are crushed and their load carrying capacities were recorded.

4.4.4 Compressive strength test

The concrete specimens were subjected to compressive strength test at a loading rate of 28 Mpa/s.

4.4.5 Flexural strength test

Flexural strength is a measure of the tensile strength of an unreinforced concrete beam or slab to resist failure in bending. In this test, the specimen is subjected to a bending moment and a bending force was applied downward on a member supported simply at its two ends. The stresses developed above the neutral axis are generally subjected to compressive stresses and those below the neutral axis to tensile stresses.

The flexural strength of the concrete beams was carried out using a third point loading in which half of the load will be applied at each third of the span length. The concrete beams were supported at their end and loaded at their interior location. Figure 4.1 shows a sample of beam prepared for flexural strength test using third point loading setup.

Fig. 4.1 Third point loading flexural strength test for Concrete beam.

These results are summarized in Table 5.15. The failure load at which the concrete beam cracks in KN and the flexural strength in MPa are recorded from the testing machine and the following formulas were also used to calculate the reliability of the test results (according to

ASTM C 78 standard).

4.4.6 Water permeability of concrete

Permeability of a concrete is mainly affected by water to cement ratio, property of cement, curing duration and hydration process. To assess the performance of changes related to durability due to the addition of glass powder replacing cement partially in concrete production, water permeability test, of non-steady, was conducted on normal concrete cubes having a dimension of 150 mm x 150 mm x 150 mm. The surfaces of the cubes were polished to remove any unwanted particles on the surfaces. The cubes where then placed in the permeability apparatus and the bolts were tightened to prevent any leakage of water.

CHAPTER FIVE

TEST RESULTS AND DISCUSSION

5.1 Introduction

There are several factors that affect the laboratory results of glass powder replacing cement both in fresh and hardened state. Such as material property, material proportion and mix design play a vital role for the desired outcome.

This chapter consists of discussion and analysis of test results on the physical and chemical properties of waste glass powder blended cements, strength development of mortars containing waste glass powder as partial replacement of ordinary Portland cement and portland pozzolana cement, the fresh and hardened properties (workability, compressive and flexural strength) and permeability of concrete containing waste glass powder at different percentages of replacements.

5.2 Test results and discussions on experiment one

In this part the test results on the physical and chemical properties of waste glass powder and blended pastes are presented, analyzed and discussed.

5.2.1 Physical and chemical properties of waste glass powder

The particle size analysis of glass powder samples showed that average size of the glass powder particles was 57.09 µm and 90% of the particles were of size less than 71.84 µm, whereas cement have an average fineness of 50.19 µm which is smaller than the glass powder and 90% of the particles were less than 69.65 µm which is less than the glass powder (obtained by linear interpolation). On the other hand, Figure 3.2 (Gradation of glass powder and cement) shows for sieve sizes greater than 91.17 µm (where the two graphs meet) the glass powder curve is above cement curve. This shows that the glass powder is finer than the cement for higher sieve sizes and coarser for lower sieve sizes. But on average glass powder is coarser than cement.

The specific gravity (2.46 g/cm^3) and Blaine surface area (264 m^2/kg) of glass powder is lower than the OPC used with specific gravity (3.15 g/cm^3) and Blaine surface area (316 m^2/kg) respectively (See Table 3.3). Table 5.1 and Figure 5.1 show the fineness of blended powders using blain air permeability method.

Table 5.1 Blain Fineness of glass powder and blended powders.

S. No.	Code	Blain air permeability (m^2/kg)
1.	GP0	316
2.	GP5	304
3.	GP10	291
4.	GP15	280
5.	GP20	271

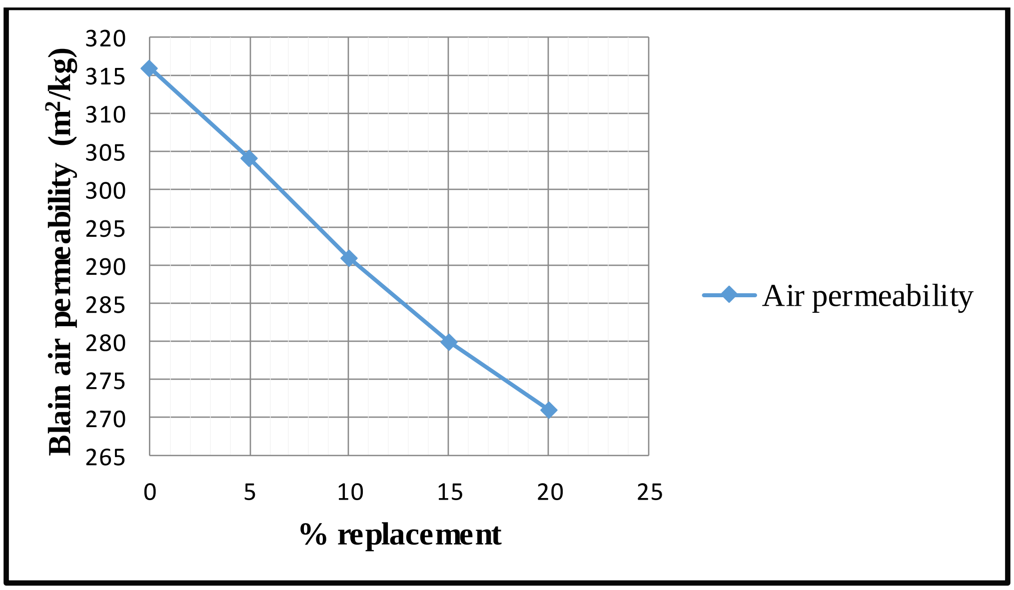

Fig. 5.1 Blaine Fineness of glass powder and blended powders (m^2/kg).

Table 5.1 shows the Blaine fineness of glass powder is lower than the ordinary Portland cement, whereas the blended powders show higher Blaine fineness than the glass powder.

Surface area favors the pozzolanic reactivity of amorphous silica and other minerals [3]. However, according to ASTM C-618 specifications the composition of $SiO_2 + Al_2O_3 + Fe_2O_3 = 77.21 > 70\%$ proves that the glass powder shows pozzolanic nature and is classified as Class N Pozzolan.

The loss on ignition (LOI) value for the glass powder was found to be 0.23% which was very small compared to that specified by the same standard, ASTM C-618 (which is 10%). Moreover, the glass powder was found to have high alkali content like Na_2O (11.64%) indicating a high potential for alkali-silica reaction when used in concrete with silica rich aggregates. However, according to Shayan A. (2004), glass powder size smaller than 80 μm acts as a suppressor and does not show swelling due to ASR when used in concrete and Pereira L. (2004) confirmed that finely ground glass powders higher than 250 m^2/kg Blaine specific surface, exhibited very high pozzolanic activity.

5.2.2 Consistency of Cement and blended paste

Normal consistency tests, for the blended cements, were conducted, by Vicat apparatus, to observe the changes in water requirement of pastes due to the glass powder.

The normal consistency of the control paste (without glass powder) was 31.25%. All the other pastes blended with glass powder showed normal consistency equal and higher than the control paste. The normal consistency of GPP 0 and GPP 5 was constant (31.25%), however, at 10% replacement the normal consistency increased to 32.15%, and at 20% replacement it reached 33.45% as shown in Table 5.2 and Figure 5.2.

Table 5.2 Normal consistency of glass powder blended cement pastes.

S. No.	Code	Consistency (%)
1.	GPP 0	31.25
2.	GPP 5	31.25
3.	GPP 10	32.15
4.	GPP 15	32.85
5.	GPP 20	33.45

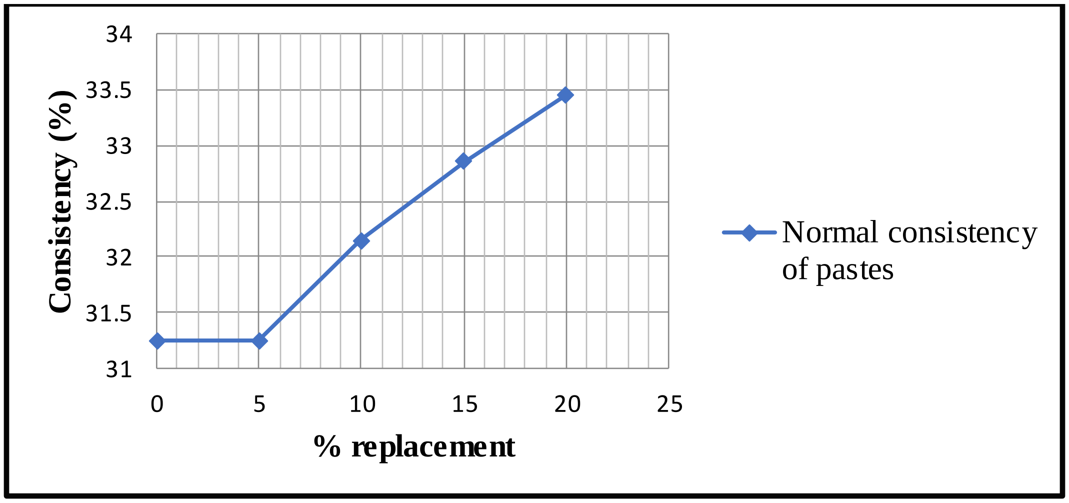

Fig. 5.2 Normal consistency of GP-OPC blended pastes.

The increment on water requirement with increasing glass powder content is probably due to the slow reactivity of glass powder particles [56].

In all cases of blending except 20% replacement of glass powder, the normal consistencies of the pastes are within the range of the normal consistency for normal ordinary Portland cement which is between 26-33% [16].

5.2.3 Setting time of cement and blended pastes

Tests for setting time were conducted to compare the setting time of the blended cements with standards and also with the control paste. The test results are shown in Table 5.3 and Figure 5.3.

Table 5.3 Initial and final setting time of glass powder blended cement pastes.

S. No.	Code	Initial setting time (min.)	Final setting time (min.)
1.	GPP 0	74	270
2.	GPP 5	80	276
3.	GPP 10	86	290
4.	GPP 15	91	302
5.	GPP 20	96	315

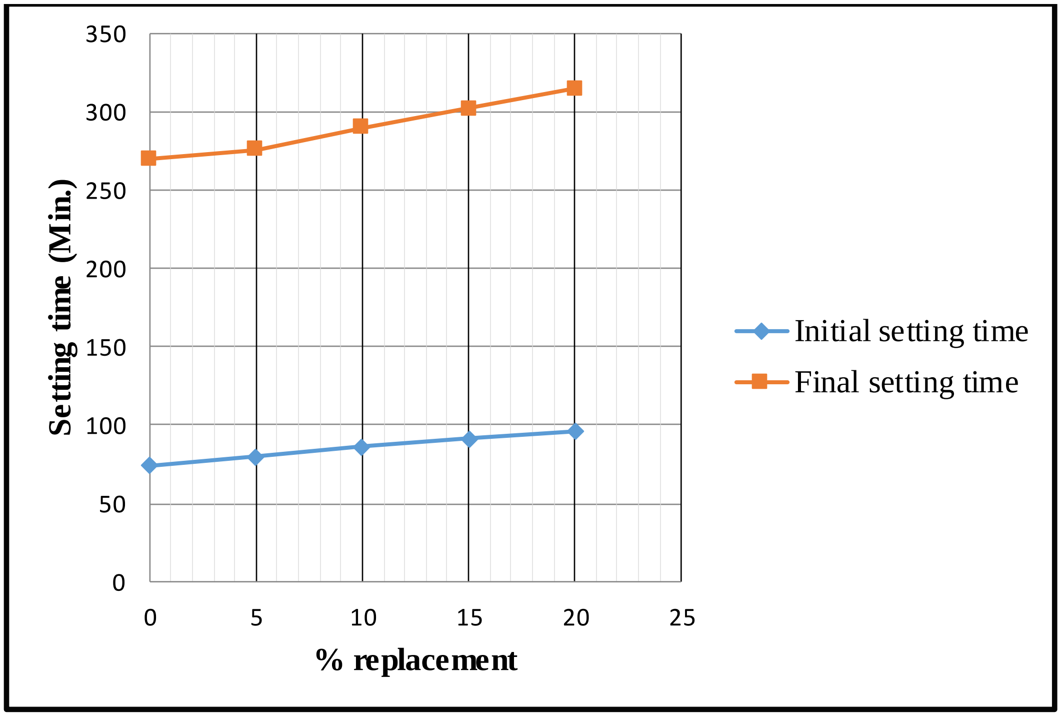

Fig. 5.3 Initial and final setting time of GP-OPC blended pastes.

The above Table 5.3 shows a trend of an increase in the initial setting time and final setting time of blended pastes. The probable reason for the increase in setting time could be due to the slow reactivity of glass powder particles [56].

The Ethiopian standard (ES C.D5.202, section 4.2.4) limits the initial setting time of cement not to be less than 45 minutes and the final setting time not to exceed 10 hrs. The results for the setting time in Table 5.3 indicated that addition of glass powder retarded the setting time; however, this retardation was within the limits specified by the Ethiopian standard. An increase in glass powder content showed a trend of increment both in the initial and final setting time of blended pastes.

5.3 Test results and discussions on Experiment Two

This part consists of test results and analysis of workability and compressive strength of control mix mortar and blended mortars. These are:

- Workability of OPC-GP blended mortars.
- Workability of PPC-GP blended mortars.

- Compressive strength of OPC-GP blended mortars.
- Compressive strength of PPC-GP blended mortars.

5.3.1 Workability of cement and blended mortars

The workability of mortar mix is tested by the flow table prior to casting into molds. The following Table 5.4 and Figure 5.4 show the workability of the control and blended mortars.

Table 5.4 Flow table values of OPC-GP blended mortars.

S. No	Mix Code	Flow (mm)
1.	GPM 0	132.5
2.	GPM 5	132.0
3.	GPM 10	130.5
4.	GPM 15	126.0
5.	GPM 20	112.0

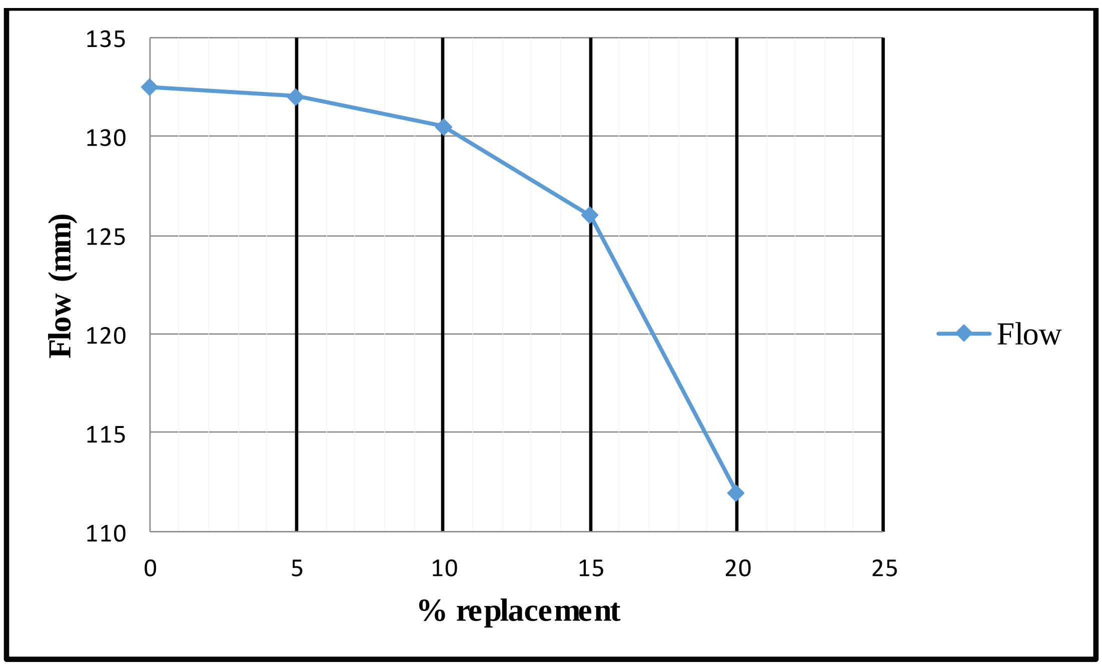

Fig. 5.4 Flow table values of OPC-GP blended mortars.

As can be seen from Table 5.4 the flow value shows a slight reduction as the glass powder content increases. This could be probably due to the angular geometry of the glass powder particles, resulting in higher interlocking of particles which in turn reduces the flow [56].

5.3.2 Compressive strength of OPC and PPC blended mortars

In this research, mortars were prepared from Dangote OPC cement and waste glass powder blended cements to study the effect of the waste glass powder on the compressive strengths of mortars.

The compressive strengths of the mortars were tested on the 3, 7, 28 and 56 days. The detail test results are given in the Appendices. But for discussion and analysis, the summarized and averaged test results for both OPC-GP and PPC-GP mortars are as shown in Table 5.5 and Table 5.6 respectively:

Table 5.5 Average compressive strength test result of OPC-GP mortar.

S. No	Code	Average compressive strength							
		3 days		7 days		28 days		56 days	
		Load (kN)	Strength (N/mm^2)	Load (kN)	Strength (N/mm^2)	Load (kN)	Strength (N/mm^2)	Load (kN)	Strength (N/mm^2)
1.	GPM 0	41.00	16.40	72.15	28.86	106.03	42.41	122.18	48.87
2.	GPM 5	45.22	18.09	75.53	30.21	110.62	44.25	123.12	49.25
3.	GPM 10	43.66	17.46	73.55	29.42	107.93	43.17	122.36	48.94
4.	GPM 12	40.95	16.38	71.95	28.78	105.83	42.33	121.53	48.61
5.	GPM 15	32.60	13.04	63.31	25.32	100.45	40.18	112.68	45.07
6.	GPM 20	29.90	11.96	58.10	23.24	90.32	36.13	105.34	42.14

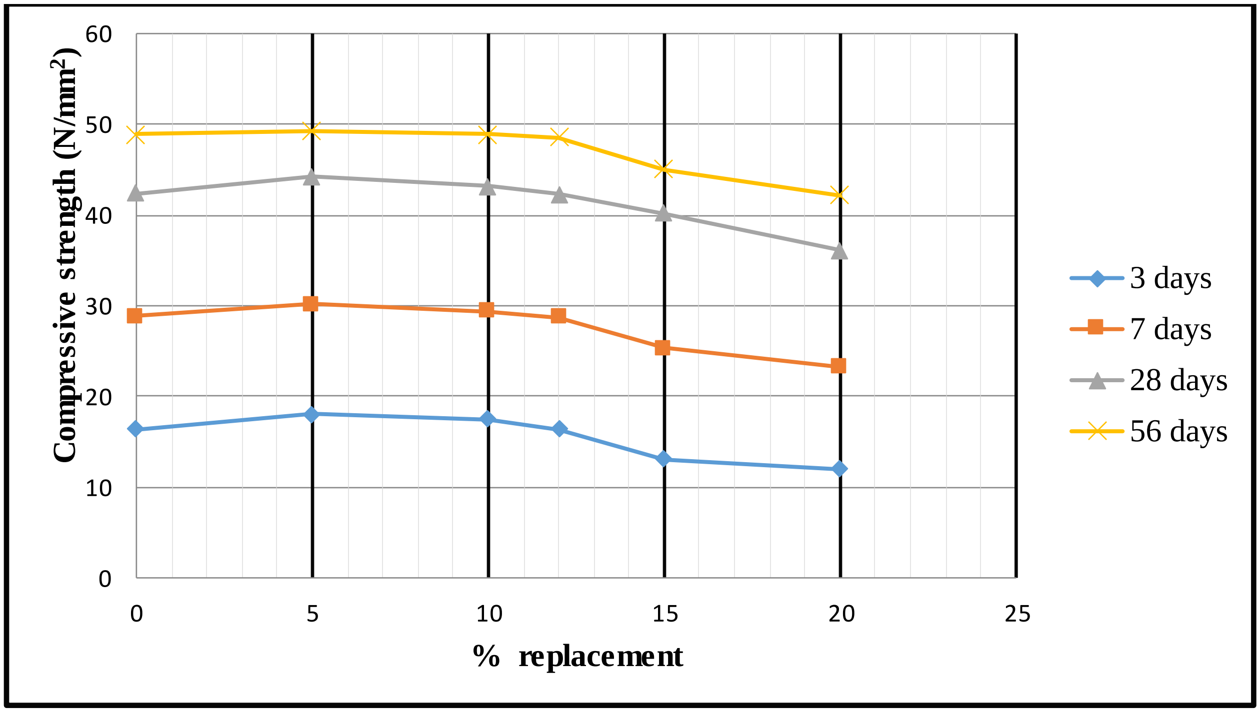

Fig. 5.5 Average compressive strength of OPC-GP mortar.

The compressive strength of OPC-GP mortar at three, seven, twenty-eight and fifty six days are compared in Figure 5.5 for different percentages of glass powder replacement.

Table 5.6 Average compressive strength of PPC-GP mortar.

S. No	Code	Average compressive strength							
		3 days		7 days		28 days		56 days	
		Load (kN)	Strength (N/mm^2)	Load (kN)	Strength (N/mm^2)	Load (kN)	Strength (N/mm^2)	Load (kN)	Strength (N/mm^2)
1.	GPM 0	26.81	10.72	41.12	16.45	79.29	31.72	92.86	37.14
2.	GPM 5	25.39	10.16	38.31	15.32	63.41	25.36	79.44	31.78
3.	GPM 10	23.43	9.37	36.28	14.51	61.43	24.57	77.98	31.19
4.	GPM 15	21.35	8.54	34.14	13.67	58.17	23.27	75.36	30.14
5.	GPM 20	19.95	7.98	25.85	10.34	53.71	21.48	71.94	28.78

To study the indirect pozzolanic effect of glass powder, mortar specimens were prepared for both OPC and PPC blended glass powder as shown in the above two tables. The aims of these tests were to figure out the existence of pozzolanic reaction in the glass powder blended pastes. As can be seen from Table 5.5, the glass powder at 5% and 10 % replacement with OPC have shown a higher compressive strength value than the control mix throughout the tests period i.e., 3, 7, 28 and 56 days. Moreover, the 12% replacement has also shown a nearly equal strength as that of the control mix with slight reduction in compressive strength by 0.12%, 0.28%, 0.19% and 0.53% throughout the test periods compared to the control mix at the 3, 7, 28 and 56 days. A similar trend was found by undergraduate research on waste glass powder as cement replacement supervised by Prof. Dr. -Ing. Abebe Dinku in Addis Ababa University [34]. However, the mortar work with PPC and glass powder has shown a reduction at all replacement percentages as can be seen on Table 5.5 and Figure 5.2.

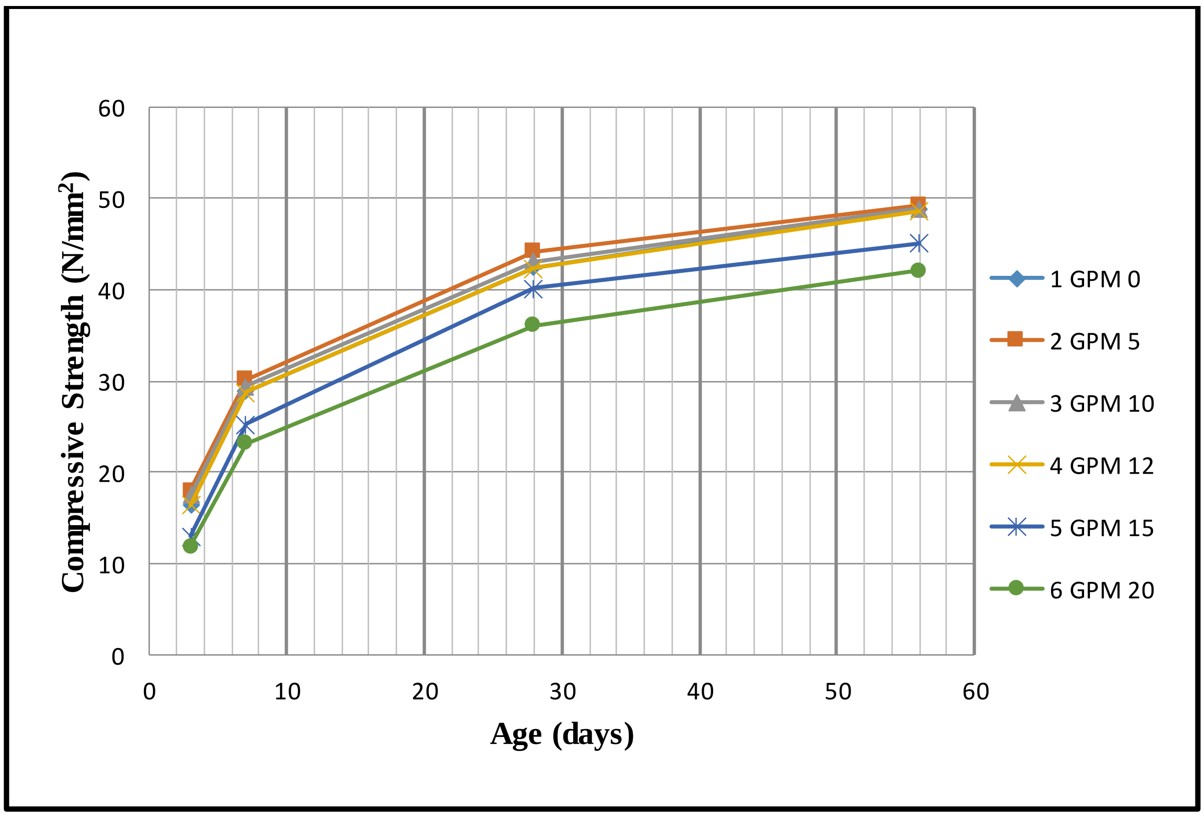

Fig. 5.6 Compressive strength of OPC-GP mortar.

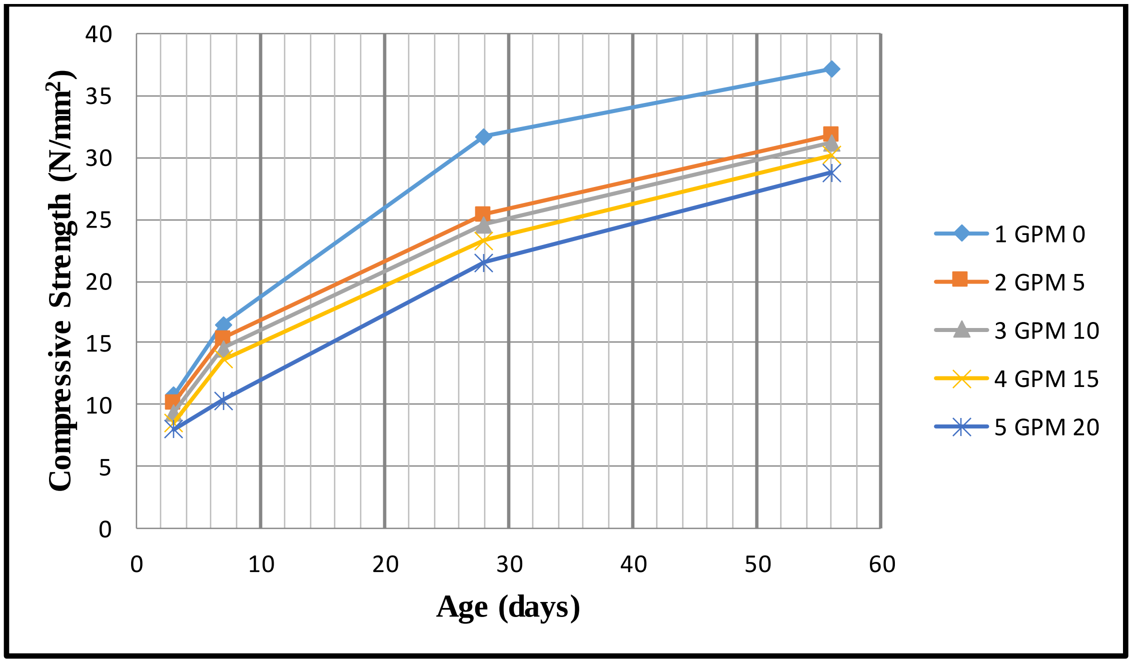

Fig. 5.7 Compressive strength of PPC-GP mortar.

As can be seen in Tables 5.5 and 5.6 above, the replacement of cement with glass powder has shown a different effect on strength development with OPC and PPC. This is due to the reason PPC contains a higher amount of silica and it under goes a secondary chemical reaction by itself. The addition of glass powder, which is reach in silica in this cement will not result in compressive strength improvement because there will be a high amount of an hydrated silica due to the competition for the $Ca(OH)_2$ released from the hydration of the cement particles. Due to this reason, the PPC-GP mortars have shown a lower compressive strength.

However, OPC on the other hand contains smaller amount of silica. Therefore, the addition of glass powder in this cement had resulted in a higher compressive strength for 5% and 10% replacement. This is probably due to the pozzolanic reaction between the glass powder and the $Ca(OH)_2$ from the cement hydration (see Fig. 5.1 and Table 5.5). Various researches also proved the existence of secondary pozzolanic reaction between OPC and glass powder using different advanced methods of analysis such as X-ray Diffraction (XRD) Analysis, Thermal Analysis or Thermo- gravimetric analysis (TGA) and Scanning Electron Microscopy (SEM) depending on different factors. However, none of these methods are available in the laboratory and that is why the indirect methods of testing Pozzolanic reaction are applied.

Strength activity index (AI) was calculated according to ASTM C 618 as a measure of pozzolanic activity at 3, 7, 28 and 56 days. The Strength activity index for all OPC-GP blended mortars at 3, 7, 28 and 56 days were higher than the minimum requirement of 75% specified in ASTM C 618 except the 20% replacement of the 3 days result as shown in Table 5.7 below.

Table 5.7 Strength activity index of OPC-GP mortar specimens.

Mix code	Age of specimen			
	3 days	**7 days**	**28 days**	**56 days**
GPM 0	100	100	100	100
GPM 5	110.30	104.68	104.34	109.78
GPM 10	106.46	101.94	101.79	109.14
GPM 12	99.88	99.72	99.81	99.87
GPM 15	79.51	87.73	94.74	95.22
GPM 20	72.93	80.53	85.19	86.23

As the percentage replacement of OPC cement by glass powder increases, the compressive strength of mortar decreases. Table 5.7, for example, shows GPM 5, GPM 10, GPM 15 and GPM 20 mortars containing 5, 10, 15, and 20% glass powder, had an activity index of 104.34, 101.79, 99.81, 94.74 and 85.19% at 28 days respectively. Due to the increased replacement of cement by glass powder, the cement content in the mixture is reduced which in turn causes a reduction in hydration reaction resulting in a lower strength activity index.

At the later ages of OPC mortar specimen, the strength activity index had also shown a pattern of increasing for most of the specimens. GPM 12 mortar specimens, for instance, had a strength activity index of 99.88%, 99.72%, 99.81% and 99.87% at 3, 7, 28 and 56 days respectively. The increase in strength activity index with age could be due to the slow hydration reaction of the cement and glass powder. Therefore, this partly shows the Pozzolanic nature of glass powder.

However, the strength activity index of PPC-GP blended mortar specimens showed a decreasing pattern as shown in Table 5.8 below. As the percentage replacement of glass powder increases, the strength activity index of PPC-GP mortar specimens decreases as opposed to that of the OPC-GP mortar specimens. Moreover, most of the PPC-GP blended mortars showed a decrease in strength activity index as the age of the specimen increased and none of the PPC-GP mortars showed improvement over the control mortar mix.

Table 5.8 Strength activity index of PPC-GP mortar specimens.

Mix code	Age of specimen			
	3 days	7 days	28 days	56 days
GPM 0	100	100	100	100
GPM 5	94.78	93.13	79.95	85.57
GPM 10	87.41	88.21	77.46	83.98
GPM 15	79.66	83.10	73.36	81.15
GPM 20	74.44	62.86	67.72	77.49

5.4 Test results and discussions on experiment three

In this part, the test results on both the fresh and hardened properties of concrete with and without glass powder replacing cement at 7, 28 and 56 days are presented, analyzed and discussed.

5.4.1 Properties of fresh concrete

Slump tests were conducted to investigate the impact of glass powder on workability of fresh concrete. The objective of workability test is to assess whether the concrete is effective enough for easy compaction, placing and finishing. Slump test is the simplest test method for workability of fresh concrete.

The control concrete trial mix gave a slump of 77 mm, which is more than the targeted slump that is 25-75 mm. So as to make the slump in the targeted range, the free water to cement ratio of the mix were changed from 0.56 to 0.55. This adjustment had resulted in a slump of 54 mm which is in the required range. The slumps of all OPC-GP concrete mixes are given in the Table 5.9 below.

As the glass powder content increased, the slump of the concrete showed a slight reduction as can be seen from Table 5.9 and Figure 5.8. The decrease in slump of concrete with increasing glass powder content could be probably due to the angular geometry of the glass powder particles, resulting in higher interlocking of particles which in turn reduces slump [52]. Therefore, in order to get similar slump for the control and OPC-GP concrete, the water content should be increased as the glass powder content increased.

Table 5.9 Slump test results of OPC-GP concrete.

S. No	Mix Code	W/(C+G)	Slump value (mm)
1.	**GPC 0**	0.55	54
2.	**GPC 5**	0.558	49
3.	**GPC 10**	0.564	45
4.	**GPC 15**	0.570	42
5.	**GPC 20**	0.576	39

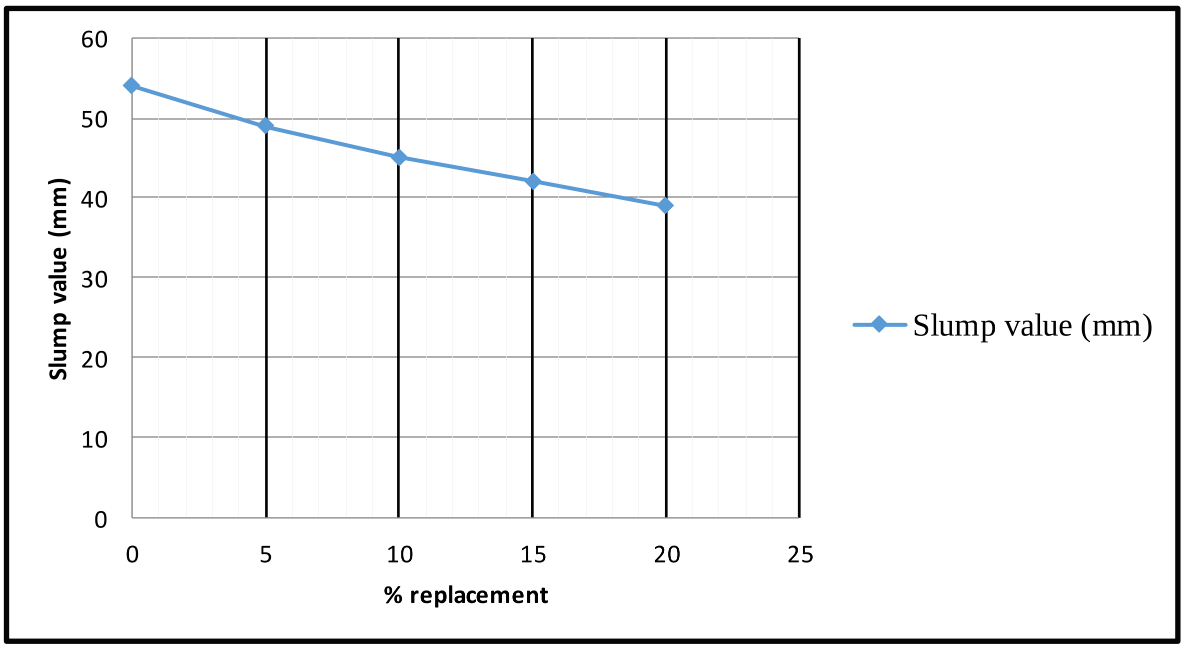

Fig. 5.8 Slump test values of Blended concrete specimens.

Fig. 5.9 Sample slump test of concrete.

5.4.2 Properties of the hardened concrete

In this part, the different properties of the hardened concrete such as unit weight, compressive strength, flexural strength and water permeability of concrete with and without glass powder are tested and analyzed in the sections below.

5.4.2.1 Test results and discussions on unit weight

The properties of concrete vary as it hardens. In this section, the unit weights of the hardened concrete specimens are discussed. The dimensions and weights of the concrete cubes were measured just prior to testing the compressive strength. These tests were conducted at 7, 28 and 56 days. The detail results of weight and dimension are given in the appendix. However, the results of unit weights of concrete specimens in this section are calculated based on the 28 days weight and dimension. Table 5.10 and Figure 5.10 show the results of unit weight and percent reduction for different percentage replacements of cement by glass powder.

Table 5.10 Unit weights of control and glass powder blended concrete.

S. No.	Mix code	OPC replaced (%)	Unit wt. (kg/m^3)	% Reduced
1.	GPC 0	0	2,348	0.00
2.	GPC 5	5	2,334	0.60
3.	GPC 10	10	2,330	0.77
4.	GPC 15	15	2,314	1.45
5.	GPC 20	20	2,306	1.79

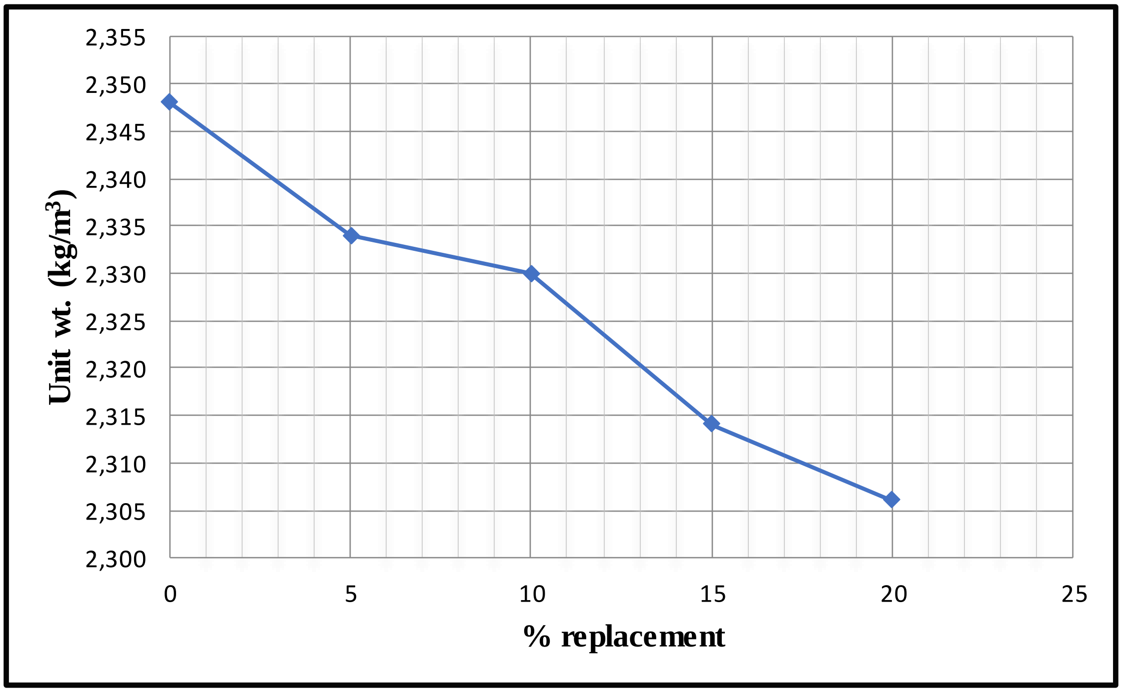

Fig. 5.10 Unit weight of concrete (kg/m^3).

As can be seen in Table 5.10, the concrete specimens showed a decrease in unit weight up to 1.79%, when the cement was replaced by glass powder by 20% in sample GPC 20. On the other hand, 0.60%, 0.77% and 1.45% reduction in unit weight were observed for 5%, 10% and 15% replacement of glass powder in sample GPC 5, GPC 10 and GPC 15 respectively. This is due to the lower density of glass powder, i.e., 2.48 g/cm^3 than density of OPC, i.e., 3.15 g/cm^3, which resulted in a reduction of unit weights of the blended concrete specimens.

Figure 5.11 shows the reduction in unit weight of concrete as glass powder content increases.

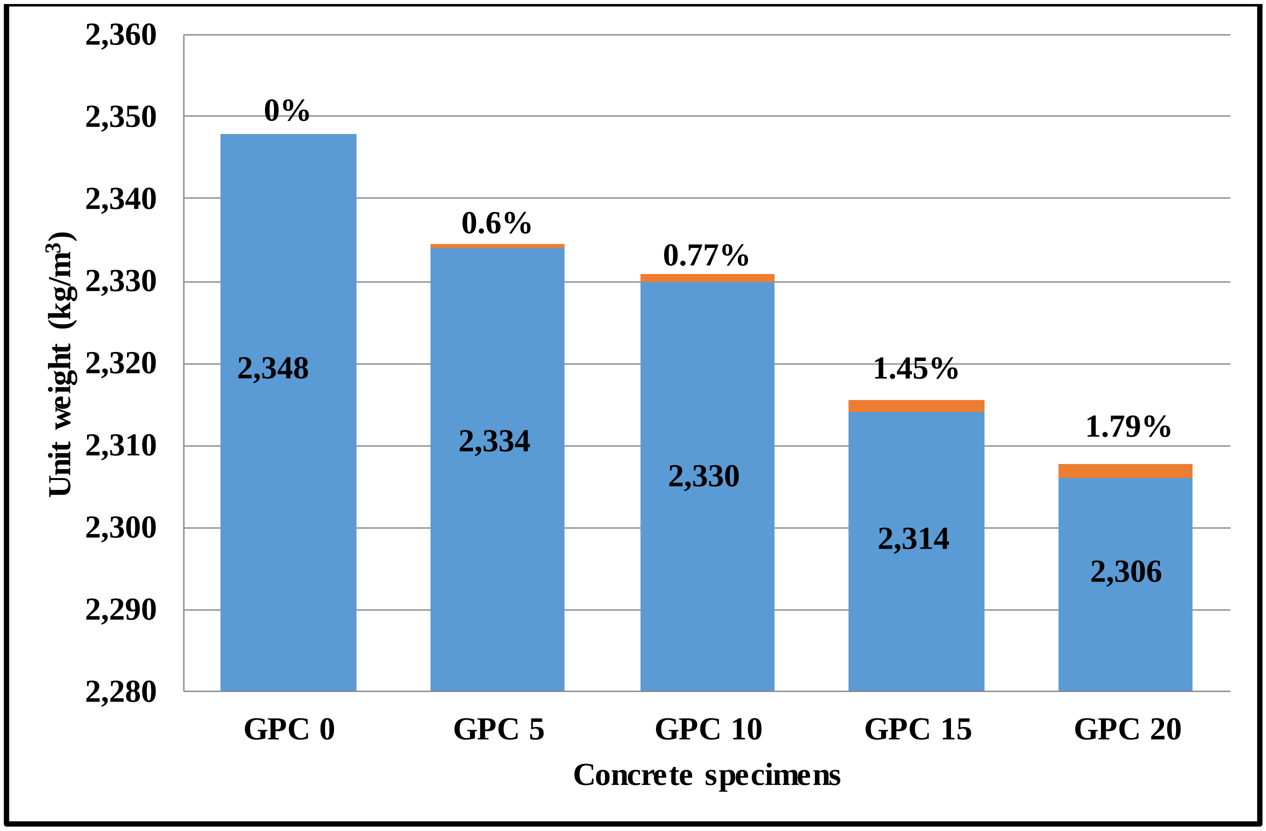

Fig. 5.11 Concrete unit weights.

The figure clearly shows a reduction in unit weight of concrete as glass powder replacement percentage increases and this makes the concrete light weight, which has many advantages such as: reduction in dead loads making savings in foundations and structural members, reduction in formwork pressure, savings in transporting and handling precast units on site.

5.4.2.2 Test results and discussions on compressive strength of concrete

The major goal of concrete structures is carrying loads coming to them. These loads may be of dead, live, earthquake, wind or snow types or their combinations. The concrete produced, therefore, must not fail under the actions of any of such loads.

The most common test for hardened concrete involves taking a sample of fresh concrete and putting it into special cube mold so that, when hard, the cubes can be tested to failure in a special machine in order to measure the strength of the concrete.

The results obtained from compression tests on hardened concrete cubes are used to check that its strength is above the minimum specified and to assess the control exercised over the production of concrete [16]. For each of the control and blended mixes of concrete cubes, the average value of the three samples was taken as their compressive strength. The following Table 5.11 shows the average compressive strength test results of the concrete cubes.

Table 5.11 Average compressive strength values of concrete.

S. No.	Mix code	Average compressive strength					
		7 days		28 days		56 days	
		Load (kN)	Strength (N/mm^2)	Load (kN)	Strength (N/mm^2)	Load (kN)	Strength (N/mm^2)
1.	GPC 0	598.64	26.61	865.58	38.47	908.55	40.38
2.	GPC 5	627.35	27.88	912.60	40.56	993.75	44.17
3.	GPC 10	599.11	26.63	872.55	38.78	928.35	41.26
4.	GPC 15	537.48	23.89	826.58	36.74	880.20	39.12
5.	GPC 20	511.39	22.73	802.50	35.67	838.50	37.27

The weight and dimensions of all the concrete cubes were measured prior to testing their compressive strengths. The photos on Figure 5.12 and Figure 5.13 were captured at AAiT, construction material laboratory when weights of concrete cubes and compressive strength tests were carried out respectively.

Fig. 5.12 Concrete specimen being weighed. Captured at AAiT material laboratory (2020).

Fig. 5.13 Concrete specimen ready for compressive strength. Captured at AAiT material laboratory (2020).

From Table 5.11, the compressive strength of the concrete with 5% and 10% replacement of glass powder have shown strength development over the control concrete mix by about 5.43% and 0.81% at 28 days, and 9.39% and 2.18% at 56 days respectively. However, GPC 15 and GPC 20 that is concrete specimens with 15% and 20% glass powder had shown a strength reduction by about 4.5% and 7.28% at 28 days, and 3.12% and 7.7% at 56 days respectively. This trend indicates that the compressive strength of the OPC-GP blended concrete decreases with increase in the glass powder content. The reason for this could be probably due to the high replacement of cement by glass powder, thus reducing cement content of the mixture which in turn causes a reduction in the hydration reaction. Figure 5.14 shows the compressive strength of control and blended concrete mixes.

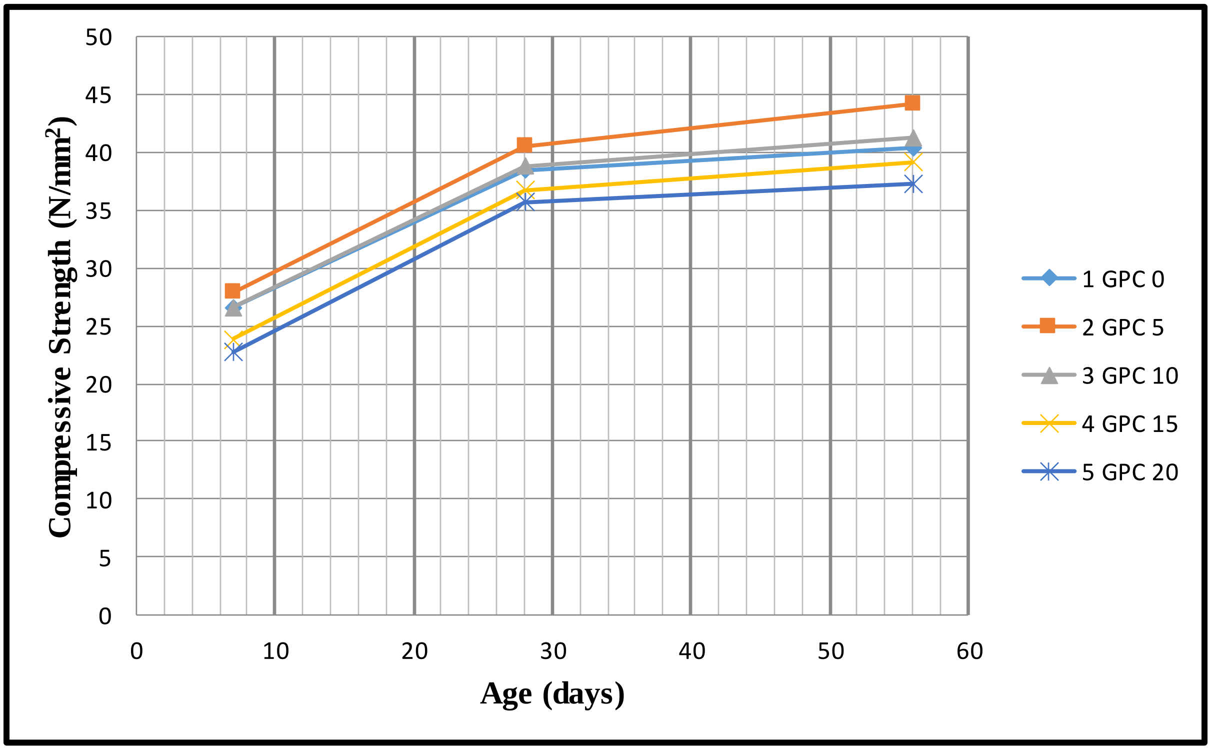

Fig. 5.14 Compressive strength of OPC-GP concrete.

The strength activity index of OPC-GP concrete specimens had also shown an increasing pattern for almost all the mixes as the age of the specimen increased like that of the OPC-GP mortar mixes. The activity index of GPC-15 that is the concrete with 15% glass powder, for instance, had a strength activity index of 89.8%, 95.5% and 96.9% at 7 days, at 28 days and at 56 days respectively. The probable reason for this could be due to the pozzolanic reaction between the glass powder and the cement i.e., if the glass powder had been only a filler such strength activity improvement over time could not be achieved. The strength activity index for all the concrete mixes are given in Table 5.12 and Figure 5.15.

Table 5.12 Strength activity index of OPC-GP concrete.

Code	Age (days)		
	7 days	**28 days**	**56 days**
GPC 0	100.0	100.0	100.0
GPC 5	104.8	105.4	109.4
GPC 10	100.1	100.8	102.2
GPC 15	89.8	95.5	96.9
GPC 20	85.4	92.7	92.3

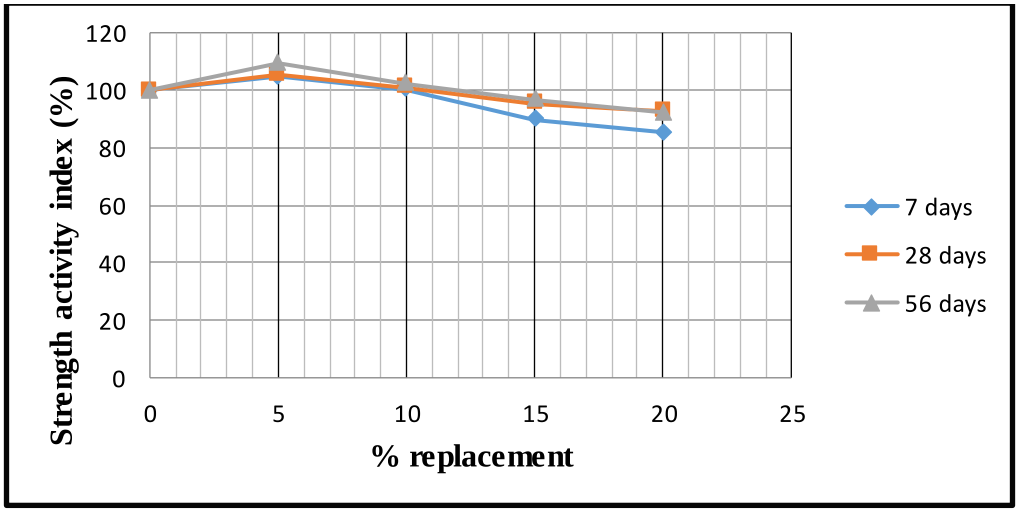

Fig. 5.15 Strength activity index of OPC-GP concrete.

5.4.2.3 Test results and discussions on flexural strength of concrete

Stresses developed in concrete structures could be due to effects at early age related to temperature during casting of the concrete or effects due to continuous fluctuation of temperature during the day and night-time during service period of the concrete structure.

The thermal stress that will be induced during early age of the concrete (due to heat from the environment and heat liberated during hydration reaction of cement) should be resisted by the concrete so as to reduce early age cracking. In a similar manner, the concrete structure will be expected to withstand the continuous temperature fluctuation that will be expected during service life of the concrete structure. Thus, for the concrete structure to withstand the stresses that will be developed during the above situations, it should be resisted by the flexural strength of the concrete [53].

Therefore, this test, was performed based on the seven and twenty-eight days of unreinforced concrete beam (of size 10 cm * 10 cm * 50 cm) with 100% Ordinary Portland cement and sample prepared with the incorporation of glass powder of 5%, 10%, 15% and 20%. For each percentage of replacement and for each day of investigation, three samples were used and the average of the three samples was taken as the flexural strength of that concrete mix at that specific day.

The calculation of the flexural stress is as follows:

$$R = \frac{PL}{bd^2} \quad \text{[Eq. 5.1]}$$

Where R = modulus of rapture, MPa,

P = maximum applied load indicated by the testing machine, N,

L = span length in, mm,

b = average width of specimen, mm, at the fracture,

d = average depth of specimen, mm at the fracture.

Table 5.13 Average flexural strengths of the concrete.

S. No.	Code	Average flexural strength			
		7 days		28 days	
		Load (KN)	Strength (N/mm^2)	Load (KN)	Strength (N/mm^2)
1.	GPC 0	9.20	4.14	9.93	4.47
2.	GPC 5	9.27	4.17	10.04	4.52
3.	GPC 10	8.71	3.92	9.98	4.49
4.	GPC 15	8.16	3.67	8.97	4.04
5.	GPC 20	7.76	3.49	8.58	3.86

Table 5.13 and Figure 5.16 show, the flexural strength of the beam had shown a reduction pattern as the glass powder content of the concrete increases. The flexural strength of GPC 5 i.e., the concrete beam with 5% glass powder, was slightly higher than the control mix at the seven day and the rest were lower than the control mix. However, the flexural strengths of both GPC 5 and GPC 10 i.e., the concrete beam with 5% and 10% glass powder in the twenty-eight days were higher than the control mix by 1.11% and 0.45% respectively.

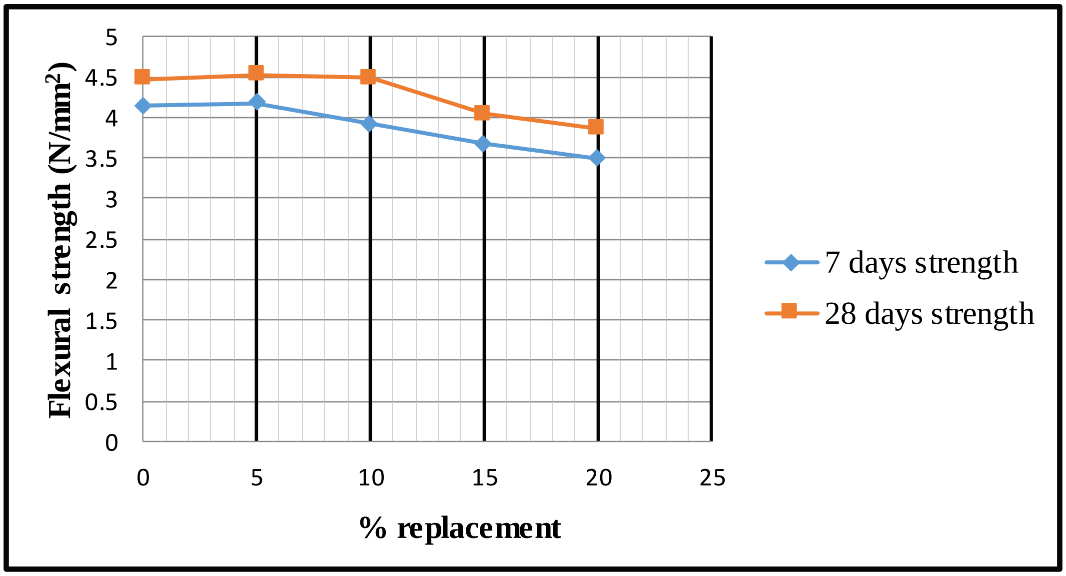

Fig. 5.16 Average flexural strength of concrete.

5.4.2.4 Test results and discussions on water permeability of concrete

Permeability is a property that governs the rate of flow of fluid into a porous solid object. It can also be defined as the ability to resist weathering action, chemical attack, abrasion, or any process of deterioration. It occurs in a hardened concrete in two forms; first from the trapped air pockets that appear due to incomplete compaction and second from the empty space that occur due to loss of mixing water by evaporation. A permeable concrete may allow the ingress of any fluid or deleterious substances which later affect the durability of the concrete structure and trigger corrosion of reinforcement if the concrete is reinforced concrete structure [54]. Figure 5.17 shows concrete specimens ready for water permeability test.

Fig. 5.17 Concrete specimens ready for water permeability test.

The pressure of the water is then adjusted to 3 bar (0.3 MPa) for the first 24 hours, 5 bar (0.5MPa) for the next 24 hours and finally 7 bar (0.7 MPa) for the last 24 hours i.e., a total of 72 hours. At the end of the 72 hours period, all the valves supplying water and compressed air to the specimens were closed and the cubes were removed from the permeability rig and split.

Upon visual examination, the portion of the specimen into which water has penetrated appears darker than the rest, and immediately after splitting, this zone was marked, and measurements were taken at 15 mm intervals to determine the average depth of penetration with more accurate way. Figures 5.18 and 5.19 show a typical concrete cube ready to be split by a compressive machine and water penetrated sample after splitting respectively. Table 5.14 shows the mean and maximum non-steady flow of water penetration depth obtained from 0%, 5%, 10%, 15% and 20% of glass powder partially replacing cement in concrete at the age of 28 days (the detailed test results are given in the appendix).

Fig. 5.18 Concrete specimen ready to be split.

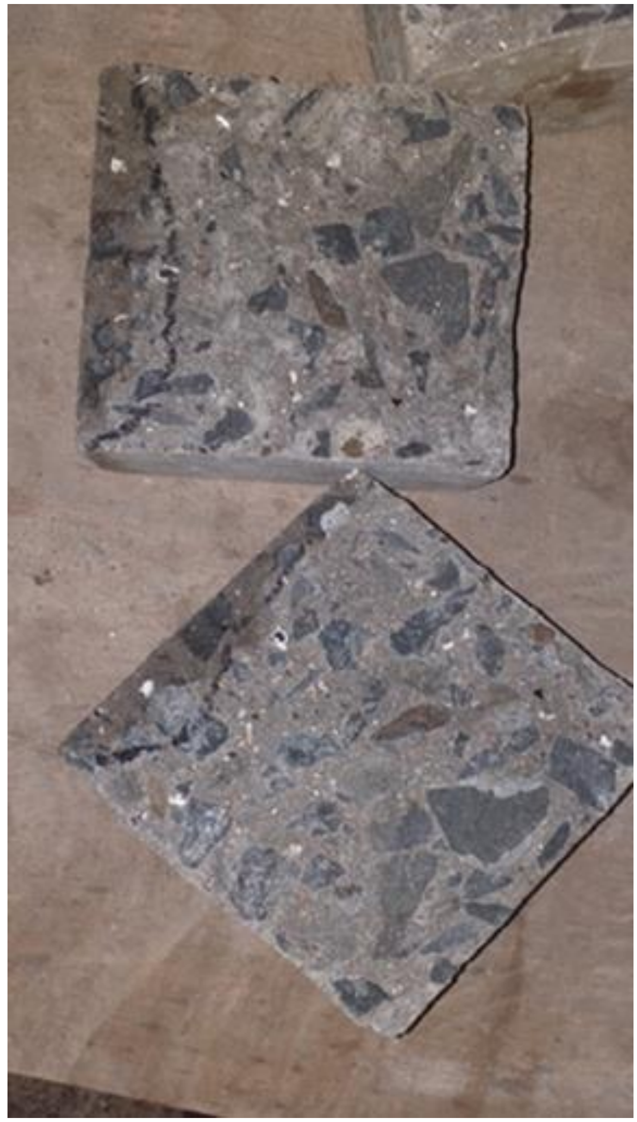

Fig. 5.19 Water penetrated samples after splitting.

The test results of the water penetration test, as can be seen in Table 5.14 and Figure 20, do not show a much significant variation over the different types of concrete specimens with different percentage of glass powder. For example, the average depth of water penetration of the specimens varied from 22.86 mm to 24.89 mm for GPC 0 and GPC 20 respectively. On the other hand, the corresponding variation for the maximum depth of penetration was from 29.32 mm to 34.87 mm for GPC 0 and GPC 20 respectively.

Therefore, the degree of variation from the most impermeable concrete to the most permeable concrete (based on maximum depth) was about 19% more than the control mix.

Table 5.14 Water penetration depth results of concrete specimens.

S. No.	Code	Penetration depth (mm)	
		Average	Maximum
1.	GPC 0	22.86	29.32
2.	GPC 5	20.74	29.24
3.	GPC 10	21.69	29.60
4.	GPC 15	23.67	29.96
5.	GPC 20	24.89	34.87

The concrete with 5% and 10% glass powder have shown some improvement on the average depth of penetration over the control concrete mix, that is GPC 5 and GPC 10 are 20.74 mm and 21.69 mm respectively which is lower than the control mix i.e., 22.86 mm. However, the maximum penetration depth results of all the specimens were higher than the control mix i.e., depth 29.32 mm except GPC 5 with depth of penetration 29.24. The following Figure 5.11 shows the penetration depths of different types of concrete specimens.

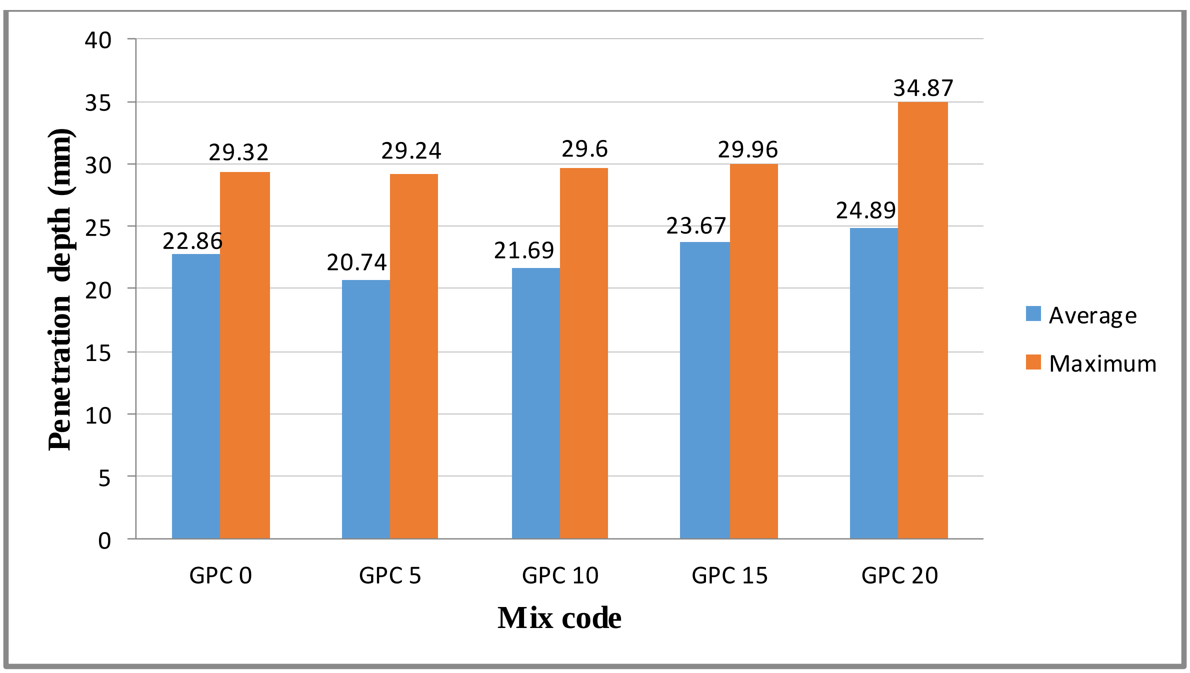

Fig. 5.20 Graph demonstrating water penetration depth of concrete.

The penetration depth of water can be used as a qualitative measure of assessment of concrete. The depth of penetration of water through concrete less than 50 mm is classified as impermeable; and depth less than 30 mm, as impermeable under aggressive conditions [6]. As can be seen from Table 5.14, all the concrete specimens in this research are impermeable concrete, whereas all the concrete, with the exception of GPC 20, are impermeable under aggressive conditions. Based on the overall experimental observations, it can be easily noted that the replacement of 5% and 10% glass powder contributed to the increase in resistance against water penetration. According to Liu (2011), this could be due to the secondary pozolanic reaction producing additional amount of C-H-S in the latter ages which could probably fill the microstructure pores which makes the concrete more impermeable. This makes the material ideal for use in concrete structures where permeability is the main priority.

CHAPTER SIX

ECONOMICAL AND ENVIRONMENTAL ANALYSIS

6.1 Introduction

The construction industry is an important sector that contributes greatly to the socio-economic growth of a nation and an investment led sector where governments show high interest especially in developing countries like Ethiopia. Now a day's, the construction industry is developing dramatically and the technology on materials usage has also increased from time to time at a high rate.

One of the modern construction materials comes in every engineer's mind is concrete, which is mainly produced from cement, aggregate and water. Cement is obtained from extraction of natural resources (rock) as raw material and processing in a factory. However, the production of cement has some adverse impacts on sustainability of environment and economical points of view. Sustainability is mainly concerned with meeting our own needs without compromising the ability of the future generations to meet their own needs in terms of natural, social and economic resources.

Therefore, so as to alleviate these problems of the cement industry, different methods were being implemented specially in the developed countries, out of which supplementary cementitious materials having lower cost of production, lower emission of Co_2, and lower energy consumption implying a more environmentally friendly and economical material.

One of these cement replacing materials, waste glass powder, was found to have a potential to be used in some parts of the world. The use of this material as a cement replacement reduces the cost of cement, the Co_2 emission, and energy consumptions of cement industries. This can minimize environmental and economic problems caused by production of large amount cement.

This part focuses on the economic and environmental benefits of using waste glass powder as a cement replacing material in concrete with the improvement of the concrete compressive strength.

6.2 Environmental benefits

One of the greatest environmental concerns in construction industry is the production of cement which consists of energy intensive industrial manufacturing processes causing severe environmental impacts at all stages of the process. These include change of landscape, depletion of natural resources due to quarrying and production process. According to researchers, the mass of raw materials needed to manufacture Portland cement is assumed to be 1.6 times as much as the mass of finished Portland cement [55]. Therefore, this can cause environmental problems like global warming due to depletion of natural resources, dust and noise, gas emissions, such as carbon dioxide emission from clinker production, which is estimated that 1 tone of clinker production releases 1 tone of Co_2 [35]. Mixing of clinker to supplementary materials called blending is considered as a very effective way to reduce Co_2 emission [55]. Thus, the use of waste glass powder as a cement replacement material will save a great deal of virgin materials.

Table 6.1 shows the amount of cement saved when partially replaced by waste glass powder at different percentages based on the results obtained from this research (section 4.4.1) and Co_2 emission forone cubic meter of concrete production.

Table 6.1 Quantity of cement saved, and carbon dioxide emission reduced.

Code	**Cement used (kg/m^3)**	**Glass powder (kg/m^3)**	**W/(C+G)**	**Cement Saved (kg/m3)**	**Reduction in Co_2 emission (kg/m3)**
GPC 0	335	0	0.55	0	0
GPC 5	318.25	13.23	0.558	16.75	16.75
GPC 10	301.50	26.47	0.564	33.50	33.50
GPC 15	284.75	39.70	0.570	50.25	50.25
GPC 20	268.00	52.93	0.576	67	67

As can be seen from Table 6.1 and Figure 6.1 show the amount of cement saved per cubic meter by using 5%, 10%, 15% and 20% waste glass powder are 16.75 kg, 33.50 kg, 50.25 kg and 67 kg from the control concrete. The amount of Co_2 emissions can be reduced by 16.75

kg, 33.50 kg, 50.25 kg and 67 kg from the control concrete, respectively.

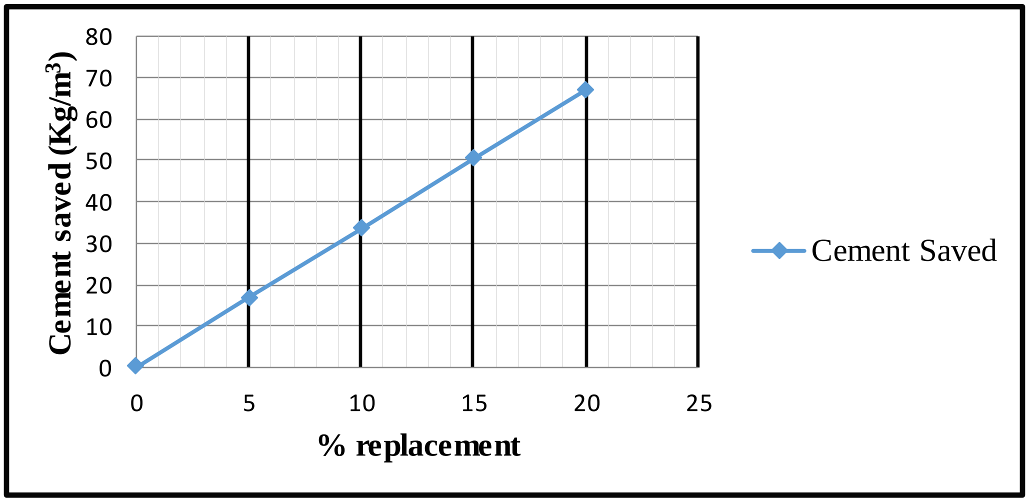

Fig. 6.1 Cement saved by using glass powder (Kg/m^3).

From the bottle glass industries in and around Addis Ababa, with an average of 250,000 tons of bottle glasses annual production, considering about 5% waste glass (based on the expansion of existing glass manufacturing companies, the establishment of the new glass bottle manufacturing company at Debre Birihan and by extrapolating and forecasting the disposal of waste glass in and around Addis Ababa) to be used as partial replacement of cement, results in reduction of about 12,500 ton of Co_2 to the atmosphere annually. Moreover, about 1,000 ton of waste glass is disposed in Addis Ababa annually, accounting for a reduction of additional 1,000 ton of Co_2 emission. Thus, a total of 13,500 ton of Co_2 emission to the atmosphere can be reduced annually.

6.3 Economic Analysis

The detail cost break down and economic analysis of using waste glass powder as partial replacement of cement in concrete production was analyzed and summarized. The researcher focused and carried out a comparative economic analysis based on the average current price of cement saved in concrete with the assumption that the glass cullet and clinker are ground to powder in the kiln simultaneously.

This comparative economic analysis was carried out based on the market price during 2020, when the market price of those materials: cement (560 birr/qtl), waste glass powder (6.50

birr/qtl), fine aggregate (750 birr/m^3), coarse aggregate (550 birr/m^3) and water (27.50 birr/m^3) were purchased for the research work (see Table 6.2).

Table 6.2 Cost comparisons between cement saved and waste glass powder used.

Code	Cement quantity (kg/m^3 and cost)	Glass powder (kg/m^3 and cost)	Cement saved (kg/m^3 and cost)	Water (Lt/m^3 and cost)	Fine aggre. used (kg/m^3 and cost)	Course aggre. used (kg/m^3 and cost)	Total cost per 1m^3 of concret
GPC 0	335 (1,876 ETB)	-	-	185 (5.09 ETB)	712 (358.39 ETB)	1256 (431.75 ETB)	2,671.23 ETB
GPC 5	318.25 (1,782.2	13.23 (8.60 ETB)	16.75 (93.80 ETB)	185 (5.09 ETB)	712 (358.39 ETB)	1256 (431.75 ETB)	2586.03 ETB
GPC 10	301.50 (1688.4 ETB)	26.47 (17.21 ETB)	33.50 (187.60 ETB)	185 (5.09 ETB)	712 (358.39 ETB)	1256 (431.75 ETB)	2500.84 ETB
GPC 15	284.75 (1594.6 ETB)	39.70 (25.81 ETB)	50.25 (281.40 ETB)	185 (5.09 ETB)	712 (358.39 ETB)	1256 (431.75 ETB)	2415.64 ETB
GPC 20	268.00 (1500.8 ETB)	52.93 (34.41 ETB)	67.00 (375.20 ETB)	185 (5.09 ETB)	712 (358.39 ETB)	1256 (431.75 ETB)	2330.44 ETB

It was possible to save 16.75 $\frac{kg}{m^3}$, 33.50 $\frac{kg}{m^3}$, 50.25 $\frac{kg}{m^3}$, and 67 $\frac{kg}{m^3}$ of cement by using 5%, 10%, 15% and 20% waste glass powder respectively. Based on these results, the average cost comparisons between quantities of cement saved and waste glass powder used for 1m^3 of concrete are presented. From Table 6.2, it can be seen than the cost of cement by the use of 5%, 10%, 15% and 20% of glass powder for 1m^3 of concrete can be reduced by 85.20 ETB, 170.39 ETB, 255.60 ETB and 340.79 ETB respectively. The deviation in cost of blended concrete compared to control concrete mainly depends on the market price of cement and waste glass powder when the materials are purchased.

From this research work it was found that about 10% replacement of cement by glass powder results in a comparable concrete characteristic in strength, durability and workability. The cost of waste glass powder is much lower than that of Portland cement. This is because the production of glass powder requires transportation and material preparation. Therefore, the researcher believes that using waste glass powder to the optimum quantity (up to 10%), generally reduces the cost of 1 m^3 of concrete by 170.39 ETB excluding the cost of clinker production, raw material preparations and other costs associated with cement production process. Thus, from the above stated evidences an economical advantage can be exploited by using waste glass powder as partial replacement of cement in concrete production.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

Based on the laboratory test results of this research, the following conclusions and recommendations are drawn.

7.1 Conclusions

In this research, the use of waste glass powder as a cement replacing material in concrete production was studied and the following conclusions are drawn after the experiment has been completed.

1. The chemical composition test result indicates that the sample glass obtained from Addis Ababa bottle and glass Share Company can be classified as class N pozzolana, as per ASTM C 618 classification.
2. Higher replacement of cement with glass powder reduced the workability of concrete and flow value of mortar.
3. The laboratory test results indicated that 5% and 10% replacement of ordinary Portland cement by glass powder resulted in better compressive and flexural strength than that of the control concrete mix and decreases as the glass powder replacement increases more than 10%. That is 15% and 20% replacements have shown 4.5% and 7.3% reduction in compressive strength at 28 days compared to the control concrete mix.
4. The experimental result showed a decrease in water penetration depth for 5% and 10% replacements of cement with glass powder considering the average results compared to the control mix and increases as the replacement percentage increases beyond 10%. However, all the concrete specimens were found to be impermeable under aggressive conditions according to A.M. Neville's classification, since they have a penetration depth less than 30 millimeter with the exception of GPC 20.
5. The use of glass powder to the optimum quantity (up to 10%), reduces the cost of 1m^3 of concrete by 6.4% (170.39 ETB) excluding the cost of clinker production, raw material preparations and other costs associated with cement production process.

7.2 Recommendations

Currently, environmental protection and sustainable use of natural resources is becoming one of the major issues of concern in the developed world, as sustainable economic growth for a country is unthinkable without it. Therefore, the use of alternative construction materials is one of the best solutions to alleviate the problem. In the countries like Ethiopia, even though the construction industry is booming these days, it is still in its infant stage and needs much more effort to be made on the use of alternative construction materials.

Therefore, based on the findings of this research, the following recommendations are forwarded:

1. This research work investigated the partial replacement of cement with glass powder has environmental and economic advantages in addition to improved compressive strength. Therefore, cement industries should be made aware of the potential of this cement replacing material and be encouraged to standardize, mix and pack for the use in the market as an alternative option.
2. Higher technology institutions in the country should carry out further studies on the use of alternative construction materials such as waste glass powder as a cement replacing material in concrete production.
3. This research work has revealed some of the fundamental physical and chemical properties of waste glass powder as a cement replacing material. Therefore, further studies are required on the following areas:
   - Studies should be carried out on the effects of different fineness of the waste glass powder with more percentage of glass powder replacement.
   - Further experimental studies should be conducted on the effects of the three types of glasses produced in and around Addis Ababa i.e., Flint, Amber and Green waste glasses.
   - Detail studies should be made to check the pozzolanic reaction of the waste glass powder using more advanced methods such as: X-ray Diffraction (XRD) Analysis, Thermal Analysis (TGA) and Scanning Electron Microscopy (SEM).

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APPENDIX A

COMPRESSIVE STRENGTH OF OPC-GP MORTARS

A-1 Three Days Compressive strength of OPC-GP mortars

No.	Age (days)	Dimension (mm)			Weight (g)	Failure load (kN)	Compressive strength (MPa)
		L	W	H			
GPM 0							
1.	3	50.17	50.08	50.11	272	42.4	16.96
2.		50.12	49.96	50.1	270	40.88	16.35
3.		50.07	50.13	49.94	269	39.73	15.89
Average					**270.33**	**41.00**	**16.40**
GPM 5							
1.	3	50.2	50.14	50.05	271	45.55	18.22
2.		50.18	49.92	50.15	269	45.30	18.12
3.		50.13	50.21	49.91	271	44.80	17.92
Average					**270.33**	**45.22**	**18.09**
GPM 10							
1.	3	50.23	50.16	50.12	270	43.55	17.42
2.		50.11	50.06	50.21	272	42.10	16.84
3.		50.3	50.12	50.19	268	45.33	18.13
Average					**270.00**	**43.66**	**17.46**
GPM 12							
1.	3	50.22	50.18	49.93	270	41.35	16.54
2.		50.16	50.24	50.17	269	43.05	17.22
3.		50.18	49.89	50.24	269	38.45	15.38
Average					**269.33**	**40.95**	**16.38**
GPM 15							
1.	3	50.13	49.87	50.19	268	31.48	12.59
2.		50.14	49.88	50.22	266	32.63	13.05
3.		50.12	50.25	49.91	267	33.70	13.48
Average					**267.00**	**32.60**	**13.04**
GPM 20							
1.	3	50.22	50.07	50.32	265	29.725	11.89
2.		50.18	49.93	50.34	262	31.60	12.64
3.		50.26	50.14	49.91	264	28.375	11.35
Average					**263.67**	**29.90**	**11.96**

A-2 Seven Days Compressive Strength of OPC-GP mortars

No.	Age (days)	Dimension (mm)			Weight (g)	Failure load (kN)	Compressive strength (MPa)
		L	W	H			
GPM 0							
1.	7	50.26	50.15	50.21	278	71.95	28.78
2.		50.19	50.22	50.32	279	69.85	27.94
3.		49.86	50.31	50.42	280	74.65	29.86
Average					**279.00**	**72.15**	**28.86**
GPM 5							
1.	7	50.24	50.33	50.19	274	75.63	30.25
2.		49.91	50.12	50.15	276	74.10	29.64
3.		50.11	50.23	50.36	275	76.88	30.75
Average					**275.00**	**75.53**	**30.21**
GPM 10							
1.	7	50.25	50.17	50.35	272	72.80	29.12
2.		50.14	50.14	50.26	274	72.43	28.97
3.		49.88	50.34	50.23	273	75.43	30.17
Average					**273.00**	**73.55**	**29.42**
GPM 12							
1.	7	50.23	50.35	50.22	271	72.2	28.88
2.		49.93	50.26	50.33	272	72.55	29.02
3.		50.24	50.36	50.27	270	71.1	28.44
Average					**271.00**	**71.95**	**28.78**
GPM 15							
1.	7	50.29	50.36	50.18	270	63.575	25.43
2.		50.24	49.86	50.28	269	62.225	24.89
3.		50.39	50.22	50.16	268	64.125	25.65
Average					**269.00**	**63.31**	**25.32**
GPM 20							
1.	7	50.25	50.31	50.44	266	58.05	23.22
2.		49.84	50.13	50.32	268	57.1	22.84
3.		50.42	50.29	50.42	267	59.15	23.66
Average					**267.00**	**58.10**	**23.24**

A-3 Twenty-eight Days Compressive strength of OPC-GP mortars

No.	Age (days)	Dimension (mm)			Weight (g)	Failure load (kN)	Compressive strength (MPa)
		L	W	H			
GPM 0							
1.	3	50.13	50.23	50.16	282	105.85	42.34
2.		50.26	49.87	50.25	281	107.65	43.06
3.		50.19	50.20	50.14	283	104.60	41.84
Average					**282.00**	**106.03**	**42.41**
GPM 5							
1.	3	50.16	50.19	50.25	278	110.58	44.23
2.		50.32	50.21	50.14	277	109.85	43.94
3.		50.22	50.13	50.28	279	111.43	44.57
Average					**278.00**	**110.62**	**44.25**
GPM 10							
1.	3	50.24	50.31	50.18	276	107.30	42.92
2.		50.33	50.15	50.30	278	107.90	43.16
3.		49.92	50.11	50.22	277	108.60	43.44
Average					**277.00**	**107.93**	**43.17**
GPM 12							
1.	3	50.27	50.23	50.31	275	104.90	41.96
2.		49.67	50.28	50.23	277	106.10	42.44
3.		50.26	50.16	50.29	276	106.48	42.59
Average					**276.00**	**105.83**	**42.33**
GPM 15							
1.	3	50.26	50.23	50.34	274	100.53	40.21
2.		50.33	49.84	50.25	275	99.63	39.85
3.		50.24	50.32	50.35	273	101.20	40.48
Average					**274.00**	**100.45**	**40.18**
GPM 20							
1.	3	50.28	50.36	50.43	272	89.70	35.88
2.		49.78	50.41	50.37	273	90.20	36.08
3.		50.29	50.35	50.44	274	91.05	36.42
Average					**273.00**	**90.32**	**36.13**

A-4 fifty-six Days Compressive strength of OPC-GP mortars

No.	Age (days)	Dimension (mm)			Weight (g)	Failure load (kN)	Compressive strength (MPa)
		L	W	H			
GPM 0							
1.	56	50.22	50.15	50.26	284	121.9	48.76
2.		50.25	49.86	50.29	283	122.1	48.84
3.		50.31	50.21	50.24	285	122.55	49.02
Average					**284.00**	**122.18**	**48.87**
GPM 5							
1.	56	50.32	50.28	50.18	280	122.45	48.98
2.		49.95	50.24	50.33	282	123.1	49.24
3.		50.34	50.25	50.36	281	123.8	49.52
Average					**281.00**	**123.12**	**49.25**
GPM 10							
1.	56	50.34	50.28	50.41	278	122.175	48.87
2.		50.42	50.38	50.32	279	122.375	48.95
3.		49.89	50.36	50.39	280	122.525	49.01
Average					**279.00**	**122.36**	**48.94**
GPM 12							
1.	56	50.35	50.31	50.44	275	122.2	48.88
2.		49.87	50.34	50.41	278	122.425	48.97
3.		50.33	50.29	50.43	278	119.95	47.98
Average					**277.00**	**121.53**	**48.61**
GPM 15							
1.	56	50.36	50.18	50.26	275	109.65	43.86
2.		50.43	49.88	50.33	276	113.1	45.24
3.		50.44	50.37	50.35	274	115.3	46.12
Average					**275.00**	**112.68**	**45.07**
GPM 20							
1.	56	50.31	50.28	50.34	272	104.88	41.95
2.		50.36	49.56	50.45	274	106.73	42.69
3.		50.47	50.52	50.37	273	104.43	41.77
Average					**273.00**	**105.34**	**42.14**

APPENDIX B

COMPRESSIVE STRENGTH OF PPC-GP MORTARS

B-1 three Days Compressive strength of PPC-GP mortars

No.	Age (days)	Dimension (mm)			Weight (g)	Failure load (kN)	Compressive strength (MPa)
		L	W	H			
GPM 0							
1.	3	50.13	50.23	49.94	268	27.6	11.04
2.		50.21	49.92	50.18	266	26.35	10.54
3.		50.16	50.25	50.07	267	26.475	10.59
Average					**267.00**	**26.81**	**10.72**
GPM 5							
1.	3	50.36	49.77	50.28	265	25.60	10.24
2.		50.19	50.31	50.24	263	25.78	10.31
3.		50.23	49.74	50.26	264	24.80	9.92
Average					**264.00**	**25.39**	**10.16**
GPM 10							
1.	3	49.82	50.26	50.17	262	23.63	9.45
2.		50.23	50.34	49.92	263	22.18	8.87
3.		50.22	50.37	50.31	261	24.48	9.79
Average					**262.00**	**23.43**	**9.37**
GPM 15							
1.	3	49.79	50.19	50.28	259	21.15	8.46
2.		50.31	50.23	50.37	258	21.60	8.64
3.		50.39	50.27	50.41	257	21.30	8.52
Average					**258.00**	**21.35**	**8.54**
GPM 20							
1.	3	50.36	49.86	50.23	255	19.4	7.76
2.		49.91	50.24	50.33	257	20.15	8.06
3.		50.35	50.41	50.26	256	20.3	8.12
Average					**256.00**	**19.95**	**7.98**

B-2 seven Days Compressive strength of PPC-GP mortars

No.	Age (days)	Dimension (mm)			Weight (g)	Failure load (kN)	Compressive strength (MPa)
		L	W	H			
GPM 0							
1.	7	50.24	49.89	50.17	274	41.35	16.54
2.		50.27	50.31	50.34	278	39.7	15.88
3.		49.79	50.28	50.32	276	42.3	16.92
Average					**276.00**	**41.12**	**16.45**
GPM 5							
1.	7	50.16	49.72	50.24	271	37.05	14.82
2.		49.73	50.38	50.25	269	38.475	15.39
3.		50.21	49.94	50.36	273	39.4	15.76
Average					**271.00**	**38.31**	**15.32**
GPM 10							
1.	7	50.33	49.82	50.26	269	35.525	14.21
2.		49.78	50.38	50.24	270	35.75	14.30
3.		50.38	49.94	50.27	268	37.55	15.02
Average					**269.00**	**36.28**	**14.51**
GPM 15							
1.	7	50.37	49.98	50.41	265	33.78	13.51
2.		49.87	50.33	50.38	264	35.05	14.02
3.		50.29	49.91	50.36	263	33.68	13.47
Average					**264.00**	**34.17**	**13.67**
GPM 20							
1.	7	50.39	49.83	50.41	260	24.65	9.86
2.		49.86	50.44	50.33	261	25.55	10.22
3.		50.45	50.36	49.93	262	27.35	10.94
Average					**261.00**	**25.85**	**10.34**

B-3 Twenty-eight Days Compressive strength of PPC-GP mortars

No.	Age (days)	Dimension (mm)			Weight (g)	Failure load (kN)	Compressive strength (MPa)
		L	W	H			
GPM 0							
1.	28	50.22	50.18	50.27	280	79.10	31.64
2.		50.27	49.97	50.26	278	78.63	31.45
3.		49.87	50.23	50.19	279	80.15	32.06
Average					**279.00**	**79.29**	**31.72**
GPM 5							
1.	28	50.07	50.18	50.27	271	61.73	24.69
2.		50.25	50.11	50.24	270	63.90	25.56
3.		50.23	49.88	50.29	272	64.60	25.84
Average					**271.00**	**63.41**	**25.36**
GPM 10							
1.	28	50.26	50.37	50.34	269	61.33	24.53
2.		50.18	49.95	50.26	271	62.55	25.02
3.		50.24	50.21	50.32	270	60.43	24.17
Average					**270.00**	**61.43**	**24.57**
GPM 15							
1.	28	50.36	50.41	50.37	268	57.88	23.15
2.		50.23	49.90	50.17	267	60.03	24.01
3.		50.35	50.42	50.34	266	56.60	22.64
Average					**267.00**	**58.17**	**23.27**
GPM 20							
1.	28	50.34	50.32	50.39	264	52.33	20.93
2.		49.93	50.41	50.36	265	53.45	21.38
3.		50.39	50.46	50.38	263	55.35	22.14
Average					**264.00**	**53.71**	**21.48**

B-4 fifty-six Days Compressive strength of PPC-GP mortars

No.	Age (days)	Dimension (mm)			Weight (g)	Failure load (kN)	Compressive strength (MPa)
		L	W	H			
GPM 0							
1.	56	50.12	50.21	49.86	281	92.15	36.86
2.		49.84	50.16	50.22	280	92.35	36.94
3.		50.26	49.94	50.18	282	94.08	37.63
Average					**281.00**	**92.86**	**37.14**
GPM 5							
1.	56	50.31	49.88	50.23	274	78.85	31.54
2.		50.27	50.35	50.27	277	80.1	32.04
3.		49.83	50.28	50.36	275	79.375	31.75
Average					**275.33**	**79.44**	**31.78**
GPM 10							
1.	56	50.25	50.34	49.87	273	76.9	30.76
2.		49.98	50.23	50.31	275	78.1	31.24
3.		50.37	50.27	50.38	274	78.95	31.58
Average					**274.00**	**77.98**	**31.19**
GPM 15							
1.	56	50.32	50.26	50.34	271	75.30	30.12
2.		50.19	50.26	50.28	270	74.93	29.97
3.		49.92	50.21	50.32	273	75.85	30.34
Average					**271.33**	**75.36**	**30.14**
GPM 20							
1.	56	50.43	50.37	50.45	268	72.35	28.94
2.		50.29	50.35	50.42	269	72.825	29.13
3.		50.37	50.17	50.28	271	70.65	28.26
Average					**269.33**	**71.94**	**28.78**

APPENDIX C

COMPRESSIVE STRENGTH OF OPC-GP CONCRETE

C-1 seven Days Compressive strength of OPC-GP Concrete

No.	Age (days)	Dimension (mm) L	W	H	Weight (g)	Failure load (kN)	Compressive strength (MPa)
GPC 0							
1.	7	151.26	150.47	152.14	7952	598.64	26.61
2.		152.19	151.24	150.37	7969	598.64	26.61
3.		151.17	152.28	151.46	7958	598.64	26.61
Average					**7959.67**	**598.64**	**26.61**
GPC 5							
1.	7	152.17	151.32	150.89	7955	627.35	27.88
2.		152.33	151.28	151.56	7953	627.35	27.88
3.		151.21	152.32	151.47	7956	627.35	27.88
Average					**7954.67**	**627.35**	**27.88**
GPC 10							
1.	7	151.74	152.29	153.17	7931	599.11	26.63
2.		153.49	152.41	152.24	7924	599.11	26.63
3.		152.87	152.27	151.78	7922	599.11	26.63
Average					**7925.67**	**599.11**	**26.63**
GPC 15							
1.	7	153.22	152.37	154.13	7911	537.48	23.89
2.		152.87	152.48	153.15	7898	537.48	23.89
3.		154.17	152.94	153.45	7889	537.48	23.89
Average					**7899.33**	**537.48**	**23.89**
GPC 20							
1.	7	153.86	154.25	53.33	7875	511.39	22.73
2.		154.74	153.67	153.94	7867	511.39	22.73
3.		153.89	154.65	154.49	7882	511.39	22.73
Average					**7874.67**	**511.39**	**22.73**

C-2 Twenty-eight Days Compressive strength of OPC-GP Concrete

No.	Age (days)	Dimension (mm) L	W	H	Weight (g)	Failure load (kN)	Compressive strength (MPa)
GPC 0							
1.	28	149.89	150.48	151.47	7979.84	853.20	37.92
2.		151.43	149.32	152.22	7982.67	868.05	38.58
3.		152.18	153.34	152.66	7994.21	875.48	38.91
Average					**7985.57**	**865.58**	**38.47**
GPC 5							
1.	28	152.15	151.38	152.41	7941.64	896.85	39.86
2.		153.24	152.64	153.43	7932.52	913.05	40.58
3.		151.67	150.85	151.59	7928.47	927.90	41.24
Average					**7934.21**	**912.60**	**40.56**
GPC 10							
1.	28	151.79	153.46	152.87	7914.13	872.78	38.79
2.		153.27	151.62	152.38	7910.28	857.03	38.09
3.		154.52	153.19	153.44	7914.49	887.85	39.46
Average					**7912.97**	**872.55**	**38.78**
GPC 15							
1.	28	153.49	152.34	152.59	7889.86	841.05	37.38
2.		152.87	152.43	151.94	7893.46	809.55	35.98
3.		153.45	152.27	153.48	7890.87	829.13	36.85
Average					**7891.40**	**826.58**	**36.74**
GPC 20							
1.	28	152.37	151.59	151.88	7872.64	792.90	35.24
2.		149.86	151.23	150.74	7868.77	803.03	35.69
3.		151.44	152.18	151.83	7877.22	811.58	36.07
Average					**7872.88**	**802.50**	**35.67**

C-3 Fifty-six Days Compressive strength of OPC-GP Concrete

No.	Age (days)	Dimension (mm)			Weight (g)	Failure load (kN)	Compressive strength (MPa)
		L	W	H			
GPC 0							
1.	56	151.49	150.87	152.34	7910.56	883.58	39.27
2.		149.96	151.14	150.89	7914.24	910.80	40.48
3.		152.17	150.65	151.27	7917.07	931.28	41.39
Average					**7913.96**	**908.55**	**40.38**
GPC 5							
1.	56	152.28	151.43	150.89	7859.71	987.53	43.89
2.		149.56	151.27	152.61	7861.59	994.05	44.18
3.		151.89	152.21	150.76	7867.48	999.68	44.43
Average					**7862.93**	**993.75**	**44.17**
GPC 10							
1.	56	151.44	151.79	152.34	7803.89	899.33	39.97
2.		152.18	153.47	151.69	7811.46	928.13	41.25
3.		153.87	151.94	152.88	7807.73	957.60	42.56
Average					**7807.69**	**928.35**	**41.26**
GPC 15							
1.	56	149.67	151.72	150.82	7742.54	875.03	38.89
2.		152.63	151.47	153.25	7751.38	880.43	39.13
3.		151.35	153.49	152.76	7748.67	885.15	39.34
Average					**7747.53**	**880.20**	**39.12**
GPC 20							
1.	56	152.17	150.85	151.69	7738.91	832.05	36.98
2.		149.79	151.67	150.48	7736.67	832.95	37.02
3.		151.87	152.64	153.37	7739.45	850.50	37.8
Average					**7738.34**	**838.50**	**37.27**

APPENDIX D

FLEXURAL STRENGTH OF OPC-GP CONCRETE

D-1 Seven Days flexural strength of OPC-GP concrete

No.	Age (days)	Dimension (cm)			P (kN)	σ (MPa)
		L	W	H		
GPM 0						
1.	7	50.14	10.16	10.19	9.04	4.07
2.		49.86	10.21	10.17	9.38	4.22
3.		50.21	10.17	10.11	9.18	4.13
Average						**4.14**
GPM 5						
1.	7	50.23	10.15	10.12	9.29	4.18
2.		50.43	10.13	10.29	9.16	4.12
3.		50.26	10.11	10.14	9.36	4.21
Average						**4.17**
GPM 10						
1.	7	50.13	10.16	10.17	8.73	3.93
2.		50.25	10.22	10.11	8.62	3.88
3.		50.32	10.09	10.13	8.78	3.95
Average						**3.92**
GPM 15						
1.	7	50.24	10.07	10.15	8.31	3.74
2.		50.19	10.13	10.08	8.20	3.69
3.		50.31	10.21	10.17	7.96	3.58
Average						**3.67**
GPM 20						
1.	7	50.33	10.09	10.14	7.82	3.52
2.		50.28	10.05	10.12	7.71	3.47
3.		50.16	10.14	10.07	7.73	3.48
Average						**3.49**

D-2 Twenty-eight Days flexural strength of OPC-GP concrete

No.	Age (days)	Dimension (cm)			P (kN)	σ (MPa)
		L	W	H		
GPM 0						
1.	28	50.24	10.15	10.19	9.91	4.46
2.		50.33	10.09	10.12	10.02	4.51
3.		50.18	10.16	10.08	9.87	4.44
Average						**4.47**
GPM 5						
1.	28	50.26	10.14	10.21	9.98	4.49
2.		50.38	10.21	10.18	10.07	4.53
3.		50.29	10.07	10.16	10.09	4.54
Average						**4.52**
GPM 10						
1.	28	50.26	10.16	10.07	9.93	4.47
2.		50.22	10.13	10.06	9.98	4.49
3.		50.35	10.08	10.13	10.02	4.51
Average						**4.49**
GPM 15						
1.	28	50.21	10.17	10.06	9.13	4.11
2.		50.35	10.04	10.12	8.98	4.04
3.		50.24	10.19	10.22	8.80	3.96
Average						**4.04**
GPM 20						
1.	28	50.34	10.25	10.17	8.64	3.89
2.		50.26	10.08	10.19	8.38	3.77
3.		50.32	10.14	10.16	8.71	3.92
Average						**3.86**

APPENDIX E

WATER PENETRATION TEST RESULTS

	Mix Code	GPC 0	GPC 5	GPC 10	GPC 15	GPC 20
Water penetration depths measured at 15 mm intervals (mm)	D1	18.26	17.84	19.06	20.15	20.36
	D2	22.23	18.43	20.35	21.64	20.86
	D3	25.17	19.35	22.42	23.33	22.39
	D4	27.19	23.40	24.67	24.81	24.85
	D5	29.32	26.36	27.33	25.44	28.63
	D6	27.44	29.24	29.60	28.14	32.37
	D7	24.15	23.32	23.12	29.96	34.87
	D8	21.22	21.44	19.46	26.47	30.47
	D9	19.24	17.24	18.11	22.52	23.31
	D10	19.11	16.13	17.13	19.65	19.16
	D11	18.18	15.37	17.34	18.28	16.49
Average (mm)		**22.86**	**20.74**	**21.69**	**23.67**	**24.89**
Maximum (mm)		**29.32**	**29.24**	**29.60**	**29.96**	**34.87**

APPENDIX F

SAMPLE PHOTOS TAKEN DURING THE RESEARCH WORK

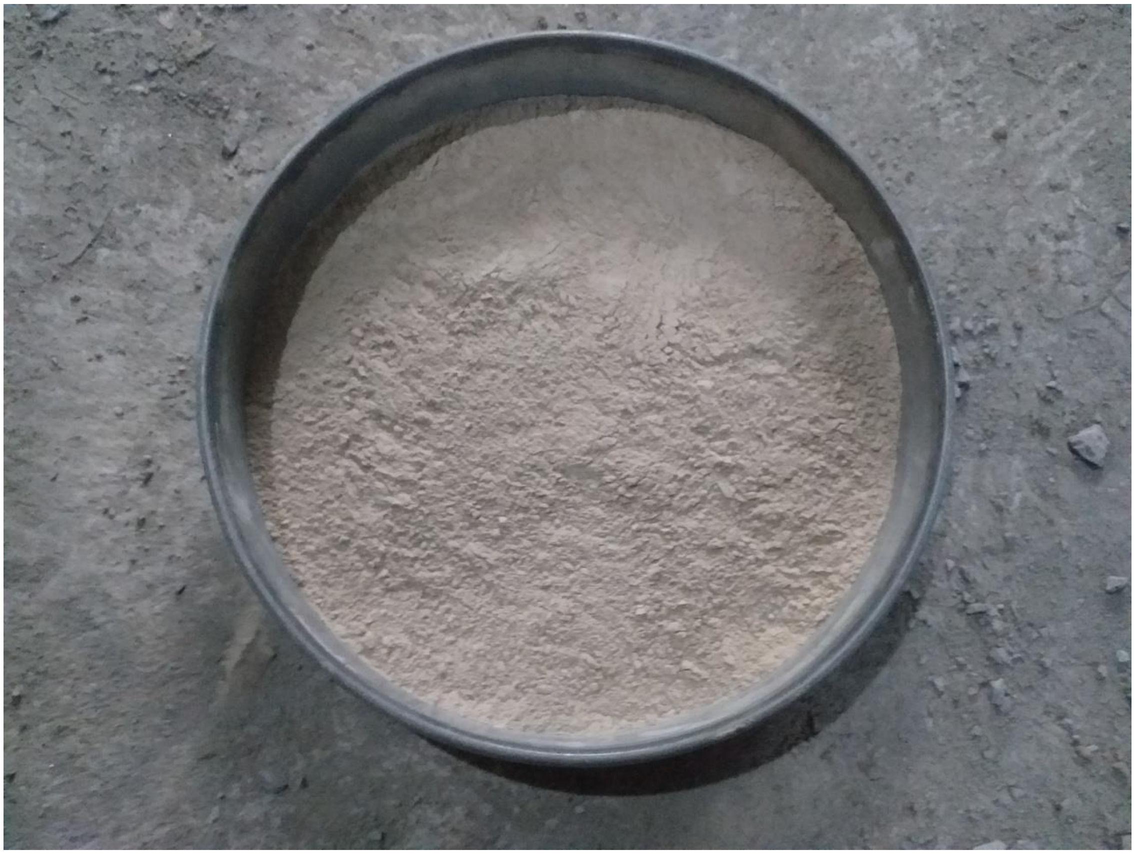

Photo 1. Glass Powder.

Photo 2. Fine aggregate under test.

Photo 3. Blain air permeability apparatus.

Photo 4. Mortar casted and troweled for compressive strength test.

Photo 5. Mortar specimen under compression test.

Photo 6. Flow table apparatus for mortar.

Photo 7. Mortar specimens after compressive strength test.

Photo 8. Concrete ingredients of different batches ready for mixing.

Photo 9. Oiled concrete molds.

Photo 10. Concrete beam ready for flexural strength test.

Photo 11. Slump test.

Photo 12. Concrete ingredients being mixed.

Photo 13. Concrete casted for compressive strength and flexural strength testing.

Photo 14. Concrete cube being weighed.

Photo 15. Concrete cube under compression test.

Photo 16. Concrete beam being weighed.

Photo 17. Concrete beam under flexural strength test

Photo 18. Concrete beam after flexural strength test

Photo 19. Concrete specimens assembled on water permeability testing apparatus.

Photo 20. Splitting the permeability cube (left) and depth of water being measured (right).

APPENDIX G

CHEMICAL COMPOSITION OF GLASS POWDER

APPENDIX H

SPECIFIC GRAVITY OF GLASS POWDER