INVESTIGATION ON FERROCK BASED CONCRETE AS AN ENVIRONMENTALLY-FRIENDLY AND DURABLE CONCRETE ALTERNATIVE

Beka Derbe Gari

A Thesis submitted to The Department of Civil Engineering

School Of Civil Engineering & Architecture

Presented in partial Fulfillment of the Requirements of Masters of Science in Civil Engineering (Specialization in Construction Engineering and Management)

Office of Graduate Studies

Adama Science and Technology University

July, 2023

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled Investigation on Ferrock Based Concrete as an Environmentally-Friendly and Durable Concrete Alternative is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation. It is being submitted for the partial fulfilment for the award of the degree of Master of Science in Civil Engineering (Construction Engineering and Management) at Adama Science and Technology University School of School of Civil Engineering and Architecture.

Beka Derbe Gari	__________________	_______________
Name of student	Signature	Date

RECOMMENDATION OF ADVISOR

I hereby certify that I have read and evaluated this thesis entitled Investigation on Ferrock Based Concrete as an Environmentally-Friendly and Durable Concrete Alternative prepared under my guidance by Beka Derbe Gari submitted in partial fulfilment of the requirements for the degree of Mater‘s of Science in Civil Engineering (Construction Engineering and Management). Therefore, I recommend that the candidate has fulfilled the requirements and hence he/she can submit the thesis to the department for further review and evaluation.

Bahiru Bewket (Ph.D.)	________________________	________________
Advisor/Supervisor	Signature	Date

APPROVAL SHEET

I hereby certify that all the correction and recommendation suggested by the board of examiners are incorporated into the final thesis entitled Investigation on Ferrock Based Concrete as an Environmentally-Friendly and Durable Concrete Alternative by Beka Derbe Gari.

Major Advisor/Supervisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis open defense by Beka Derbe Gari have rqead and evaluated his final thesis Ferrock as an Environmentally-Friendly and Durable Concrete Alternative against Sulfate Attack and examined the candidate. This is, therefore, to certify that the final thesis has been accepted in partial fulfillment of the requirement of the degree of Master of Science in Civil Engineering (Construction Engineering and Management).

Chairperson	Signature	Date
Examiner 1	Signature	Date
Examiner 2	Signature	Date

Finally approved and acceptance of the final thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the candidate's Department Graduate Council (DGC) and School Graduate Committee (SGC).

Department Head	Signature	Date
School Dean	Signature	Date
Office of Postgraduate Studies, Dean	Signature	Date

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ABSTRACT

Concrete is the world's most abundant building material which is strong and durable. There are, however, some chemical environments under which the useful life of even the best concrete will be short, the sulfate corrosion being one of the most frequent and detrimental processes, unless specific measures are taken. As a result, experts have been searching for more durable, cost-effective and environmentally friendly cement substitutes. In this research paper an attempt has been made to evaluate the workability, strength and durability properties of concrete made of partial replacement of cement with ferrock. The percentage of ferrock adopted is 0, 5, 10, 15 and 20%. Hence, this study investigated the possibility of using ferrock as partial replacement of cement in concrete, to produce an environmentally friendly, economical, strong and durable concrete against sulfate attack. This concrete has been made from Iron Powder, Fly ash, Lime Powder, glass powder with and without oxalic acid, on reaction with CO_2 *and water produces Iron Carbonates, which is the hardened product. In the study an attempt is made to understand the variation in compressive and flexural strength by replacing up to 20 % of cement by ferrock cement with and without oxalic acid and their workability, water absorption and durability in sodium sulfate solution after 28 days of soaking at room temperature is examined. There were nine different sets of mixes including the control mix used for investigations with constant water-cement ratio of 0.491 and slump ranging between 75-100 mm for concrete having a compressive strength of 25 MPa. Concrete containing ferrock based cement with oxalic acid as cement replacement showed high compressive and flexural strength than the control at a replacement rate of 5 and 10% after 7 and 28 days of water curing, as the percentage replacement is increased from 10 to 20% gradual loss in compressive as well as flexural strength is observed in both ferrock mixes. The durability study against sulfate attack showed that only 20% replacement using ferrock without oxalic acid showed more mass loss than the control concrete, the rest performed well. The presence of oxalic acid resulted in stronger and more durable concrete. 10% replacement of cement with ferrock containing oxalic acid can save up to 5.9% cost. The energy used by cement production is ten times higher than the energy used by the production of ferrock and water used by cement is 45 times higher than the use of water by ferrock production creating a negative balance and resulting in almost 21 times lesser contribution to global warming potential.*

Keywords: Ferrock, Sulfate attack, Durability, Oxalic acid, Conventional concrete

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

AASHTO	American Association of State and Highway Transportation Officials
ASTM	American Society for Testing and Materials
ACI	American Concrete Institute
EN	European standard
DEF	Delayed Ettringite Formation
OPC	Ordinary Portland cement
CA	Coarse Aggregate
XRD	X-Ray Diffraction
FA	Fine Aggregate
MPa	Mega Pascal
SCM	Supplementary cementitious material
C-25	Compressive strength of 25 MPa
C-S-H	Calcium Silicate Hydrate
C-A-H	Calcium aluminate hydrate
FA	Fly Ash
GGBFS	Ground Granulated Blast Furnace Slag
GHG	Greenhouse Gas
LOI	Loss of Ignition
MK	Metakaolin
HRM	High Reactive Metakaolin
PC	Portland cement
SEM	Scanning Electron Microscopy
XRD	X-ray diffraction
Kg	Kilogram

LIST OF CHEMICAL FORMULAS

P_2O_5	Phosphate Oxide
SiO_2	Silica Oxide
SO_3	Sulfur tri Oxide
Na_2O	Sodium Oxide
K_2O	Potassium Oxide
Fe_2O_3	Iron Oxide
$FeCO_3$	Iron Carbonate
$MgSO_4$	Magnesium Sulfate
Na_2SO_4	Sodium Sulfate
$Ca(OH)_2$	Calcium Hydro Oxide
$CaCO_3$	Calcium Carbonate
$MgCO_3$	Magnesium carbonate
CaO	Calcium Oxide
Al_2O_3	Aluminium Oxide
MgO	Magnesium Oxide
H_2O	Water
C_3S	Tri calcium silicate
C_2S	Di calcium silicate
C_3A	Tri calcium aluminate
C_4AF	Tri calcium alumina ferrite
$Mg\ (OH)_2$	Brucite

CHAPTER 1

1 INTRODUCTION

1.1 Background of the Study

Concrete is an essential part of infrastructure development, the global concrete industry has a substantial impact on the economics and development of a nation. It is the most widely used man-made substance in the world and the second most consumed material after water (Adesina, 2020). Concrete is a composite material made of fine and coarse aggregate and bonded together with the cement, water (cement paste) that hardens over time. The ecological impact of concrete mainly occurs in its manufacturing and application process. The cement industry is one of the main producers of carbon dioxide (CO_2), and greenhouse gases (Bhartiya & Dubey, 2018). Globally, cement production in accounted for approximately 8% of total carbon dioxide (CO_2) emissions (Dinesh Kumar & Reddy, 2018). Because of the demand on the infrastructure caused by an exponential rise in population, urbanization, and industrialization, all natural and virgin materials are depleting. Large-scale building materials are needed for these aspects, as well as electric power for on-going demands. As a result, there will be more coal burned in thermal power plants to produce energy (Kumar et al., 2015).

When exposed to its intended service environment, Portland cement concrete's durability is described as its capacity to withstand weathering action, chemical assault, abrasion, or any other process of deterioration to maintain its original form, quality, and serviceability (ACI Committee 201, 2016). There are several environmental elements that have an impact on how long concrete constructions last, with sulphate corrosion being one of the most prevalent and harmful processes (Merida & Kharchi, 2015). Sulphates that are solid do not damage concrete, but when the chemicals are in solution, they enter concrete that is porous and interact with the hydrated cement products. Of all the sulphates magnesium sulphate causes maximum damage to concrete (Swaroop et al., 2013).

Only 5-7% of the anthropogenic CO_2 produced by concrete manufacturing industries globally was determined to be their fault. Since no additional GHGs are exchanged in this industry, just roughly 3% of the total GHG emissions caused by human activity are at fault. Making this century into another system that serves the global framework will be its true test. This involves a delicate investigation of the services that are accessible to give the neighbourhood secure buildings and structures (Karthika et al., 2021). This problem lead scientists to develop different sustainable alternatives to cement, one of these newly developing concrete breakthrough, named Ferrock, was created by David Stone. Ferrock offers cement a carbon-negative substitute while utilizing a range of waste streams to create a versatile building material. Ferrock is a binder that is a blend of iron powder, fly ash, lime powder, metakaolin and oxalic acid. Iron oxide reacts with carbon dioxide and water produces iron carbonate. It can enhance the environment by absorbing the atmospheric carbon dioxide for its hardening process. By the use of ferrock the rate of emission of most dangerous greenhouse gases are reduced (Shivani et al., 2022).

Nowadays it's giving promising results as a choice to concrete and a far greener construction material. According to analysis (atomic absorption spectroscopy), completely cured samples have a weight-based capture of CO_2 of between 8 and 11%. As a result, unlike Portland cement, which is a significant generator of CO_2 and other air pollutants during manufacturing, Ferrock is carbon negative (Vijayan et al., 2020).

The research was undertaken to investigate the workability, durability, compressive and flexural strength, environmental effect and cost of partially replacement cement with ferrock.

1.2 Statement of the Problem

The main reason for the author to do this research is to examine an environmentally friendly, workable, strong and durable alternative to conventional concrete by using ferrock concrete. When subjected to a variety of atmospheric conditions, the majority of rivers and soils containing aggressive chemicals, and an excessive amount of other chemical exposures, concrete will function well. However, in some chemical situations, even the finest concretes durability is hindered and the concrete will have a short usable life unless special precautions are followed. Exposure to sulfates, saltwater, acids, and carbonation are the main areas of concern (ACI Committee 201, 2016). In order to improve the strength, economy, environmental friendliness and durability it is necessary to improve concrete problems or look for a durable concreting alternative to replace cement in concrete in these harsh chemical environments. Therefore this research is done to find sustainable construction material which can be used to help improve the durability as well as strength of the conventional concrete using ferrock cement concrete by incorporating oxalic acid as an admixture.

On the other hand as the world's population increases, the need to have different infrastructures mainly residential houses, schools, drinking water supply lines and roads increase, another factor that the building industry needs to take into account is the rising scarcity of natural sand and aggregate. Even while it might not seem like a priority, pressure from environmentalists and conservationists throughout the world will keep lawmakers and building engineers motivated to explore for workable alternatives to natural resources (Lekshmi, 2016). If the depletion of natural resources continues there will be shortage of Cement, this would cause a huge damage to the concrete industry, which directly affects the development of a country as well as the employment rate. Due to this factors and the elevation of GHG emissions, the author decided to study ferrock as an environmentally friendly and durable concrete alternative against sulfate attack.

1.3 Objectives of the Study

1.3.1 General Objective

The general objective of the study is to produce an environmentally friendly and durable concrete alternative to the conventional concrete using ferrock cement concrete incorporating oxalic acid as an admixture.

1.3.2 Specific Objectives

The specific objectives of this study are:

- To characterise the raw materials that are used for the production of ferrock based concrete and C-25 conventional concrete.
- To investigate the workability, water absorption, sulfate attack resistance, compressive and flexural strength of ferrock based concrete and C-25 conventional concrete.
- To investigate the effect of Oxalic acid on strength development and durability of partial replacement of cement with ferrock.
- To examine the morphological structure of ferrock based concrete and C-25 conventional concrete using SEM.

- To investigate the environmental impact of using ferrock based concrete compared to the conventional concrete including cost comparison.

1.4 Scope of the Study

This experimental research is conducted in Adama Science and Technology University. Scope of the research paper is not confined to literature reviews on this still developing concrete material but also laboratory tests are conducted. To understand the material property used to make concrete the normal consistency of cement, physical property of fine and coarse aggregates including gradation, density, moisture content and specific gravity were conducted. The fresh property of concrete containing ferrock and C-25 concrete is examined by slump test to determine its workability. Laboratory tests for hardened concrete such as compressive and flexural strength are conducted to compare it with the control group. Durability tastes such as water absorption and sulfate attack are done to better understand partial replacement of cement by ferrock and its durability in specimens fully submerged in 5% sodium sulphate solutions to gain a more fundamental understanding of the associated damage mechanisms. In addition to durability the effect of oxalic acid on strength development and durability of ferrock based concrete is studied by preparing two different mixes of ferrock cement, one batch containing oxalic acid and the other batch is prepared without oxalic acid, these experimental groups are then compared with a control group which is a C-25 concrete exposed to the same curing process. The research additionally addresses SEM test to identify the phase of the material. In doing so to save the natural resource, to utilize waste and by- product from other industries, minimize emission of CO_2 in production of cement.

1.5 Significance of the Study

One of the main tasks of structural design is the selection of the right building materials. The study offers numerous advantages for construction sectors to use a substitute construction material that can protect the structures by boosting the strength and durability of concrete when the structure is subjected to hostile environment. Other research projects will benefit greatly from this study's understanding of the effects of ferrock based concrete on the workability, durability, compressive and flexural strength and its morphology. In addition to cost, ferrock participates in the efforts to minimizing environmental problems due to the emission of CO_2 to the atmosphere as a result of cement production.

It is also believed that the users can grasp the knowledge of how the combination of ferrock and Portland cement can be used in concrete and to what percentage it is effective in production of concrete. Therefore, the result of the study may have environmental, economic and technical advantages upon successful utilization of ferrock in concrete.

1.6 Limitations

Due to time, cost and resource constraints, the research has the following limitations; only water curing was adopted for this research since it is the ideal environment in the study area so the effect of carbon curing on partial replacement of ferrock cement in concrete is not studied. Only up 20% partial replacement of OPC is studied. During the investigation slump cone test is the only fresh concrete property that is included in studied and hardened concrete properties like compressive strength, flexural strength, SEM analysis, water absorption and sodium sulfate attack resistance tests. Other hardened concrete properties like split tensile strength, air content, chemical attack and other tests like XRD were not conducted due to time, budget, and laboratory constraints.

1.7 Organization of the Thesis

The first chapter deals with the introduction part, following chapter 1, chapter 2 presents an overview of literature review on previous experiences basic principles, history, and applications of cement replacement materials are outlined in order to better define specific aspects on properties and performance of pozzolanic cement replacement material. The review part highlighted the different properties of ingredients of concrete and review of related research on industrial waste based partial replacement materials of cement in concrete. Chapter 3 demonstrates the materials, methods and testing programs of the study. In the material section cement, sand, coarse aggregate, water, and ferrock making ingredients are described well. In the test program section different strength and durability test methods and procedures are discussed briefly. Chapter 4 presents the result and discussion part of the study. Finally, a comprehensive summary of this research study and its major conclusion and recommendations are presented on chapter 5.

The annex gives the results of the individual physical testes of cement, fine and coarse aggregate tests, water absorption, sulfate attack resistance, compressive and flexural strength of each concrete specimen; Graphs are used to show trends and to describe relationships. Statically analysis of the data collected is presented with tables.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction

In comparison to other materials used to make concrete, cement has the highest embodied carbon which results in higher overall embodied energy of concrete. Therefore, in order to conserve our environment while meeting the future demand for concrete, it is paramount to source alternative binders from wastes materials to be used in concrete production (Adesina, 2020). From the 20th century, there had been an increase in the economic consumption of mineral admixtures by the cement and concrete industries. The increasing demand for cement and concrete is conformed to by partial replacement of cement. Significant cost savings can result when by-products are used as a partial replacement for the energy acute Portland cement (Varshney, 2016).

Waste materials which are having cementious properties and can be used in concrete are becoming worldwide practice. This cementious property waste materials becoming increasingly important because need of more sustainable binding products is required. The environmental impact of cement is significant because its manufacturing emits large amount of CO_2 and greenhouse gases. Waste material such as Slag, Silica fume, Rice husk ash, Corn cob ash, Sawdust ash, Glass powder, Bottom ash and Cement kiln dust are having pozzolanic properties which can partially replace the cement (Bhartiya & Dubey, 2018).

This chapter discusses concrete making ingredients special focus was given to cement and supplementary cementicious materials obtained from other industry by products and their maximum percentage replacement of cement. The impact of these waste-based cement replacement materials on cement hydration is also researched using a variety of literatures. The definition of ferrock, the method by which it achieves its strength, the impact of cement and ferrock on the environment, as well as the shortcomings of earlier studies on ferrock-based concrete, are all discussed here.

2.2 Construction Industry and the Environment

There's a lot of talk these days about climate change and what can be done about it. One big area often overlooked in the conversation is the built environment. Perhaps the most often utilized material for foundations, bridges, and buildings on roadways is concrete. Every person on the earth receives about 1 tonne of cement annually. Due to its widespread use worldwide, it is important to accurately estimate how this substance may affect the environment (Karthika et al., 2021). Concrete is also known as the "basis of modern civilisation." Environmental problems including air pollution, skin conditions, breathing problems, global warming, climate change, and other issues are brought on by the large emission of carbon dioxide into the atmosphere during cement production. For every ton of cement produced, more than eight tons of CO_2 are released. The effect is an increase in environmental pollution (Puthoor, 2022). Therefore, this thesis examines how environmentally friendly materials like ferrock may replace conventional concrete.

The global buildings and construction sector, (including the construction and usage of buildings) accounts for around 39% of all energy-related CO_2 emissions and 36% of final energy use. The good news is that the built environment is already undergoing a fundamental transformation in order to significantly decrease its carbon footprint and switch from the existing paradigm to a sustainable, closed-loop system (Agencia Internacional de Energía, 2018).

2.3 Concrete

Concrete is by far the most important building material. Annual production totals more than 10 billion tons worldwide. The causes of this acceptance are widely recognized. Concrete has high mechanical and durability qualities when correctly prepared and produced. It is mouldable, versatile, somewhat fire resistant, widely accessible, and affordable. Its ability to be engineered to almost any reasonable set of performance specifications, more so than any other material currently available, is perhaps its most intriguing feature (Meyer, 2009).

Concrete as a building material is more sustainable compared to other materials such as glass, steel, etc. However, the high consumption of this material has overridden its sustainable advantage due to the high emission of carbon dioxide and the consumption of natural resources. Therefore, the concrete industry is burdened to play a significant role in ensuring the world achieves a net-zero carbon dioxide emission by 2050. The significant role of the concrete industry in achieving a sustainable environment can be attributed to the industry being one of the major contributors to the world's anthropogenic carbon dioxide emission.

The major carbon emission from the concrete industry is from the production of its main binder which is Portland cement (Adesina, 2020).

The production of Portland cement is also very energy intensive, requires large amounts of water, which is particularly burdensome in those regions of the earth that are not blessed with an abundance of fresh water. Finally, the demolition and need of disposal of concrete structures, pavements, etc., creates another environmental burden. Construction and demolition debris contribute a considerable fraction of solid waste in developed countries, and concrete constitutes its largest single component (Meyer, 2009).

The demand for cement and concrete is likely to increase due to the rapid population expansion and urbanization anticipated over the decades to come, necessitating the adoption of quick solutions and mitigation measures to lessen their negative effects on the environment and mitigate the impacts on climate change (Belaïd, 2022).

The carbon dioxide emission from the concrete industry can be classified into two major groups which are from the raw material and concrete construction as shown in Table 2.1. The majority of the carbon dioxide emissions are from the mining, processing and transportation of raw materials used for making concrete (Adesina, 2020).

Table 2.1 Source of carbon dioxide in concrete (Adesina, 2020).

Source of carbon dioxide in concrete	**Process**
Raw materials	Mining Processing Transportation
Concrete Production	Mixing Casting Transportation Compaction Curing

The difficulties outlined above are mostly caused by Portland cement's lack of environmental friendliness. One could therefore reduce these challenges to the following simple formula: Use as much concrete as feasible while using as little Portland cement as possible. This entails using supplementary cementitious materials, particularly those that are by-products of industrial operations, to substitute Portland cement and recycled materials to replace natural resources (Meyer, 2009).

2.3.1 Cement

Since ancient times, people have used cement. The Macedonians of ancient Greece, as well as the ancient Egyptians and Romans, are known to have utilized hydraulic binder first. The first forms of clinker-based hydraulic cements contained basic calcium compounds, for which the major raw materials are limestone (calcium carbonate) and clay (silicon oxide compounds). In order to create basic cement, calcium carbonate (limestone) must be converted to calcium oxide (lime), by a process known as calcination (from the Latin calcinare). The calcination process for a typical modern cement clinker, where calcium carbonate and silicon oxides are combined at elevated temperature (1,450 ^{0}C) (Imbabi & , Collette Carrigan, 2012), is:

$3CaCO_3 + SiO_2 \rightarrow Ca_3SiO_5 + 3CO_2$ ………………………………………… Equation 2.1

Cement production follows a linear path, as a processed mixture of crushed limestone, clay, sand, and iron is first formed then enters the pyro processing phase. Pyro processing entails the kiln, which includes the calcination and sintering processes, and the heat-induced chemical process produces cement clinker. CO_2 and dust are formed as part of the process at this point, in addition to the emission of CO_2 as a fuel combustion product. Once the clinker is cooled, it is mixed with Pozzolan ash and gypsum, depending on the type of cement the consumer’s demand, and ground to end up with finished cement. In Saudi Arabia, the cement demand almost exclusively consists of Portland types I and V, and Pozzolan cement. The finished product may either be sold to the market or stored for future sale (Matar & Elshurafa, 2017).

Portland cements are the most common Calcium–Silicate–Hydrate (C–S–H) hydraulic cements in use today. The first Portland cement was originated by the English bricklayer Joseph Aspin in Leeds in the 1800’s, after he had experimented with earlier types of cement such as Roman and other Natural cements. The composition of a typical Portland cement is 65% calcium oxide; the rest is generally a mixture of aluminum, iron and silica (Imbabi & , Collette Carrigan, 2012).

There are numerous types of cement because of the use of different sources for calcium and different additives to regulate properties. Table 2.2 gives an overview of important cement types (Worrell et al., 2001).

Table 2.2 Summary of the main cement types, composition, and raw materials needed (Worrell et al., 2001).

Cement type	**Composition**	**Remarks**
Portland	95% clinker 5% gypsum	Gypsum improves workability of cement
Portland slag	60% clinker 40% slag, pozzolana, fly ash	
Portland pozzolana		
Portland fly ash		
Iron Portland (Germany)		
Blast furnace	20%–65% clinker 35%–80% blast furnace slag	Only granulated slag can be used, not air cooled
Pozzolanic	60% clinker 40% pozzolana	Important in countries with volcanic materials
Masonry	Mixture of clinker and ground limestone	Binder for brick work

In the end, three choices have the most effect on emissions. One is fuel selection, where one option is to choose to burn more expensive but less polluting fuels. The second is by making an investment in more energy-efficient pyro processing machinery. The final alternative is to only utilize electricity that is purchased from the grid rather than producing it on-site; of course, this choice is not one that focuses on reducing emissions because it just transfers part of the industry's emissions to the power sector. In order to minimize emissions, the cement sector can combine all three possibilities (Matar & Elshurafa, 2017).

2.4 Cement production in Ethiopia

The first cement factory, with a yearly production capacity of 30,000 tons, was erected by the Italians in Dire Dawa town in 1938. The Ethiopian government constructed two 70,000-ton-per-year cement mills in the 1960s, one in Massawa (Eritrea) and the other in Addis Abeba. At Mugher, two production lines with a combined installed capacity of 600,000 tons were erected in the years 1984 and 1991. From 2004 to 2012 there was a shortage of cement because of the boom in the construction industry. The construction of the Grand Ethiopian

Renaissance dam which is one of the largest hydropower plants in the country, housing projects, and private investments has increased the cement demand in the country. Furthermore, it has caused an increase in the price of cement. The government has permitted the private sector to import cement in an effort to resolve this issue. Although the government permitted cement imports, the lack of available foreign currency and other variables rendered it difficult to meet the nation's cement needs. In response to these events, new cement mills were constructed, while older facilities underwent expansions (Tesema & Worrell, 2015).

For the period of 2015 to 2025 the Federal Democratic Republic of Ethiopia Ministry of Industry has developed new strategies to guide the growth of Ethiopia’s cement industry. By the end of 2025, the nation is expected to be using 19.97 million tons of cement, but the amount needed is anticipated to be 25.16 million tons. According to this, 8.01 million tons of extra capacity will be available by the end of 2025. The amount of cement consumed per person is predicted to rise from 62 kg to 179 kg by 2025. Enhancing the Ethiopian cement sector by encouraging the manufacturing of green cement is one of the government's strategic initiatives (Dure Mulatu et al., 2005).

In Ethiopia, Given the vast geographical size and massive population, various construction activities are being undertaken by the Federal Government, Regional Governments, Public Sector Undertakings and other organizations, including the private sector that generates a huge demand for cement. The primary causes of the enormous demand for cement are significant expenditures in housing projects, universities, infrastructure, power production facilities, irrigation systems, industrial zones, airport fields, railroads, and road development projects (Abebe Demissew, 2020).

Due to the extensive construction and infrastructure development projects the Chinese government is engaged in, China is the global leader in both cement consumption and production According to 2022 estimates, the Chinese production was 2100 million metric tons per annum (M.Garside, 2023.), (see Figure 2.1)

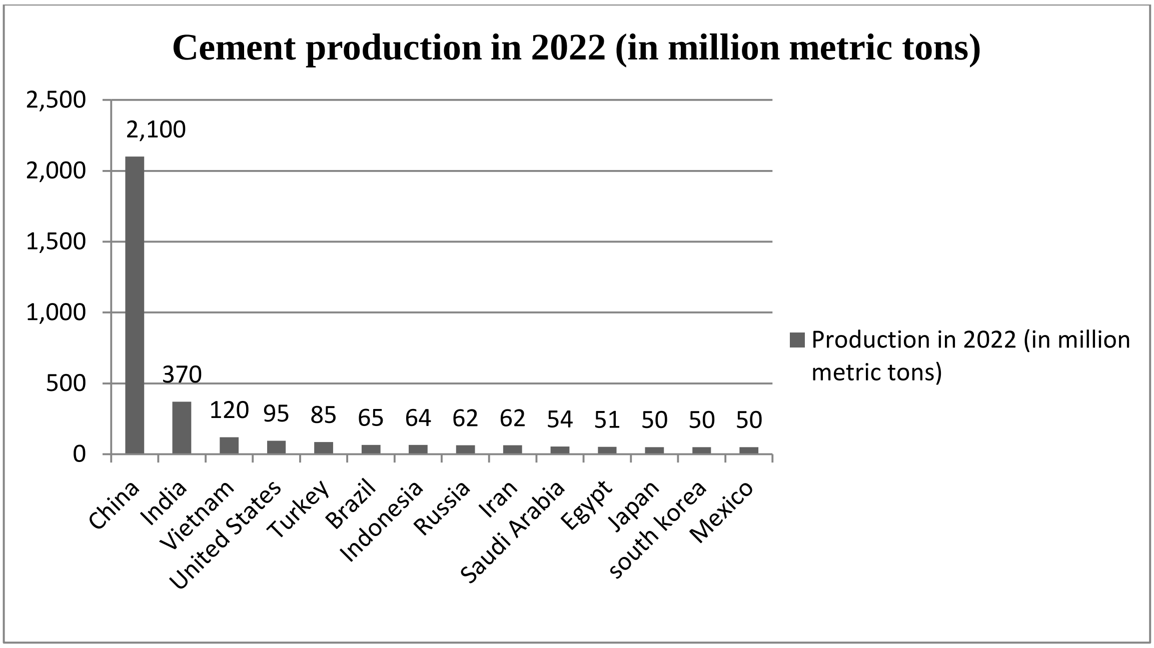


Figure 2.1 Major countries worldwide in cement production in 2022(in million metric tons)

(M.Garside, 2023.)

2.5 Green or Environmentally Friendly Concrete

The buildings in which we live and work have a tremendous impact on our global environment. Sustainability or green building 'seeks to balance resource efficiency, health, and social concerns throughout the life cycle of a structure (Tafheem et al., 2011). Green concrete is taken to mean environmentally friendly concrete. This means concrete that uses less energy in its production & produces less carbon dioxide than normal concrete is green concrete (Lekshmi, 2016). Concrete which is made from concrete wastes that are eco-friendly are called as "Green concrete". Green concrete is the production of concrete using as many as recycled materials as possible and leaving the smallest carbon footprint as possible. The other name for green concrete is resource saving structures with reduced environmental impact for e.g. Energy saving, CO_2 emissions, waste water (A Baikerikar, 2014). It is environmentally friendly concrete. This means it uses less energy in its production & produces less carbon dioxide than normal concrete is green concrete (Lekshmi, 2016).

While a normal construction practices are guided by short term economic considerations, sustainable construction is focused on best practices which emphasize on long term affordability, durability and effectiveness. At each stage of the life cycle of the construction, it increases ease and quality of life, while minimizing the negative environmental impacts and increasing economic sustainability of the construction (Nagarkar, 2017). More than six billion tons of concrete are produced annually-about one ton per person on the planet. Concrete is made from cement, water, sand and gravel. The cement is made by heating raw materials such as limestone and clay to very high temperatures until they chemically react. This process uses massive amounts of energy (about five present of the world's use per year) and releases about a ton of carbon dioxide per ton of cement made (Tafheem et al., 2011).

2.6 Review on Some of the Natural and Waste-Based Cementitious Materials

Modern society places a great deal of emphasis on protecting the environment, and enormous amounts of waste or by-products produced by various industries are given particular consideration. The best option for a large reduction of these materials in many industries is their reuse or recycling. This strategy might be advantageous for the building sector since it allows for the reuse of huge amounts of trash or by-products in the development of new projects. Among various options, different pozzolanic waste materials are most widely used as supplementary cementitious materials in concrete production, making it more sustainable (Marinković & Dragaš, 2018).

Table 2.3 Sources of supplementary cementitious materials (Adesina, 2020).

Supplementary cementitious materials	
Derived from wastes	**Derived from natural sources**
Fly ash	Metakaolin
Slag	Calcined shale
Silica fume	Calcined clay
Rice husk ash	Volcanic ash
Corn cob ash	Zeolitic tuffs
Sawdust ash	Diatomaceous earth
Glass powder	Limestone
Bottom ash	
Cement kiln dust	

The major aim of this review is to identify the workability, mechanical strength and minimum and maximum level of replacement of waste in waste-based cementitious material. This section also presents an overview of waste-based cementitious materials in terms of physical and chemical properties and thermal performance. This offers the use of industrial wastes in cementitious materials and their current state of development to increase their replacement level in cementitious material.

2.6.1 Limestone

Limestone is sedimentary rock consisting principally of calcium Carbonate ($CaCO_3$). With an increase in magnesium carbonate ($MgCO_3$), limestone grades into dolomite or dolo stone [$CaMg(CO_3)_2$] (British Geological Survey, 2016). Limestone is the most common form of calcium carbonate which is used extensively for the manufacture of cement. Cements in different types are made mainly by calcining a mixture of about 75% limestone and 25% clay to form a calcium silicate clinker which is then ground and mixed with a small amount of gypsum (Gudissa & Abebe, 2010). Portland limestone cement is thus, one of the alternative cement types that can be produced in our cement industries. The raw materials for production of such cement type are sufficiently available and it requires lesser energy for production, and has less CO_2 and NO_2 emissions. It is also economical for countries like Ethiopia where OPC and PPC cement types are the only types of cement used for all construction purposes (Thalada et al., 2022).

According to European standard (EN 197) limestone used as a main constituent in cement production shall meet the following requirements (Gudissa & Abebe, 2010): The $CaCO_3$ content shall be ≥ 75% by mass , Clay content methyene blue absorption should be 1.2 g/100 g, and total organic material content shall be ≤ 0.2% by mass.

Generally, the PLC concretes having up to 10% limestone, provide competitive properties with PC concretes. Adding higher percentages of limestone to cement produces less competitive concrete properties. The PLC concretes indicate satisfactory compressive strength and generally demand less water than PC concretes (Ramezanianpour et al., 2009).

The investigation has revealed that replacement of ordinary Portland cement by fine limestone powder from 5% to 10% with Blain fineness value of 4000 to 4500 cm^2/gm satisfies the standard compressive strength requirement of high early strength cement (CEN 42.5) as per the standard requirements of EN 197-1 (Gudissa & Abebe, 2010).

2.6.2 Fly ash (FA):

Pulverized coal is burned in thermal power plants, and one of the by-products of this process is fly ash. About 1500°C (2700°F) is the temperature at which coal burns. During combustion, the coal's mineral impurities—clay, quartz, shale, and feldspar—melt and disperse with the exhaust gases. The molten substance cools and hardens into spherical particles as it rises with the gas flow. Special filters or electrostatic precipitators are used to capture this fine-grained materials (Marinković & Dragaš, 2018). FA has received attention as a problematic solid waste during the past several decades as a result of thermal power stations' and companies' traditional disposal practices, which have polluted and ruined fertile fields all over the world (Mahvash et al., 2017).

Fly ash can be classified into C and F categories, according to Suraneni et al. (2021). Class C fly ashes are generally produced from lignite or sub-bituminous coal. They can be used as hydraulic materials since they are defined by having between 10% and 15% calcium oxide in their chemical makeup. Class F fly ash (pozzolanic), with composition of <18% CaO, and Class C fly ash (pozzolanic and latent hydraulic) with >18% CaO (Suraneni et al., 2021).

According to Joshi (2017) as the cement was replaced with fly ash, the reduction in compressive strength of concrete was higher at the age of 7 days as compared to 28 days. This occurs as the secondary hydration due to pozzolanic action is slower at initial stages for fly ash concrete. The compressive strength of concrete decreases with increase in fly ash content, the reduction in compressive strength of concrete at the age of 28 days was found to be 4.57%, 12.20% and 20.55% for 10%, 20% and 30% replacement of cement with fly ash. Not more than 30% of cement should be replaced with fly ash; otherwise it may lead to significant reduction in the compressive strength of concrete.

The strength of concrete decreases as the fly ash concentration in all grades of OPC rises. This is to be expected since the secondary hydration due to pozzolanic action is slower at initial stage for fly ash concrete. The reduction is more at earlier ages as compared to later ages. In all three OPC classes, the rate at which concrete strength increases with age is essentially the same. At 90 days, concrete with 20% fly ash concentration is comparable to regular concrete (Marthong, 2012).

In addition to having excellent workability, fly ash concrete also permits slumps that are comparable to conventional concrete but with a lower water-cement ratio. In addition, it lessens bleeding, cracks, and heat of hydration. It is a more economical alternative to Portland cement (Shivani et al., 2022). When the w/b ratio and binder concentration were modified to produce concrete with the same 28-day strength as the control concrete, the addition of fly ash to the mix reduced drying shrinkage. Fly ash incorporation lowered concrete's sorptivity early on, and it continued to decline after six months. At 28 and 180 days, the fly ash concretes produced better results in terms of resistance to chloride ion penetration. Thus, by incorporating up to 40% Class F fly ash in the total binder, high strength concrete with decreased permeability may be designed (Nath & Sarker, 2011).

2.6.3 Silica Fume (SF):

The silicon and ferrosilicon industries produce silica fume as a by-product. SiO_2 vapours are created when high-purity quartz is reduced to silicon at temperatures up to 2000 °C. These vapours then oxidize and condense into tiny non-crystalline silica particles in the low-temperature zone (Siddique, 2011). The silica fume has been proven to increase the compressive strength and toughness of concrete, the presence of this admixture has been shown definite in snowballing the electrical resistivity and the durability of concrete bare to aggressive situations like chloride comprising environments (Parthasarathi et al., 2017).

To investigate the increase in the compressive strength of concrete, an experimental study was carried out on it by Sharma & Tech (2018) by adjusting the proportion of silica fume as 0%, 5%, 10%, and 15% accordingly. Based on experimental research, it was discovered that adding 10% more silica fume to concrete increased its compressive strength. After a 10% addition to the concrete, it was discovered that the compressive strength gradually decreased.

Concrete's compressive strength improves when silica fume replacement levels rise between 8 and 12%, below which no appreciable change in compressive strength should be anticipated. If the replacement amount exceeds 12%, a declining trend in compressive strength is anticipated. Up to a limit of 10- 15%, the split tensile strength of concrete exhibits an increasing trend. It may be claimed that when the w/c ratio rises, the split tensile strength declines, followed by an increase in silica fume replacement. However, flexure strength in the replacement range of 10-15% exhibits a similar pattern (Imam et al., 2018).

When silica fume percentage rises from 0% to 20%, the usual consistency increases by around 40%, the range of 10-15% silica fume replacement level has been shown to produce the best compressive strength and flexural strength after 7 and 28 days, respectively. Beyond 10% silica fume replacement, the increase in split tensile strength is essentially negligible, although increases in flexural tensile strength were noted up to 15% replacements. The flexural strength appears to be more significantly impacted by silica fume than the split tensile strength. When 10% Silica fume was substituted for cement, the weight loss and compressive strength percentage were found to be lowered by 2.23 and 7.69 when compared to other mixes (Amudhavalli & Mathew, 2016).

Concrete mixed with silica fume has better durability characteristics than OPC concrete, such as resistance to water absorption, permeability, sulphate attack, and chloride penetration (Imam et al., 2018).

2.6.4 Recycled Glass (RG)

Due to the absence of a local glass manufacturing sector that might operate as a viable recycling outlet, the disposal and recycling of waste glass have grown to be a significant problem in Hong Kong, Finding a sustainable option to reuse and recycle trashed glass is extremely important (Ling et al., 2011). There are many different kinds of glasses, but the ones that are most frequently used in the fabrication of sheets and containers include soda-lime, lead, boro-silicates, and barium. Soda lime glass has a composition of around 70% SiO_2, 15% Na_2, and 12% CaO, making it a pozzolanic cementitious material (Bhagat et al., 2020).

Waste glass may successfully replace natural fine aggregate in cement mortars without degrading the samples' compressive strength. A considerable reduction in heat conductivity and a reduction in the sorptivity of cement mortars are also caused by the addition of waste glass fine particles (Bhagat et al., 2020).

Concrete compressive strength was not decreased by the cement substitution after 28 days because of the pozzolanic reaction between glass powders and cement hydration products, if the replacement is below 30%. Also, the resistance to chloride ion and water penetration continuously increases with increasing glass powder content up to 60% cement replacement. At 60% replacement level, the electrical resistivity and water penetration depth were reduced by 95% and 80%, respectively, while the compressive strength was maintained as 85%. These improvements in durability properties are due to the refined microstructures, particularly at the interfacial transition zone (Du & Tan, 2014).

According to a study by Sharma & Tech (2018), various cubes, cylinders, and beam have been prepared by replacing cement with 0, 5, 10 and 15 % silica fume. The result showed that partial replacement of cement with silica fume had a significant effect on compressive strength, flexural strength, split tensile strength. The strength of concrete increases rapidly as we increase the silica fume content and the optimum value of compressive strength is obtained at 10 % replacement. After 10% it starts decreasing.

10 % waste glass replacement was found to be maximum after that strength continuously decreases. Waste glass can be used for making good concrete only problem rises it give rise to alkali-silica reaction in concrete containing waste glass, we have to add supplementary material like fly sash, silica fume and waste foundry sand etc. (Bhagat et al., 2020).

The optimum glass content is 20% considering mortar and concrete compressive strength at 90 days. In this age the compressive strength was found slightly higher (2%) than the control concrete specimen. In general, considering the similar performance with replaced material, glass addition can reduce cost of cement production up to 14%. In addition, production of every six ton glass powder concrete results in the reduction of each ton CO_2 emission from cement production and save the environment significantly by reducing green-house gas and particulate production. Generally, the high surface area of milled waste glass changes the kinetics of chemical reaction toward beneficial pozzolanic reaction utilizing the available alkalis before production of a potential ASR gel (Islam et al., 2017).

2.6.5 Metakaolin (MK):

Metakaolin is a high-quality pozzolonic material that is mixed with cement to increase the durability of concrete. It is not a by-product and is produced by the calcinations of pure or refined Kaolinite clay at a temperature between 650°C and 850°C, followed by grinding to achieve a finesse of 700-900 m^2/kg (Narmatha & Felixkala, 2016).

The durability of concrete and mortars is increased by blending high-quality pozzolanic substance called metakaolin with Portland cement. Metakaolin removes chemically reactive calcium hydroxide from the hardened cement paste. Concrete that has hardened has less porosity thanks to metakaolin. The density of metakaolin increases and the thickness of the interfacial zone decreases, enhancing the adherence of the cured cement paste to the sand or aggregate particles (Shah et al., 2008).

When metakaolin is used in concrete as a partial replacement for cement, it combines with $Ca(OH)_2$, one of the byproducts of cement's hydration process, to produce more C-S-H gel and so enhance the strength of the concrete (Macfarlane, 2013).

To create 100% reactive Pozzolona, highly reactive metakaolin must first undergo water processing to eliminate non-reactive impurities. High Reactive Metakaolin (HRM) is the name of such a purified, thermally activated product that is white or cream in color. Even after just one day, high reactive metakaolin exhibits substantial pozzolanic reactivity and a decrease in $Ca(OH)_2$. Additionally, a clear densification of the cement paste has been detected. This densification provides a benefit by increasing strength and reducing permeability. The high reactive metakaolin is having the potential to compete with silica fume (Shah et al., 2008).

To increase the compressive and flexural strength of the cured cement, metakaolin is used in oil well cementing. The permeability of the cured cement to liquids and gases is likewise decreased by metakaolin. Thus, using Metakaolin in place of Portland cement to a certain extent boosts construction durability while simultaneously reducing carbon dioxide emissions (Macfarlane, 2013). Chemical formula of Metakaolin is $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$.

After 28 days the compressive strength for MK 5% increases in 4.36 when compared to control specimen. The compressive strength for 10%, 15% and 20% increases in 13.73%, 17.45% and 12.44% respectively. MK 15% increases in higher strength, when compared to all other mixes. But MK 20% decreases in 4.26% from MK 15%. So MK 15% is the best proportion for add in cement (Narmatha & Felixkala, 2016).

The resistance of concrete to sulfate attack can be improved by replacing cement with metakaolin. As the MK replacement level was raised, MK concrete's sulfate resistance increased. MK replacement levels of 10% and 15% in concrete demonstrated exceptional resistance to sulfate attack. Depending on the kind of aggregate used, 10% to 15% of high-reactivity metakaolin as a partial cement replacement may be adequate to prevent harmful expansion brought on by the alkali-silica reaction in concrete (Siddique & Klaus, 2009).

2.6.6 Ground granulated blast furnace slag

Steel slag is a by-product of the steel-making process and the use of slag in various contemporary applications is a fairly recent development. There are two main slags, called blast furnace slag and steel furnace slag. Blast furnace slag is produced from the smelting of iron ore and limestone or dolomite (Samad & Shah, 2017).

Ground granulated blast furnace slag has been well recognized as an effective supplementary cementitious material to increase the acid resistance of reinforced concrete structures. The secondary hydration reaction of GGBFS can inhibit the amount of Ca(OH) 2 and produce additional calcium-silicate-hydrate gel, which refines the pore structures of concrete and thereby increase the acid resistance (Yun et al., 2020).

Manufacture of GGBFS requires lesser energy as compared with energy needed for production of Portland cement. Production of Portland cement is an energy-intensive process, while grinding of blast furnace slag needs approximately 10% of energy required for production of Portland cement. Optimum level of ground granulated blast furnace slag (GGBS) in concrete enhances compressive strength of concrete (Samad & Shah, 2017).

Ground granulated blast furnace slag compared 15 OPC to slag powder and inferred that slag has higher silica and lower calcium contents, and contains low quantities of ferric oxide. For GGBFS, the glass content is around 85% – 90%. The hydration of slag involves complex chemical and physical reactions such as adsorption, ion exchange, dissolution, and hydrolysis (Mancini et al., 2021).

It was also found that use of GGBFS accelerates hydration of ordinary Portland cement at early ages of hydration process thus, reducing water requirement of cement with increase in GGBFS content Inclusion of GGBFS improved workability of mortar/concrete and also increased setting times of cements. Strength of mortar incorporating GGBFS is associated to surface area and particle size distribution. Concrete containing 60% of slag showed better sulphate resistance than OPC (Yun et al., 2020).

2.7 Ferrock

2.7.1 History

At the University of Arizona in Tucson, David Stone was pursuing his Ph.D. in environmental chemistry when a failed experiment turned up a brand-new substance. His goal was to find a substance that could be mixed and poured similarly to cement and that would have the same strength and flexibility as concrete does (Vijayan et al., 2020).

2.7.2 Ferrock Concrete

Ferrock is a binder material used as a partial or complete replacement to cement in concrete. Ferrock was measured based on its testing with different proportions of the raw materials (Shivani et al., 2022). David Stone is a smart guy who invented ferrock, a brand-new concrete technique. According to the literatures that are now accessible, ferrock is a binder made of iron powder, fly ash, limestone, and metakaolin to transform industrial waste products into new substances.

In comparison to cement concrete, which emits 8–10% CO_2 during production and curing, ferrock absorbs 8–11% of the environment's CO_2 during curing while converting iron into iron carbonate. This makes ferrock a more environmentally friendly material (Vijayan et al., 2020; Prashanth et al., 2019).

The accepted reaction steps for this process are:

$Fe + 2CO_2 + H_2O\ Fe_2^{+} + 2HCO_3^{-} + H_2$ …………………...……………………. Equation 2.2

$Fe_2 + 2HCO_3\text{-}\ FeCO_3 + CO_2 + H_2O$ …………………………………………….. Equation 2.3

The net reaction then is

$Fe+CO_2+H_2O \longrightarrow FeCO_3+H_2$ ………………………………………………… Equation 2.4

The iron residue among the steel reacts with water and CO_2, which form an iron carbonate matrix; when it dries, it exhausts rock-like qualities called ferrock (Karthika et al., 2021).

Alternative to traditional concrete is ferrock. It acts as a waste management tool, wherever within the waste is being best utilized. Consuming carbon dioxide causes the iron to react with the carbon dioxide to generate iron carbonate, which has a strong adhesive effect on the substrate and is how ferrock gains strength. A substance known as ferrock is a binder that can be used in concrete as a partial or full replacement for cement. Ferrock was measured based on its testing with different proportions of the raw materials. The composition of ferrock was concluded as 60% iron powder, 20% flyash, 10% metakaolin, 8% limestone, 2% oxalic acid in terms of rheological characteristics (Shivani et al., 2022).

The first of two white-papers drafted by the product's founder, Dr. David Stone, in conjunction with several engineers from Arizona State University, define the flexural strength and overall durability of the compound compared to OPC. They concluded, "The fracture toughness and critical crack tip opening displacement of the iron-based binders were significantly higher than those of the OPC matrices” (Das S. et al., 2017). Porosity is also another beneficial characteristic of the iron-based material in contrast to OPC, which can be reviewed in Dr. Stone’s second white paper titled, Pore- and Micro-structural Characterization of a Novel Structural Binder based on Iron Carbonation. Additional information regarding the benefits of using recycled materials as substitute ingredients for binding material production are further defined in a short essay by the Environmental Protection Agency titled, Creating a Carbon-Negative Building Material from Recycled Glass, Steel Dust, and Carbon Dioxide . All ingredients necessary for Ferrock production are conventional industrial materials except for iron powder (Sumanta et al., 2014).

The Ferrock can be used as a partial SCM and can result in plausibly better, greener strong material if an ideal environment of 100% CO_2 curing is provided, which is not feasible. Therefore, contemporary researchers have used it partially with OPC to formulate better-performing eco-friendly material at par OPC. It can be used in the marine environment where corrosion due to saltish sea water accelerates the formation of $FeCO_3$ by providing more Fe^{++} for the chemical reaction with CO_2 , increasing production of Ferrock and adding more strength to the structure and preventing further corrosion (Vijayan et al., 2020; Prashanth et al., 2019)

Ferrock cement concrete is a stronger binding material that helps to increase the bond strength of the concrete mix without any failure. The strength gaining mechanism of ferrock cement concrete is by both air curing and water curing. Air curing is mainly done by using carbon dioxide gas in an air tight container or plastic cover and carbon dioxide gas is introduced in it (Shivani et al., 2022).

Ferrock reduces CO_2 emissions by 8 to 11% and makes constructions more cost-effective as it uses other industry wastes as a raw material. Actually it is it five times as strong as OPC; ferrock is also much more flexible and can sustain greater compression before breaking, which makes it resistant to the movement of the earth brought on by seismic activity or industrial activity. For marine-based building, ferrock is the ideal material (Karthika et al., 2021).

The well-settled idea of using pozzolanic materials in concrete is needed to be revisited in the context of utilizing industrial waste materials and byproducts such as iron dust, fly ash, metakaolin and limestone powder in the form of ferrock in SCC (Jeffy Pravitha et al., 2023).

The ferrock, developed by David Stone is purely a non-cement material which hardens by the carbonation of pozzolanic materials in the presence of oxalic acid. The chemical reaction between iron dust and CO_2 yields iron carbonate which initiates the strength of the ferrock concrete (Jeffy Pravitha et al., 2023).

2.8 Chemical Admixtures

In modern construction endeavours, concrete admixtures are often employed. Admixtures are generally used by producers to alter the characteristics of freshly mixed and hardened concrete, as well as to maintain the quality of concrete throughout mixing, shipping, placement, and curing. The use of suitable batching and concreting techniques makes the right use of admixtures feasible. An admixture's efficiency is influenced by a number of factors, including: Type and amount of cement, Water content, Mixing time and Slump and temperature (Albayrak et al., 2015).

The admixtures play an important role in the production of concrete which is suitable for the special purpose. They are used for various purposes depending upon their properties. Table 2.4 shows different types of chemical admixtures with their particle characteristics (Patel & Shah, 2013).

Table 2.4 Types of chemical admixtures

Chemical Admixtures	Function
Super Plasticizer	To reduce the water requirement by 15% to 20% without affecting the workability leading to a high strength and dense concrete
Accelerator	To reduce the setting time of concrete, helping early removal of forms and therefore used in cold weather concreting
Water Reducing Admixture	To achieve certain workability (slump) at low water cement ratio for a specified strength thus saving on the cement
Air Entraining Admixture	To entrain small air bubbles in concrete which act as rollers thus improving the workability, therefore very effective in freeze- thaw cycles as they provide a cushioning effect on the expanding water in the concreting in cold climate.
Retarder	To increase the setting time by slowing down the hydration of cement and therefore are preferred in places of high temperature concreting.

Concrete's durability, strength, chemical resistance, colour, water and cement requirements are reduced, and its working qualities are increased as a result of the application of chemical admixtures (Albayrak et al., 2015).

2.8.1 Oxali Acid

Oxalic acid and its metal oxalate salts have been used extensively in dentistry in a range of applications: as desensitisers, in cavity preparation, and as bonding agents. Oxalic acid may be a useful reaction modifier in glass-ionomer systems. It accelerated the setting reaction without affecting strength, but was limited to low concentrations because of its relatively poor solubility in water (Prentice et al., 2006). Oxalic acid accelerated the polymerization, but slowed down alite and belite hydration (Mazur et al., 2022).

2.9 Hydration of cement and cement containing SCM

The industrial adoption of new supplementary cementitious materials requires the understanding of their effects on the hydration and on the long-term properties of concrete, in order to adapt design and construction methods (Mejdi et al., 2022).

2.9.1 Cement Hydration

Water and cement interact in a process known as hydration. Cement becomes a rigid solid as a result of hydration, which increases the solid volume in cement paste. The reaction by-products, referred to as hydrates, provide cement its binding qualities and are in charge of developing strength (Bishnoi, 2008). The cement paste is heated by the extremely exothermic processes that occur during the hydration of Portland cement. When setting and early hardening occur, heat rapidly accumulates. As hydration slows, heat steadily falls and ultimately stabilizes. Because of this, 50% of the heat is produced in the first three days and 80% in the first seven days (Sánchez de Rojas Gómez & Frías Rojas, 2013; Soria, 1980).

The addition of water to OPC powder commences immediately with the cement hydration reactions. These series of chemical reactions result in the subsequent setting and hardening of the cement paste. Needle-like crystals of calcium sulfo aluminate hydrate, namely ettringite, are formed within a few minutes. The ettringite subsequently transforms to mono sulfate hydrate after a time. Two hours after the start of the cementation process, large prismatic crystals of calcium hydroxide (CH) and very small crystals of calcium silicate hydrates (C–

S–H) begin to fill the empty pores previously occupied by water and the hydrated cement particles (Saleh & Eskander, 2020). Therefore the major components of the hydrated cement paste are:

Calcium silicate hydrate: This is the most important hydration product and forms nearly 60% of the volume of solids. It is formed by a layer of sponge-like structures with a large high surface area (~500 m^2/g). The end product strength is largely contributed by the C–S–H formation and is attributed mainly by their van der Waals physical adhesion forces.

Calcium hydroxide: This is the second most abundant component with respect to the volume of solids and constitutes about 25%. It is formed of large plate-like crystals with a smaller surface area compared to C–S–H. It contributes to limited van der Waal binding forces and is relatively highly soluble compared to C–S–H, and renders the concrete reactive to acidic solutions.

Calcium sulfoaluminate: This has a minor role in the cementitious structure properties, and forms almost ~15% of the volume of solids. The chemical durability of the cementitious end product to sulfate attack is of concern, and this is attributed to the presence of the monosulfate hydrate.

The approximate hydration reactions between water and the cement components can be represented for each of the Portland cement major ingredient as follows. These equations are not stoichiometrically balanced due to the variations in the products formed and their compositions (Saleh & Eskander, 2020).

For C_3S: $C_3S+6H_2O \rightarrow C_3S_2.3H_2O+3Ca\ (HO)_2$ …………….......................... Equation 2.5

For C_2S: $C_2S+4H_2O \rightarrow C_3S_2.3H_2O+3Ca\ (HO)_2$ ………...…………………… Equation 2.6

For C_3A: $C_3A+6H_2O \rightarrow C_3A.6H_2O$ ……………………...………..………..… Equation 2.7

For C_4AF: $4C_4AF+2Ca\ (OH)_2+10H_2O \rightarrow C_3A.6H_2O+C_3F.6H_2O$ ………..….. Equation 2.8

It is clear that both silicates, C_3S and C_2S, need almost the same mass of water for hydration. However, calcium hydroxide resulting from C_3S hydration is more than twice that obtained from C_2S hydration (Saleh & Eskander, 2020).

2.9.2 Limestone –cement hydration

Thermodynamic calculations as well as experimental observations indicated that in the presence of limestone, mono-carbonate instead of mono-sulfate was stable. Thermodynamic modelling showed that the stabilisation of mono-carbonate in the presence of limestone indirectly stabilised ettringite leading to a corresponding increase of the total volume of the hydrate phase and a decrease of porosity. The measured difference in porosity between the "limestone-free" cement, which contained less than 0.3% CO_2, and cement containing 4% limestone, however, was much smaller than calculated (Lothenbach et al., 2008).

Numerous studies on the effect of limestone powder on Portland cement hydration have shown that the rate of C_3S hydration is enhanced by increasing the quantity and fineness of $CaCO_3$. This is because they produce a lot of nucleation sites for the precipitation of the hydration products (Thalada et al., 2022).

Early ages up to 7 days saw the improvement in degree of hydration. This, which is comparable to the finding of previous study, may be explained by the increased surfaces offered by the limestone for the precipitation of reaction products, which causes a large acceleration of the cement hydration in the filled systems (Bishnoi, 2008). Limestone cement was used because of its physical and chemical effects, which resulted in an increase in degree of hydration. While limestone fills the gaps between the cement particles as a result of the development of carbo-aluminate phases, replacement of 5–10% limestone is associated with an acceleration of the degree of hydration (Mohamed et al., 2015).

2.9.3 Fly ash—cement hydration

When water is added to FA blended cement, the cement hydration and pozzolanic reactions in FA–Portland cement–water mixtures do not proceed independently. The major effect of the cement on the pozzolanic reaction is the provision of the CH that reacts with the glassy silica to form the calcium silicate hydrate. In addition the alumina in the glass also forms calcium aluminate hydrate (CAH) or CASH in the presence of sulfates. The reactivity of the glassy phase depends upon both intrinsic and extrinsic factors, such as alkali content in solution. The mean degree of condensation of silicate in the glass phase of FA is larger than that of the slag and the dissociation rate of SiO_2 from the glass phase reacting with OH^- is generally lower than that of slag. The reactivity of FA is enhanced with increasing amount of glass and the basicity of glass phase and with decreasing degree of silicate condensation. In high-dosage FA blended cement, the hydration products at different stages and the formation of zeolites phase, viz., gismondine have been identified by impedance measurements (Q. Tang et al., 2016). Until 2 days, no evidence of fly ash reaction was measured and its influence on the hydration is mainly related to the “filler effect”. From 7 days on, the effects of the pozzolanic reaction were observed by the consumption of portlandite, the change of the pore solution chemistry, the formation of a presumably water-rich inner hydration product and the change of the C–S–H composition towards higher Al/Si ratio compared to the C–S–H of neat OPC. Additional strength due to the pozzolanic reaction developed after 28 days of hydration (Deschner et al., 2012).

The heat evolution profile of OPC is given in Fig. 2.2 A (Moghaddam et al., 2019). It can be divided into five parts: Stage 1: soon after cement comes in contact to water, the aluminate phase reacts with water with rapid heat evolution and combines with sulfate to form ettringite, surrounding the cement grains. Stage II: dormant or induction period, where the nuclei acquire critical size. Stage III: acceleration of hydration due to alite hydration, forming C-S-H and CH phases with a second peak. Stage IV: this is a deceleration stage and the hydration of alite phase decreases. In this stage the sulfate concentration starts diminishing and the remaining amount of aluminate interacts with ettringite to form monosulfate, which evolves a small amount of heat with a third hydration peak. Stage V: in this stage slow hydration occurs, belite hydrates slowly form C-S-H and C-H at a slow rate. Here the cement grains are covered with hydration products and the hydration becomes diffusion controlled.

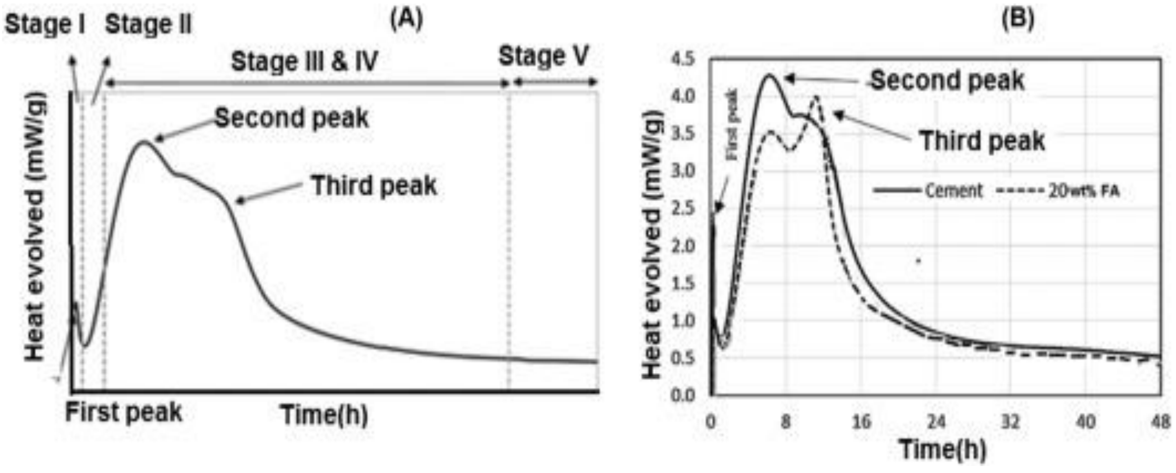


Figure 2.2 (A) Heat evolution during Portalnd cement hydration of (B) effect of 20 wt.% fly ash on heat of hydration of Portland cement (Moghaddam et al., 2019).

Effect of 20 wt.% FA on heat evolution during OPC hydration is given in Fig. 2.2 B (Moghaddam et al., 2019). In the presence of FA heat evolution is decreased. This may be due to a dilution effect. FA has low pozzolanic activity during the initial period of hydration and is chemically inactive up to 7 days.

2.9.4 Glass Powder- Cement Hydration

The hydration heat emission rate and hydration heat decrease gradually while the induction and acceleration period increase with the increase of GP content. According to Krstulovic-Dabic model, the hydration process of composite cementitious materials containing GP is controlled by a variety of complicated reaction mechanisms, which can be divided into three periods: nucleation and crystal growth (NG), phase boundary reaction (I), and diffusion (D). The NG and I process are shortened after incorporating GP (Chang et al., 2015).

Mortars with 10 and 20% GP replacements reach strengths equivalent to the control OPC mortar at the age of 56 days and above. The early age strengths (1 and 2 days of hydration) are also similar to the control, which suggests that the reaction rate of cement in GP blends is greater than that in the OPC system (Mejdi et al., 2022).

In the presence of GP, the time to reach the peak hydration rate is shortened, possibly because fine glass powders can accelerate the cement hydration via the adsorption of calcium ions from the liquid phase and play as nucleation and growth sites for C-S-H and other hydrates. At the same time, the high content of alkalis (Na_2O) in GP may act as catalyst in the formation of calcium silica hydrate at an early age (Jawed & Skalny, 1978; Khmiri et al., 2013)(Jawed et al. 1978; Khmiri et al. 2013). The time corresponding to the peak rate reduces from 418 minutes for OPC paste to 377 minutes for paste with 60% glass powder paste (Du & Tan, 2014).

2.9.5 Effect of iron in cement hydration

The hydration of blended cements with up to 70 wt% iron-rich slag was investigated by Hallet et al. (2022). Isothermal calorimeter revealed a retarding effect of the slag on Portland cement hydration during the first day, while from 2 days onwards the reaction extent of C_3S, C_3A and C_4AF increased. The slag reacted to 20-30% after 150 days resulting in AFm phases, as well as a new phase with a layered double hydroxide structure with (Mg + Fe)/Al around 3. Fe was also detected in the C-S-H phase of the blended cements, whereas no clear increase of Fe (III)-containing hydrates was observed. The Ca/Si atomic ratio of C-(A)-S-H in the blended cements decreased with increasing slag content, while the Al/Ca ratio increased only slightly (Hallet et al., 2022).

SEM study about the micro structure of cement mortar containing nanoparticles and ordinary cement mortar showed that Fe_2O_3 nanoparticles fills the pores completely and reduces the large crystals of $Ca(OH)_2$ and the hydrate products are denser and compact (Abdoli Yazdi et al., 2011). Strength increased strongly from 28 days onwards, showing significant contribution of the slag to compressive strength at later ages (Hallet et al., 2022).

2.10 Durability of Concrete

The most widely used and most resilient building material in the world is concrete. Compared to other construction materials, concrete requires less upkeep and repair (Tafheem et al., 2011). Durability and a long service life are sometimes used interchangeably. It is typical to add a broad reference to the environment when describing durability since durability under one set of conditions does not always imply durability under another. No material is naturally resistant to wear and tear; environmental interactions cause changes in the microstructure and, as a result, the characteristics of materials over time. When a material's qualities under certain conditions of usage have deteriorated to the point that its further use is deemed harmful or unprofitable, it is presumed that the substance has reached the end of its useful life (Swaroop et al., 2013). This contributes to the environmental value of this versatile building material. Concrete's durability will be determined by how well it is designed, detailed, and implemented to withstand abrasion, chemical assault, weathering action, and other degradation processes throughout the course of its intended service life. When exposed to the environment, durable concrete will maintain its original shape, quality, and functionality (ACI Committee 201, 2016).

When subjected to a variety of atmospheric conditions, the majority of waters and soils containing hostile chemicals, as well as many other types of chemical exposure, concrete will function properly. However, in some chemical situations, even the finest concrete will have a short usable life unless special precautions are followed. Pressure applied to one side of concrete makes it more susceptible than it would otherwise be because the pressure tends to shove the aggressive solution into the concrete. Exposure to sulfates, saltwater, salt from seawater, acids, and carbonation are the main areas of concern (ACI Committee 201, 2016).

2.11 Environmental Related Causes of Concrete Durability Problems

Durability problems related to environmental causes include the following: steel corrosion, delamination, cracking, carbonation, sulphate attack, chemical attack, scaling, spalling, abrasion and cavitation. Important degradation mechanisms in concrete structures include the following: Freeze-thaw damage, Alkali-aggregate reactions, Sulfate attack, Microbiological induced attack, Corrosion of reinforcing steel embedded in concrete carbonation of concrete and chloride induced, Abrasion, Mechanical loads (Swaroop et al., 2013).

2.12 Sulfate Attack

One of the most aggressive environmental deteriorations that affect the long-term resilience of concrete buildings is sulfate attack. Many civil engineering constructions exposed to sulfate environments, such as piers, bridges, foundations, concrete pipes, etc., are affected by the sulfate attack on concrete, which causes expansion, cracking, and degradation (Al-Akhras, 2006). One of the primary causes of the expansion and degradation of concrete structures is sulfate attack. Sulfate ion interactions with various hydration products in the concrete structure are thought to be the cause of this expansion (S. W. Tang et al., 2015). Most soils contain some sulphate in the form of calcium, sodium, potassium and magnesium. They occur in soil or ground water. Water used in concrete cooling towers can also be a potential source of sulphate attack on concrete. Therefore sulphate attack is a common occurrence in natural or industrial situations. Solid sulphates do not attack the concrete severely but when the chemicals are in solution, they find entry into porous concrete and react with the hydrated cement products. Of all the sulphates magnesium sulphate causes maximum damage to concrete (Swaroop et al., 2013).

The most commonly occurring salts for sulfate resistance tests are sodium sulfate (Na_2SO_4) and magnesium sulfate ($MgSO_4$), as these salts most commonly occur in the water and soil that surround the concrete structure. These cation types (Na^+ or Mg^{2+}) related to sulfate ions define the mechanism of attack and significantly influence concrete deterioration (Skalny et al., 2002).

2.12.1 Sulfate attack with Na_2SO_4

Sodium sulfate (i.e. sulfate ion) reacts with hydration products of cements, resulting in the formation of ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) and gypsum ($CaSO_4 \cdot 2H_2O$). The provision of Ca^{2+} ions, necessary for ettringite and gypsum formation, is supplied by portlandite (CH) or by decalcification of C-S-H gel. Decalcification of C-S-H gel affects the loss of bonding and it is very dangerous. Gypsum is usually formed under mortar/concrete surface. In this region, aluminium ions are primarily consumed for the formation of ettringite and, therefore, sulfate ions can react only with the remained calcium ions and form gypsum (Chabrelie et al., 2011).

2.12.2 Sulfate attack with $MgSO_4$

The interaction of ion species from MgSO4 solution and hydration products of cements gives M-S-H gel and brucite ($Mg(OH)_2$) in addition to gypsum and ettringite, which are common reaction products in both solutions (Na_2SO_4, $MgSO_4$). M-S-H gel does not have binding capacity. In the presence of brucite, decalcification of C-S-H gel is more prominent due to brucite low solubility (Mäkká et al., 2022). The saturated solution of brucite has a pH of 10.5, which is too low to maintain the stability of C-S-H, and the stability of calcium aluminate sulfate. The reaction of $MgSO_4$ with calcium hydroxide is also followed by the formation of brucite layer on the specimen surface and gypsum under it (Skalny et al., 2002).

Nosouhian et al, (2015) have carried out a research on the influence of magnesium sulfate concentration on durability of concrete. The results suggested that the 5% magnesium sulfate solution is considered to be the most deteriorating environment from the compressive strength reduction viewpoint, while the 14.7% magnesium sulfate solution is observed as the most severe environment from expansion aspect (Nosouhian et al., 2015).

2.13 Sources of sulfate

The sources of sulfate include Soils: It is a relatively slow process, because the sulphates have to be dissolved first, and in the case of the gypsum, it has slow solubility. Direct dry contact would not have an impact, but with the rain the process is accelerated, Sub-soil water: It would be the most aggressive situation, because there is direct contact, dissolved salts and capillarity, Water with salts (aerial): Generally occurs near the sea, Seawater: The sulphates are in solution, in direct contact with the concrete, so there is also a mechanical effect. However, concrete is protected by carbonation and the formation of brucite. The presence of sulphate and chloride ions decreases the aggressiveness of sulphates, Aggregates: Before the sulphate decomposition, an oxidation reaction must to take place and the sulphate has to migrate to the cementing paste. This process takes a long time to occur, others: For example, industrial waters would have sulphate ions in solution (Menéndez et al., 2018).

2.14 Types of Sulfate Attacks

The sulphate attack on cement concrete comprises two main categories internal and external sulphate attack (Nadir & Ahmed, 2022).

2.14.1 Internal Sulfate Attack

Since it was first discovered in the middle of the 1980s, the damage caused by an internal sulphate attack is relatively "new" in comparison to the "conventional" external sulphate attack. Two different mechanisms of Delayed Ettringite Formation (DEF) caused by internal sulphate attack (Ali, 2013). There are three conditions mentioned by Alwash (2005) for the internal sulphate attack to take place: (Ali, 2013; Alwash J.H., 2005).

Preliminary micro cracks are needed where deposition of ettringite crystals can occur, It occurs in a sulphate- free environment for the late sulphate release from gypsum-contaminated aggregate, sulfur- rich clinker phase and high- sulphate cement, It occurs in a moist environment favoring diffusion of SO_3 and other ions (Ca^{++} and aluminate) through water- saturated capillary pores (Ali, 2013; Alwash J.H., 2005).

2.14.2 External sulfate attack

The chemical reaction of a sulphate, which is present in rich soil or ground water, with the cement paste determines the external sulphate attack generated damage, which is the traditional sulphate attack. Soils containing sodium, potassium, magnesium and calcium sulphates are the main sources of sulphate ions in ground water. Therefore, the three following conditions must be fulfilled: High permeability of concrete, Sulphate- rich environment and Presence of water (Ali, 2013).

2.15 Mechanisms of sulfate attack

The two best recognized chemical consequences of sulfate attack on concrete components are the formation of ettringite and gypsum. The formation of ettringite can result in an increase in solid volume, leading to expansion and cracking. The formation of gypsum can lead to softening and loss of concrete strength (ACI Committee 201, 2016). The mechanism of sulphate attack on concrete involves two chemical reactions: combination of sulphate ions and hydrated calcium aluminate to form calcium-sulfoaluminate (ettringite) ($3CaO.Al_2O_3.3CaSO_43H_20$), and the combination of sulphate ions with calcium ions to form gypsum. The reaction of sulphate ions with the $Ca(OH)_2$ in the concrete to form gypsum is called acidic type of sulphate attack (Adetukasi et al., 2020).

$Ca (OH)_2 + Na_2SO_4 \longrightarrow CaSO_4 + 2NaOH$ (Gypsum) ………….………………… Equation 2.9

$Ca (OH)_2 + MgSO_4 \longrightarrow CaSO_4 + Mg(OH)_2$ (Gypsum brucite) ……………… Equation 2.10

The presence of ettringite or gypsum in concrete, however, is not in itself an adequate indication of sulfate attack; evidence of sulfate attack should be verified by petrographic and chemical analyses. When the attacking sulfate solution contains magnesium sulfate, brucite ($Mg(OH)_2$, magnesium hydroxide) is produced in addition to ettringite and gypsum. Some of the sulfate-related processes can damage concrete without expansion (ACI Committee 201, 2016). The $CaSO_4$ precipitates as $CaSO_4.2H_2O$ (secondary gypsum). The high concentration of sodium chloride (NaCl) in sea water increases the solubility of gypsum and prevents its rapid crystallization. It also increases the solubility of $Ca(OH)_2$ and $Mg(OH)_2$. The result is leaching of these compounds which make the concrete weak. The second type of attack mainly results from the chemical reaction between the tricalcium aluminate (C_3A) present in Portland cement and sulphate ions supplied by the aggressive environment. By this reaction, ettringite is formed. The chemical reaction can be represented as: (Adetukasi et al., 2020).

$MgSO_4+[Ca(OH)_2+3CaO.Al_2O_3.CaSO_4.18H_2O] \longrightarrow Mg(OH)_2+Ca).Al_2O_3.3CaSO_4.32H_2$ ……………………………………………………………………………………….Equation 2.11

$Na_2SO_4+ [Ca (OH)_2+3Ca).Al_2O_3.CaSO_4.18H_2)] \longrightarrow 2NaOH + 3CaO.Al_2O_3.3CaSO_4.32H_2O$ ……………………………………………………………………………… Equation 2.12

The reaction products, i.e. gypsum and ettringite have greater volume than the compounds they replace. The increase in volume due to gypsum has been reported to be more than double the original volume and that due to expansion causes cracking of the matrix, which leads to the loss in strength and disruption. Marine sulphate attack leaves the concrete soft and brittle. The leaching of compounds and softening of concrete due to sulphate attack are further aggregated by the presence of chlorides in seawater (Adetukasi et al., 2020).

2.16 Cement Production and the Environment

2.16.1 Energy consumption

Energy use is the main environmental problem with the production of cement and concrete. The production of cement is one of the energy-intensive industrial manufacturing processes. A total of 1,758 kWh of direct fuel are needed for every ton of cement produced, including fuel for mining and transporting raw materials. The sector produces a lot of CO_2, nitrous oxide, and sulphur emissions because of its heavy reliance on coal. A significant portion of the power consumed is produced from coal (Babor et al., 2009).

Cement industry is one of the most energy intensive industrial sub-sectors. It accounts for almost 15% of the total energy consumed by manufacturing (Mokhtar & Nasooti, 2020). The grinding of the raw materials consumes roughly 26% of the total electrical power utilized throughout the cement production process. The rotary burner's energy is used up throughout the grinding operation. The grinding of coal, raw materials, and clinker uses around 65% of the cement plant's total electrical energy (Atmaca & Kanoglu, 2012). The great majority of the energy used to produce cement is used to operate the rotary cement kilns. Dry-process kilns are more energy-efficient than earlier wet-process kilns because energy is not required to drive out moisture. Modern dry-process kilns commonly use waste heat from the exhaust gases of the kiln burners to warm the materials in a pre-heater (Babor et al., 2009).

2.16.2 Emissions from Cement Industry:

Due to the "high volume process" of cement production, sufficient supplies of raw materials, thermal fuels, and electrical power are needed (Devi et al., 2017). The main environmental impacts of the manufacture of cement in general are related to the following categories as:

1. **Carbon dioxide Emissions**

When cement is produced, carbon dioxide emissions come from two very distinct sources. The greatest source is burning fossil fuels to run the rotary kiln, which emits around 3/4 t of CO_2 every ton of cement. In the cement kiln, the chemical conversion of limestone to lime also generates CO_2. Combining these two sources, for every ton of cement produced, 1.25 t of CO_2 is released into the atmosphere. Worldwide, cement production now accounts for more than 1.6×10^9 t of CO_2 emissions from all human activities (Babor et al., 2009).

The emission sources at different stages of the product life cycle process are: The combustion of fossil fuel in the clinkering process to heat the raw material of limestone ($CaCO_3$) produces CO_2 at temperatures exceeding 1450°C, the calcination process (raw material conversion) in cement production process also generates a significant amount of CO_2 and indirect emission from transportation and delivery of raw materials and finished goods (Hendriks et al., 2004).

2. **Dust: Dust**

The primary sources of emissions are the cement mills, clinker cooler, kiln system, and raw mills. The fact that hot exhaust gas or exhaust air is passing through pulverized material to create an intricately distributed combination of gas and particles is a common characteristic of these process processes. The nature of the particulates generated is linked to the source material itself, that is, raw materials (partly calcined), clinker or cement (Karstensen, 2006).

Table 2.5 Types of dust and their generation causes at cement plants (El-Fadel et al., 2004)

Type	**Generation mechanism**
Raw material dust	Quarrying, crushing and handling of raw material
Feed material	dust Feeding, milling, stacking, blending, reclaiming, conveying, and transferring of feed material
Cement kiln dust	Feeding and processing of materials involving counter current circulation of hot gases
Clinker dust	Cooling involving air circulation and open-storage of clinker
Cement dust	Feeding, milling, conveying, bagging and loading of cement materials

3. **Noise**

The preparation and processing of raw materials, the burning of clinker, the production of cement, the storage of materials, as well as the dispatch and transportation of the finished goods, all contribute to noise emissions throughout the whole cement manufacturing process (Hadži-Nikolova et al., 2019). The heavy machinery and large fans used in various parts of the cement manufacturing process can give rise to noise and/or vibration emissions, particularly from: chutes and hoppers, any operations involving fracture, crushing, milling and screening of raw material, fuels, clinker and cement; exhaust fans; blowers; duct vibration (Mishra & Siddiqui, 2014).

4. Bad Odour

Odour emissions from a well-run facility are seldom a concern, although they may be primarily linked to emissions from the processing and storage of conventional or alternative fuels. In unusual circumstances, the presence of nitrogen compounds in the raw materials may result in ammonia emissions, which, even at low quantities, may produce odours (Karstensen, 2006).

2.16.3 Environmental & Health Impacts

The cement industry uses a lot of energy and significantly contributes to global warming. Emissions to the air and energy usage are the main environmental, health, and safety concerns related to cement manufacturing. Massive amounts of fossil fuels and non-renewable raw materials are needed to make cement. According to estimates, the manufacture of cement accounts for 5-6% of all the carbon dioxide greenhouse gases produced by human activity (Mishra & Siddiqui, 2014). The environmental impact of air pollution from cement manufacturing is quickly spreading around the world. Scholars share the belief that there is a connection between pollution from cement factories and the problem of health impairment on communities nearby. These emissions have negative effects on humans and the environment, with serious consequences for human health and the sustainability of the ecosystem (Devi et al., 2017).

Cement manufacturing is a highly energy intensive process, which involves intensive fuel consumption for clinker making and resulting in emissions. Beside Fuel consumption, the calcining process is a major source of emissions such as NOx, SOx, CO_2, particulate matters etc. These emissions are not only deteriorating air quality but also degrading human health. Scientific evidence indicates that air pollution from the combustion of fossil fuels causes a spectrum of health effects from allergy to death (Mishra & Siddiqui, 2014).

2.17 Research Gap

Previous researchers conducted a variety of studies on ferrock concrete as full and partial substitutions for cement, despite the current knowledge on ferrock concrete there are limitations on the studies of the effect of oxalic acid in strength development and durability of partial replacement of cement with ferrock and durability of ferrock based concrete under external sulfate attack. The effect of admixtures such as oxalic acid on the strength development and durability of the use of ferrock cement as partial cement replacement are not studied. This study examines the physical properties of aggregates that are used to make concrete, mechanical strengths such as compressive and flexural strength of ferrock based concrete with and without oxalic acid. Durability of ferrock based concretes against sulfate-attack on specimens that are totally submerged in 5% sodium sulfate solutions are studied using the mass loss method, to compare them with the control C-25 concrete. Also environmental and economic analysis is done to better understand the effect of ferrock on the environment and economy.

A number of researchers throughout the world have studied the methods for replacing cement with ferrock based concrete. Concrete made from ferrock can be stronger and help cut reduce greenhouse gas emissions. However, because of the higher cost of iron particles and oxalic acid, ferrock concrete has a higher initially cost than normal concrete. To reduce the initial cost of ferrock-based concrete, cast iron powder wastes from torno houses in Adama city were used in place of iron powder in this study. The effects of adding ferrock cement into the concrete mix were also investigated in terms of workability, strength, water absorption, microstructure, and durability against sulfate attack, environmental and economic aspects.

On the other hand, there is no literature on the use of ferrock cement as cement replacement in concrete production in Ethiopia. Therefore, this study was conducted to fill these gaps and thereby to generate evidence on the effect of the level of replacement cement with ferrock cement (0 to 20%) on the performance of concrete, which the country is consuming in a large amount, with respect to workability, strength and durability.

CHAPTER 3

3 MATERIALS AND METHODS

3.1 Methodology

3.1.1 Research Approach and Design

This specific research is designed as experimental type of research which is based on both qualitative and quantitative research approach. The primary data for this research were the results obtained from the experimental investigation. The results of the experiment were the workability of fresh concrete, Durability, flexural and compressive strength of hardening concrete. Published books, standards and journals will be considered as secondary data as evidence for the purpose of collecting the required information.

3.1.2 Study design

This research used an experimental research design method to investigate the effect of partial replacement of cement up to 20% with ferrock on properties of C-25 concrete and find to what percentage value it can be used without compromising the mechanical strengths of concrete and durability against sulfate attack. The study was made by conducting different experimental works on the properties of materials and test on the end result of the concrete specimen. The properties of the materials for the concrete were studied in order to verify the suitability of the materials for the concreting work. The concrete was prepared by the weight of cement partially replaced with ferrock by different proportions and keeping the other ingredients constant.

The stages involved in the study include:

1. Collecting samples
2. Preparation of samples for each laboratory test
3. Laboratory test on cement, fine and coarse aggregate for development of mix design
4. Casting of concrete molds
5. Curing of concrete samples
6. Laboratory test on concrete samples

3.1.3 Study Area

Adama city is a city in the central Oromia Region of Ethiopia, located in the East Shewa Zone 99 km southeast of Addis Ababa. It is located at 8° 33′ N latitude and 39° 16′ E longitude. The city is suited in Rift Valley, on flat terrain characteristics and surrounded by mountains and ridged topography. Adama city sits between the base of an escarpment to the west, and the Great Rift Valley to the east.

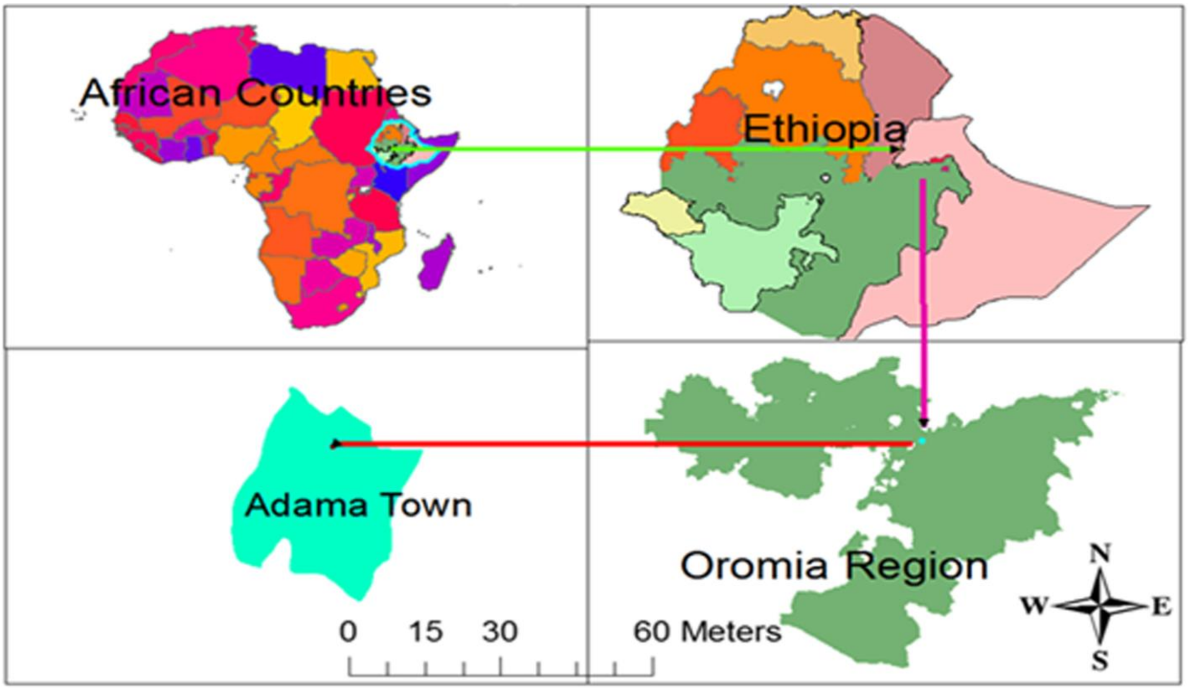


Figure 3.1 Map of the study area, Adama town

3.2 Materials

The characteristics of ferrock and C25 concrete making materials that will be used for the research will be examined and appropriate mix design will be used

Table 3.1 Summary of materials used in the study

Materials used in the study	
Cement	Fly ash
Coarse Aggregate	Limestone Powder
Fine Aggregate	Crushed glass powder
Water	Oxalic acid
Cast Iron powder	

3.2.1 Cement

For this research, Ordinary Portland cement (OPC) – National cement brand 42.5N is bought from the available market at Adama city used for concrete production. The same type of cement was used for all the trial mixes and the amount added per mix was kept constant. The specific gravity of Type 1 cement is 3.15.

3.2.2 Coarse aggregate

According to ASTM C33, coarse aggregate consists of crushed stone with particle size of 4.75mm and above. Coarse aggregate is used in concrete to provide strength and durability. The normal weight coarse aggregates for the Ethiopian construction sector are produced by both, traditional and modern means. Traditionally coarse aggregate is produced by heating a boulder at a higher temperature and crushing it by a hammer using a manual labour to the required approximate sizes. Aggregates produced using such method are usually flaky and do not satisfy the grading requirements set by standard recommendations. On the other hand, the modern way of aggregate production requires aggregate crushing machines so that the quarry is either drilled, blasted or dug with special mechanisms, fed to crushers, crushed, sieved and separated according to their sizes. This method enables to classify aggregates based on their maximum aggregate sizes and enable engineers to suggest unique mix proportion to arrive at the required concrete quality production (Dinku, 2005). The coarse aggregate used in the experimental investigation was crushed rock from the available market in Adama city.

Figure 3.2 Prepared Coarse aggregate

3.2.3 Sand

According to ASTM C33, aggregates which are less than 4.75mm are designated as sand and retained by 0.75mm. For this study, locally available well graded river sand was used as a fine aggregate. The major sand supply for the construction works in and around Adama is the Awash basin located about 20-40 km southeast of the city. The method of quarring sand is generally very old and the producers do not attempt to clean and grade the sand right from the source.

Figure 3.3 Fine aggregate

3.2.4 Water

A crucial component of concrete is water. A portion of the water used for mixing is used in the hydration of cement, and the right amount of water is needed to give concrete its desired workability. The quantity and quality of water must thus be carefully considered. Since chemicals that are present in water cause concrete to lose some of its strength and durability. Normal tap water supplied by Adama City Water and Sewerage Authority found in the laboratory area was used for concrete mixing.

3.2.5 Cast iron powder

Major constituent of ferrock is the iron powder which is obtained from the wastes of steel industries and mines which in-turn does a waste management and it doesn’t sum up on to the carbon dioxide content in the atmosphere during its manufacturing process. Iron powder is examined and stated that they are elongated and angular in shape. However, the large surface area helping it to provide greater reactivity (Sumanta et al., 2014). Iron powder is the waste product from steel mills during scrap steel processing from other industries through shot blasting. It is having a specific density of 2.8 g/cm^3, containing Fe metallic particles to the extent of 93% (Nadir et al., 2022).

The iron powder for this thesis is obtained from Torno houses located in adama city; the powder is extracted from shavings of automotive brake disk done in the torno houses. Iron powder used passing 75μm sieve and retained on the pan was used as a powder which acts as a cement replacement agent.

Figure 3.4 Cast iron powder collected and sieved from torno house

Cast iron is one of the oldest ferrous metals in commercial use. It is primarily composed of iron (Fe), carbon (C) and silicon (Si), but may also contain traces of sulfur (S), manganese (Mn) and phosphorus (P). It has a relatively high carbon content of 2% to 5% (Prakash Suryawanshi et al., 2019).

Table 3.2 Chemical composition of Cast iron (ASTM A247-10, n.d.)

Chemical Composition	Typical range* (%)
Fe	>93%
C	2.5%-4%
Si	1%-3%

3.2.6 Fly ash

Fly ash is a fine powder which is a by-product from burning pulverized coal in electric generation power plants. Fly ash is a pozzolan, a substance containing aluminous and siliceous material that forms cement in the presence of water. When mixed with lime and water it forms a compound similar to Portland cement (A Baikerikar, 2014). Use of fly ash concrete reduces CO_2 and is thus environment friendly. It has good cold weather resistance and non-shrink material. Based on this class F fly ash passing 75µm sieve and retained on the pan was used as a powder which acts as a cement replacement agent.

Figure 3.5 Coal ash (Fly Ash) collected from AIKA Addis Textile factory

As shown in Table 3.2, the sum of the first three constituents (SiO_2, Al_2O_3, and Fe_2O_3) of coal ash collected from AYKA is greater than 70% which indicates that the sample fly ash classified as an ASTM Class F fly ash. As per ASTM C-618 recommendation LOI of the given fly ash should be below 12 so as the sample fly ash.

Table 3.3 Chemical composition Coal ash (Kifle, 2019)

Chemical composition	**AYKA fly ash**
SiO_2	52.54
Al_2O_3	34.66
Fe_2O_3	1.34
CaC	0.16
MgO	0.01
Na_2O	1.08
K2O	0.01
MnO	0.01
P_2O_5	0.01
TiO	0.55
H_2O	1.25
LOI	6.85
$SiO_2+Al_2O_3+Fe_2O_3$	88.54
Classification	**Class F**

3.2.7 Limestone Powder

Addition of limestone powder provides easier grind ability, reduced water demand, increased strength and less bleeding in concrete. Limestone due to its reactive nature provides nucleation sites for clinker hydration products, and reduces heat of hydration. Addition of limestone will improve workability (Shivani et al., 2022). Limestone powder used in this research is prepared by grinding raw limestone collected from Habesha cement Factory and passing 75mm sieve and retained on the pan was used as a powder which acts as a cement replacement agent.

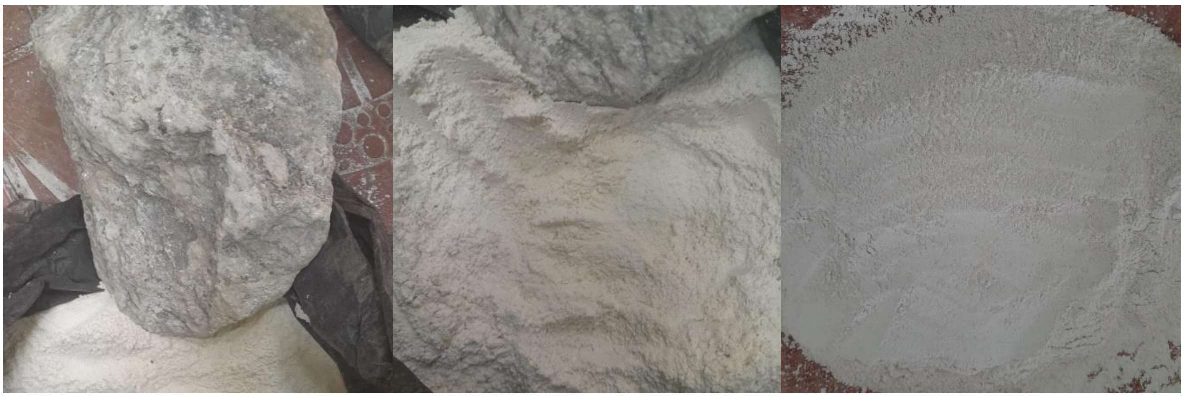


Figure 3.6 Limestone collected from Habesha Cement Factory

Limestone powder used in this research is prepared by grinding raw limestone collected from Habesha cement Factory and passing 75µm sieve and retained on the pan was used as a powder which acts as a cement replacement agent.

Table 3.4 Chemical composition of limestone powder (Thalada et al., 2022)

Chemical composition	**Limestone Powder (%)**
$CaCO_3$	93.75
SiO_2	2.58
Fe_2O_3	0.12
Al_2O_3	1.03
CaO	53.16
MgO	0.4
SO_3	-
K_2O	-
Na_2O	-
LOI	41.76

3.2.8 Crushed glass powder

Waste glass powder was used, which is produced from colour less bottles that are mostly known as soft drink bottles. These bottles were collected from restaurants in Adama city. The collected bottles were washed and cleaned to remove paper labels and dust or any undesired materials. After drying, they were crushed manually by hummer and then grinded with hand passing 75µm sieve and retained on the pan was used as a powder which acts as a cement replacement agent.

Table 3.5 Chemical composition of glass powder (Du & Tan, 2014).

Compositions	**Glass Powder**
SiO_2	72.08
Al_2O_3	2.19
Fe_2O_3	0.22
CaO	10.45
MgO	0.72
SO_3	-
Na_2O	13.71
K_2O	0.16
TiO_2	0.1
Cr_2O_3	0.01

Figure 3.7 Crushed glass powder

3.2.9 Oxalic acid

Oxalic acid is a weak organic alpha, omega-di carboxylic acid having formula $C_2H_2O_4$ or $(COOH)_2$. It is broadly used as a cleaning agent, like weak acid, e.g. vinegar, to remove stains from different surfaces. Its use in ferrock-based concrete as a catalyst increases the reaction for increased formation of $FeCO_3$, cost-benefit analysis versus strength achievement suggests using oxalic acid in the range of 2% of binder quantity (Prashanth et al., 2019). Oxalic acid is a weak acid and is reported to act as an accelerator for cement hydration reaction. This may also be helpful in the formation of a protective electrical double-layer film around the cement particle during gel state (Shivani et al., 2022).

3.3 Research Methods

In material research, a method is a logical, well-thought-out plan for conducting experimental studies. This study uses both qualitative and quantitative research methods to interpret and discuss the research output. The research design being employed was an experimental research design. This section clearly outlines the research procedures employed and the type of test conducted to accomplish research objectives. The experimental test results were analysed by Excel. The results of the analysis were presented in the form of tables, graphs, and charts. The experiments were conducted in Adama Science and Technology University.

The main target of this study is to produce ferrock cement concrete and asses the fresh concrete properties, durability and mechanical properties in the hardened state. Literature review reading was made for providing understanding of ferrock concrete focusing on its mechanical properties, fresh properties, durability, mix design considerations, placing and finishing. The currently available and modified test methods used to evaluate the compressive and flexural strength of ferrock concrete were studied. Material collection was made after the literature review has been made.

3.3.1 Tests on cement

3.3.1.1 Normal consistency taste

ASTM C187 Standard Test Method for Amount of Water Required for Normal Consistency of Hydraulic Cement Paste, The normal consistency of hydraulic cement was checked to know the amount of water required to make a neat paste of satisfactory workability. It is determined using Vicat apparatus. This apparatus measures the resistance of the paste to the penetration of a plunger or needle of 300gm released at the surface of the paste. This performed according to ASTM C187.

1. A 500 g cement sample with a measured quantity of clean water is thoroughly mixed with in 3 min. by means of a trowel.
2. Quickly form the cement paste in the approximate shape of the ball with gloved hand by tossing 6 times from one hand to another through a free path of about 6 in. (150 mm) so as to produce a neatly spherical mass that may be easily inserted in to the vicat ring mold.
3. Immediately after filling the mold, level the paste and lower the plunger gently and bring it in contact with the surface of the paste
4. Tighten the screw setting the movable indicator to the upper zero mark of the scale and release the plunger immediately.
5. Thirty seconds after releasing the plunger record its penetration.
6. The paste is said to be of normal consistency when the rod settles 10±1 mm below the original surface within thirty seconds.
7. Repeat the above procedures varying the proportion of water until a paste of normal consistency is obtained.
8. The amount of water required for normal consistence is then expressed as a percentage by weight of the dry cement.

Figure 3.8 Taste for normal consistency of cement paste using vicat apparatus

3.3.2 Testes for Fine Aggregate

A. Silt Content of Fine Aggregate

Sand often contains dust, silt, clay, and loam. Sand containing such particles weakens concrete's compressive strength and short-term resilience. Testing sand's silt concentration and comparing it to allowed limits is therefore crucial. Finding out how much silt existed within the sand is the main objective of this test. For this experiment, sample sand, clean water, a graduated jar, a spoon, a dish for taking a sand sample, and a funnel were used. The following are detailed procedures that were followed based on (ASTM C 117).

Test Procedure for Silt Content

1. The researcher took a graduated cylinder having a capacity of 1000 ml.
2. 300 ml of sand was poured into the cylinder.
3. Approximately 3/4 of the jar was filled with water.
4. The jar was shaken vigorously for about a minute.
5. The jar was left for an hour to allow the silt to settle on the layer of sand.
6. The amount of fine forming a separate layer on the top was measured.
7. The silt content was calculated based on Equation (3.1).

$$\text{Silt content} = \frac{\text{silt deposited above the sand}}{\text{Deposit of clean sand}} * 100 \quad \text{……...……………...……..…… Equation 3.1}$$

Figure 3.9 Taste for silt content of sand

B. Sieve Analysis (Gradation Taste) of Fine Aggregate

The process of sieving granular material through a succession of sieves with successively decreasing mesh sizes and weighing the quantity of material retained in each sieve as a percentage of the total mass is known as sieve analysis. This method is used to determine the particle size distribution of granular material. Hence, the aim of this test was to determine the fineness modulus of fine aggregate with the help of a series of IS sieves having (4.75 mm, 2.36 mm, 1.18 mm, 0.6mm, 0.3 mm, 0.15, and pan) sizes from top to bottom, respectively, 500 g of fine aggregate, balance, sieve shaker, shovel, and sieve brush. The test procedure was in accordance with (ASTM C136). The range of fineness modulus is between 2.3 to 3.1 (ASTM C33).

Taste procedure for gradation of fine aggregate

1. The researcher weighted a sample of 2 kg of fine aggregates.
2. The sample was quartered
3. From the quartered sample, weighing 500 g
4. The empty sieves were weighted, and the data was recorded properly
5. The pan was placed on the bottom and the other sieves were put on the pan with increasing opening sizes of the sieves.
6. Placed the 500 g of sample on the top of the sieves (having a larger opening size).
7. Smashed the sample for about l0 minutes in a sieve shaker.
8. Each sieve, together with the aggregate retained on it, was measured and the weight retained on each sieve was calculated.
9. The gradation chart was filled in and the fineness modulus was computed.

$$\text{Finess modulus} = \sum \frac{\text{Cummulative \% of retained by mass}}{100} \quad \text{.................................} \text{ Equation 3.2}$$

Figure 3.10 Sieve analysis taste for fine aggregate

C. Unit Weight of fine aggregate

Unit weight also known as bulk density and conducted according to ASTM C 29; the unit weight of the fine aggregates is between 1280 to 1920 kg/m which helps to determine the weight of sand in a given volume of graded sand.

Taste procedure

1. Fill the measure one-third full and level the surface with your fingers. Rod the layer of aggregate with 25 strokes with the tamping rod evenly distributed over the surface. Then fill measure to two-thirds capacity, level and rod as before. Finally, fill the measuring cup to overflowing and rod as above.
2. Level the surface of the aggregate with your fingers in such a way that any slight projections of the large pieces of the coarse aggregate approximately balance the larger voids in the surface below the top of the measure.
3. When roding the first layer, do not allow the rod to strike the bottom of the measure forcibly. In roding, the second and third layers use only enough force to cause the taping rod to penetrate the previous layers of aggregate.
4. The fine aggregate was weighed and the data were recorded as follow:

$$\text{Unit weight} = \frac{A-B}{C}$$ ……………………………………………………...…..…. Equation 3.3

Where: A - Weight of sample + cylinder = 6.922g

B - Weight of cylinder = 4.734 g

C - Volume of cylinder = 0.001375 m^3

D. Specific gravity and Water Absorption of Fine Aggregate

According to ASTM C 128, the bulk specific gravity of fine aggregates ranges between 2.6 to 2.8. Due to the time that this research is under taken was rainy time it was must to identify the water absorption and moisture content carefully. According to ASTM C 128 to test the increase in weight of aggregate due to water in the pore of the material so the water absorption of the material must be tested. Absorption is a measure of the total pore volume accessible to water. It's also useful for mix design moisture adjustment.

Preparation of test specimen:

1) Approximately 1 kg of the fine aggregate was prepared.
2) At 110°C, the sample was dried to a constant weight in a suitable pan. Allow it to cool for 24 hours and then make it saturated.
3) The excess water was decanted with care to avoid loss of fines, spreading the sample on a flat, non-absorbent surface exposed to a gently moving current of warm air.
4) The sample was stirred frequently to get homogeneous drying until achieving the saturated surface dry condition by using the cone test for surface moisture.
5) Hold the mold firmly on a smooth, non-absorbent surface with a large diameter. Placed a portion of partially dried fine aggregate loosely in the mold by filling it to the brim and heaping additional materials above the top of the mold.
6) Lightly tamp the sand into the mold with 25 light drops of the tamper about 5 mm above the top surface of the sand.
7) The surface was adjusted by removing loose sand from the base and lifting the mold vertically. If surface moisture was still present, the sand would retain the molded shape. When the sand slumped slightly, it indicated that it had reached S.S.D. condition.

Procedure:

1. The S.S.D sample was weighted at 500g
2. Partially fills the Pycnometer with water and put 500 g of saturated surface dry aggregates into the Pycnometer.
3. Then they filled the pycnometer with additional water to fill it to 90% of its capacity.
4. The pycnomneter was rolled and inverted to eliminate all air bubbles.
5. Place the Pycnometer in a water bath at 23 °C for an hour.
6. Brought the water level in the pycnometer to its calibrated capacity.
7. Then, the total weight of the pycnometer, specimen, and water was measured.
8. The researcher removed the fine aggregate from the pycnometer, dried it to a constant weight at 105 °C, cooled it in room temperature air for one hour, and measured it.
9. The weight of the pycnometer filled to capacity with water was determined at 23°C, and the following data were recorded:

A - Weight of the sample, SSD = 500g

B - Weight of pyconometer + water = 1590g

C - Weight of pyconometer + water + sand to calibration mark = 1902g

D - Weight of oven dried sample on air = 495 g

$$\text{Bulk specific gravity } (SSD) = \frac{\text{A}}{(\text{A+B−C})} \quad \text{………………………..…………..… Equation 3.4}$$

$$\text{Aparent specific gravity } = \frac{\text{D}}{(\text{B+D−C})} \quad \text{…………………………………..…..… Equation 3.5}$$

$$\text{Absorption, \%} = \frac{(\text{A−D})}{\text{D}} * 100 \quad \text{………………………….……………..…… Equation 3.6}$$

3.3.3 Tastes for Coarse Aggregate

a) Sieve Analysis of Coarse aggregate

The local quarry's coarse aggregate should be graded in order to identify the distribution of its particle sizes Hence, the aim of this test is to determine the fineness modulus of coarse aggregate with the help of apparatus like a series of IS sieves of Sizes (25mm, 19 mm, 12.5 mm, 9.5 mm, 4.75 mm, and pan) from top to bottom, respectively, 5,000 g of coarse aggregate, a balance, sieve shaker, shovel, and sieve brush. Gradation test was performed as per ASTM C136. 25 mm nominal maximum aggregate size was taken to conduct this study.

Procedure for sieve analysis for Coarse Aggregate

1) 20 kg of coarse aggregates were weighed.
2) From the quartered sample, 5 kg was taken.
3) A representative sample was selected by quartering.
4) The empty sieves were weighted and the data was recorded properly.
5) Placed the 5 kg of sample on the top sieves (which have a large opening size).
6) Smashed the sample for about 10 minutes in a sieve shaker.
7) Each sieve, together with the aggregate retained on it, was measured and the weight retained on each sieve was calculated.
8) The gradation chart was filled in and the fineness modulus was computed. The range of fineness modulus of coarse aggregate according to ASTM C33 is 5.5 -8.

$$\text{Finess modulus} = \sum \frac{\text{Cummulative \% of retained by mass}}{100} \quad \text{…………..……..……… Equation 3.7}$$

Figure 3.11 Sieve analysis taste for coarse aggregate

b) Unit Weight, Specific Gravity, and Water Absorption of Coarse Aggregate

Specific gravity and water absorption capacity of coarse aggregate are determined based on (ASTM C127) standard. The unit weight of aggregate ranges from 1200 to 1 1750 kg ASTM C29.

1. Fill the measure one-third full and level the surface with your fingers. Rod the layer of aggregate with 25 strokes with the tamping rod evenly distributed over the surface. Then fill the measure to two-thirds capacity, level and rod as before. Finally, fill the measuring cup to overflowing and rod as above.
2. Level the surface of the aggregate with your fingers in such a way that any slight projections of the large pieces of the coarse aggregate approximately balance the larger voids in the surface below the top of the measure.
3. When roding the first layer, do not allow the rod to strike the bottom of the measure forcibly. In roding, the second and third layers use only enough force to cause the taping rod to penetrate the previous layers of aggregate.
4. The coarse aggregate was weighted, and the data was recorded as follows.

A - Aggregate plus cylinder weight = 6.952 kg

B - Weight of the empty cylinder = 4.734 kg

C - Volume of the cylinder (m) =0.001375 m^3

The unit weight of coarse aggregate can be computed by using Equation 3.3 above

Test Procedures

1) The researcher took the sample of coarse aggregate by using the sample splitter.
2) The sample was sieved w with a 4.75 mm sieve, and the sample passing through the 4.75 mm sieve was ignored.
3) The sample was washed to remove dust.
4) Put the sample in the oven at 105°C for 24 hours.
5) The sample was taken out of the oven, left to cool, and then the weight was measured.
6) The sample was submerged in water for 24 hours.
7) The researcher removed the sample from the water and rolled ít in a large absorbent cloth until all visible films of water were removed.
8) The required weight of the sample in its (S.S.D) condition was taken.
9) The researcher immediately placed the S.S.D sample in the sample container, determined the weight in water at 23 °C, and recorded the data.

Oven dry weight (ODW) = 4966gm

Weight of saturated surface dry sample on air (SSD in air) = 5000 g

Weight of saturated surface dry sample in water (SSD in water) = 3215g

$$\text{Bulk specific gravity (SSD)} = \frac{(\text{SSD in air})}{(\text{SSD in air})-(\text{SSD in water})} \quad \text{Equation 3.8}$$

$$\text{Aparent specific gravity (SSD)} = \frac{(\text{ODW})}{(\text{ODW})-(\text{SSD in water})} \quad \text{Equation 3.9}$$

$$\text{Water absorption} = \frac{(\text{SSD})-(\text{ODW})}{(\text{SSD})} * 100 \quad \text{Equation 3.10}$$

3.3.4 Mix Design

Mix design is the process of proportioning concrete mixtures. It is a suitable method to determine the ingredients in concrete. For this particular project sufficient number of data sample were used to ensure the accurate and representative result. ACI 318 states a strength test as the average strength of three specimens of the same age fabricated from the sample taken from the single batch of the concrete for normality check. 108 data samples were casted and tested for compressive strength test by partially replacing cement using ferrock with and without the addition of oxalic acid up to 20% by mass of cement including the control mix. Out of 108 data samples 48 of them contain Oxalic acid as an accelerator, 12 of them are control and the rest does not contain oxalic acid they are all cured with normal tap water.

Table 3.6 Mix code designation

Mix' s	Mix code designation
Mix 0%	Control mix or no addition of ferrock
WOMix 5%	5% replacement of cement by ferrock without oxalic acid
WOMix 10%	10% replacement of cement by ferrock without oxalic acid
WOMix 15%	15% replacement of cement by ferrock without oxalic acid
WOMix 20%	20% replacement of cement by ferrock without oxalic acid
WMix 5%	5% replacement of cement by ferrock with 2% oxalic acid
WMix 10%	10% replacement of cement by ferrock with 2% oxalic acid
WMix 15%	15% replacement of cement by ferrock with 2% oxalic acid
WMix 20%	20% replacement of cement by ferrock with 2% oxalic acid

3.3.4.1 Material proportioning

The ACI Method of concrete mix design will be used to design one control group of C-25 grade of concrete. Standard cast iron moulds of size 150*150*150mm will be used in the preparation of concrete cubes for compressive strength tests and specimens with dimensions of 100*100*500mm will be used to measure flexural strength. The materials in this research were proportioned and their weight were determined (see appendix 2).

The material proportions used to conduct this study. Table 3.7 indicates the estimates ingredients for meter cube of C-25 concrete and Table 3.8: described the quantity of material used to prepare the sample for the study.

Table 3.7 The estimated ingredients for production of meter cube of C-25 concrete

Water	185.74 kg/m^3
Cement	393.07 kg/m^3
Fine Aggregate	782.26 kg/m^3
Coarse Aggregate	1066.5 kg/m^3

Table 3.8 Quantity of materials in kg for different percentage replacement of ferrock

% replacement of ferrock	Cement (kg)		Fine aggregate (kg)	Coarse aggregate (kg)	Water (kg/)
	OPC	Ferrock			
Per 0.5427 m^3	213.32	0	783.26	1066.5	185.74
WOMix 5%	202.65	10.67	425.08	578.79	100.80
WOMix 10%	191.99	21.33	425.08	578.79	100.80
WOMix 15%	181.32	32.00	425.08	578.79	100.80
WOMix 20%	170.66	42.66	425.08	578.79	100.80
WMix 5%	202.65	10.67	425.08	578.79	100.80
WMix 10%	191.99	21.33	425.08	578.79	100.80
WMix 15%	181.32	32.00	425.08	578.79	100.80
WMix 20%	170.66	42.66	425.08	578.79	100.80

3.3.4.2 Ferrock mix proportions

The composition of ferrock was concluded as 60% iron powder, 20% flyash, 10% metakaolin, 8% limestone, 2% oxalic acid in terms of rheological characteristics (Shivani et al., 2022). For this experimental study metakaolin is replaced by crushed up glass powder (Dinesh Kumar & Reddy, 2018). Oxalic acid is excluded for half of the mix in order to determine its effect in ferrocks cement replacement.

Table 3.9 Mix proportions of Ferrock

Ferrock	100%	100%
Iron powder	60%	60%
Fly ash	20%	20%
Glass powder	10%	12%
Limestone	8%	8%
Oxalic acid	2%	0%

3.3.5 Batching, Casting and curing of concrete specimens

Batching of concrete is the process of measuring concrete ingredients to get concrete mixtures. For this specific experiment, batching by weight was preferred over volume batching to get a proper mix of concrete ingredients since it is difficult to find the exact volume of granular materials because of their voids.

Casting concrete is the process of preparing and mixing the concrete according to the mix design proportion. All ingredients of concrete mixes were measured by volume according to their mix design. The concrete production was made using an Electric Cement Mixer. Based on the proportion of coarse aggregate, sand, cement and ferrock are dry mixed for 2 minutes. After dry mixing, the specified quantity of water was then added, and the mixture subsequently mixed for another 4 minutes. To test the workability of concrete a slump test was made by slump cone and the mould specimens were cleaned and applied with oil before casting. After the casting is done the casted concrete specimens were removed from the adjusted steel moulds after 24hrs of casting. The curing was carried out according to ASTM C511 (Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes). The specimens were immediately transferred into metal tanks containing water at room temperature for the curing to start. Curing then continued with the specimens fully submerged underwater at room temperature for 7 and 28 days. The test specimens were removed from the curing metal tank 24 hours before testing. The cubes were kept submerged underwater throughout the curing period to ensure there was no reduction in the strength of the specimens.

Figure 3.12 Mod preparation and Casting of concrete specimens

Figure 3.13 curing of concrete specimens and

A trial mix proportions were used for mix of conventional concrete to achieve C25 grade of concrete. The control group is prepare as C25 and two different ferrock cement one having oxalic acid and the second without oxalic acid was added on the basis of percentage to cement content of conventional concrete. C25 grade of concrete were designed to give a slump value of 75-100 mm and a 28 day compressive strength of 25MPa. Cube and beam moulds of size 150mm*150mm*150mm and 100mm*100mm*500mm respectively were casted. The moulds were oiled properly prior to the casting of the specimens.

The C25 concrete grade was produced using three mix series besides the control mix; each one incorporating 0%, 5%, 10%, 15% and 20% cement replacement using ferrock. Tests were conducted on the constituent material. The mixing was made in dry state, trial batch were made at first. Then, according to ASTEM C 143 the workability of fresh concrete is measured by slump test which carried out before casting the concrete. The procedures used for the slump test were as follows: slump tests were measured using a mould in the shape of a frustum of a cone with a base diameter of 200mm, a top diameter of 100mm, and a height of 300mm. The mixed concrete was checked for workability by filling the standard slump cone with three layers by rodding each layer with 25 times according to ASTM C143. Between each mix, the tools were cleaned using tap water to ensure that there was no contamination between the mixes. After checking the slump the mixed concrete was placed in the mould and was well compacted in three layers with the help of vibrator was carried out. The types of slump i.e. zero, true, shear or collapsed are then recorded.

Figure 3.14 Slump taste for concrete mix

3.3.6 Hardened Concrete Test

Hardened concrete is one of the most durable and robust building materials available, capable of supporting structural and service loads. One of the goals of hardened concrete testing is to guarantee that the concrete used has the strength and durability required.

3.3.6.1 Compressive strength taste

The compressive strength of the cubes is an indication of their ability to resist compressive loads. A higher compressive strength indicates that the cubes are more capable of resisting compressive loads. The compressive strength of concrete cubes is typically measured at 28 days, but it can also be measured at other ages ASTM C39. Balance, mold, temping road, compressive test machine, trowel, shovel, and brush were for the test. A concrete cube of size 150mm*150mm*150mm were cast to investigate the compressive strength of ferrock based and normal concrete. The researcher determined the compressive strength after 7 and 28 days of curing by using an automatic compressive strength test machine at Adama Science and Technology University, Construction Material Laboratory, in accordance with (ASTM C39). Compressive strength taste is conducted as follows; Place the cubes in the compression testing machine, Using compression test machine with a loading rate of $14N/mm^2/min$ and a maximum load capacity of 3000KN, compressive stress will be applied slowly until the specimen fails, and record the maximum load attained. Compressive strength will be calculated by dividing the maximum load attained by the cross-sectional area of the specimen and the corresponding unit weight. Finally, compressive strength results will be reported according to ASTM C39/C39M-09. The compressive strength test was done at 7^{th} and 28^{th}

day of curing. During the tests, the results such as mass of individual cube, the applied load, and other data were recorded on standard formats.

$$\text{Compressive strength} = \frac{\text{Applies Load}}{\text{Cross sectional Area of the sample}} \text{ .... Equation 3.11}$$

The strength range between the highest and lowest individual test was calculated and found to be below 15% of the mean. The strength range is calculated by subtracting the lowest test value from the highest test value. The mean is calculated by adding all of the test values and dividing by the number of test values. In this case, the strength range is below 15% of the mean. This means that the difference between the highest and lowest test values is less than 15% of the average test value. This indicates that the concrete is relatively consistent in its strength.

Figure 3.15 Compressive strength taste using Automatic compressive machine.

3.3.6.2 Flexural strength taste

The flexural strength of the beams is an indication of their ability to resist bending loads. A higher flexural strength indicates that the beams are more capable of resisting bending loads ASTM C293. For flexural strength, specimens (of dimension 100mm*100mm*500mm) concrete beams will be prepared with the cross-sectional dimensions and geometry specified in ASTM C78/C78M-17. The specimens will be casted in a suitable form and curing will be applied as defined in ASTM C31/C31M- 17a. ASTM C293 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Four-Point Loading) is used for this research, and follows the following procedure:

Procedure

1. Prepare the concrete beams in accordance with the relevant ASTM standard.
2. Place the beams in the four-point loading apparatus.
3. Apply a load to the beams at the third point, increasing the load at a rate of 1400 N/min until the beams fail.
4. Record the maximum load applied to each beam.
5. Calculate the flexural strength of each beam as follows:

Flexural strength = Load at failure / (Beam width x Beam depth^2)

Figure 3.16 Four point loading Flexural Strength testing machine

3.3.7 Durability Test

3.3.7.1 Water absorption taste

Water absorption is the measure of water penetration resistance of concrete specimens. A concrete cube of sample size of 150mm*150mm*150mm were cast to investigate the water absorption capacity of ferrock based and normal concrete. This research examined the water absorption of normal and ferrock based concrete at curing periods of 28 days to determine the water tightness of concrete. The water absorption test procedure followed was: after 28 days of curing, the samples were taken out of the curing water and dried at a temperature of 105^0 C for 24 hours, weighed, then immersed in curing water for 72 hours, weighed again, based on (ASTM, C1585), and the highest water absorption limit is 10%. The increase in weight as a percentage of the original weight is expressed as water absorption. The water absorption and percent reduction can be computed based on the formula:

$$\text{Absorption after immersion in } \% = \frac{(B-A)}{A} * 100 \text{ .... Equation 3.12}$$

Where: A - Mass of oven dried sample in air

B - Mass of surface dried sample in air after immersion

3.3.7.2 Sulfate Attack Resistance of Concrete Cubes

The test method for the chemical resistance of concrete is specified in the ASTM C 1012. However, this method is for mortar, and the behaviour of mortar and concrete under chemical attack might not be the same. One of the ways of knowing the deterioration mechanism of concrete under the exposed chemical solution is the mass loss method as shown by equation 3.12 (Devi et al., 2017; Shirayma, K. and Yoda, A, 1991).

The lower limit of the exposure proposed by the ASTM C1012 test method is the use of 50mg/L Na_2SO_4 concentration in water solution. In this sulfate attack experimental study, JSTM C7401 testing method is used. This test method assesses the chemical resistance of concrete by immersing test specimens into acid or alkaline solutions for a prescribed period and by comparing changes in the measurements against control specimens. The sulfate resistance of concrete can be quantified by measuring changes in weight occurring in specimens stored in chemical solutions (kefelegn et al, 2022 McCarthy, M. J. and Thomas, D. D., 2019).

In this experimental investigation, cubes of concrete of 150mm*150mm*150mm from control and ferrock based concrete were casted, which were cured for 28 days in water, were used. After the final day of curing, the specimens were removed from the water, and the excess film of water on the surface was cleaned using a standard preliminary surface cleaning process and weighed as initial mass. Then the identified specimens were immersed in the 5% sodium sulfate solutions for another 28 days. After the prescribed duration, the specimens were removed from the solution and their final weight was recorded. Then, sulfate resistance of the specimens in terms of weight loss was determined using equation (3.13).

$$\text{Mass loss } = \frac{(W1 - W2)}{W1} * 100 \text{ .... Equation 3.13}$$

Where, W_1 = Initial mass of cube specimens (Kg)

W_2 = Mass weight cube specimens after a prescribed exposure period (Kg)

3.4 Cost comparison

The material cost of the produced concrete per unit volume was calculated for each proportion of concrete containing ferrock cement on the current base price of materials from the local market of Adama city. Finally the cost difference was analysed by using economic regression that shows the optimum cost of replacement with strength.

3.5 Method of Data Analysis

Data analysis is an essential task for ensuring that the researchers have all the relevant data for making contemplated comparison and analysis. Quantitative data analysis involves two considerations. The first is that standard and literature, by advancing relationships between variables via research questions. The second is to ensure that, especially if using a computer, the data have been input correctly. The data that will be collected from laboratory results and analysed based on descriptive and quantitative research methods approach. During the experiment, C25 concrete is prepared in the usual condition (control group), and the others will be 'experimental group'. The process will be examining the truth of a statistical hypothesis, relating to the stated research problem, using comparative experiment. The experiment will be conducted and will be recorded to compare effects of such dependent variable in production of concrete specimens. The design will be represented by Graphical Description and MS Excel Program technique will be used for data collection and analysis of the recorded data. The interior morphology of concrete was studied using SEM. After 28 days of curing a concrete sample from both ferrock based samples and control concrete was obtained from the middle of the concrete and submitted to SEM image analysis at 10 kV by mounting small broken samples on brass stubs.

3.6 Methodology flow chart

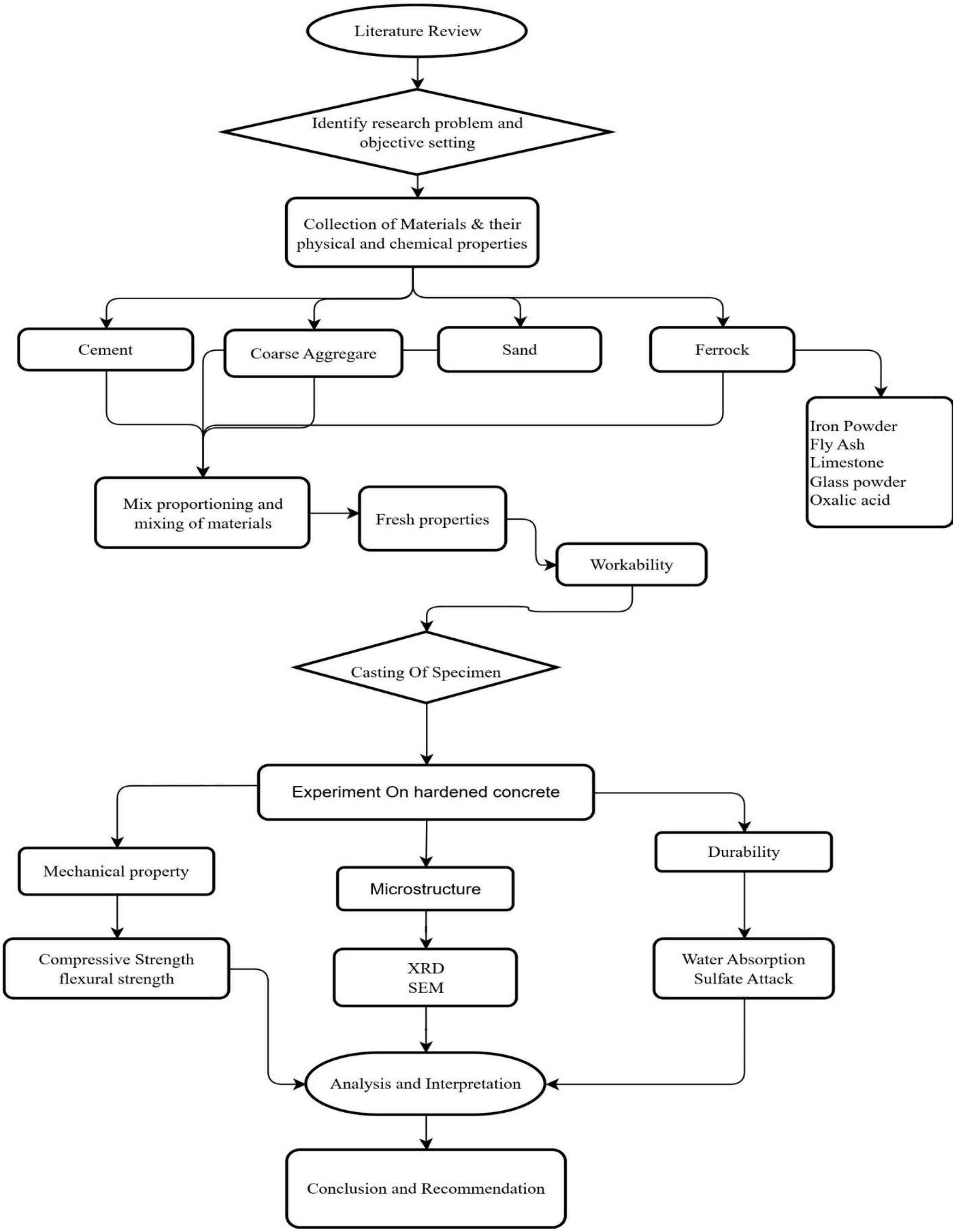


Figure 3.17 Methodology flow chart

CHAPTER 4

4 RESULTS and DISCUSSIONS

4.1 Introduction

In this chapter analyses and discussions of laboratory test results focusing on partial replacement of cement with ferrock to understand its suitability is presented. After testing physical properties of coarse and fine aggregates, concrete mix designs were undertaken based on the test results of all ingredients.

In this experimental research the effect of ferrock on properties of fresh and hardened concrete with available construction materials within constant water-cement ratio, with different percentages of ferrock replacing the cement, with and without the addition of oxalic acid. According to the research objective, the effect of ferrock usage on concrete properties, such as workability, compressive & flexural strength and durability of concrete have been studied at dosages of ferrock is increased from 0%, 5%, 10%, 15% and 20% to replace cement by weight.

4.2 Material Taste Result and Discussion

4.2.1 Taste on Cement Paste

4.2.1.1 Normal consistency of cement paste

Normal consistency of pastes containing ferrock based cement and control mixes are shown in Table 4.1. The amount of water required for normal consistency is determined using the following formula.

$$\% \text{ water} = \frac{\text{Weight of water in g}}{\text{Weight of cement in g}} * 100 \qquad \text{Equation 4.1}$$

The paste is said to be of normal consistency when the rod settles 10$\pm$1 mm below the original surface within thirty seconds, usually the range of water-cement ratio for normal consistency is between 26% and 33% ASTM C187. The control paste or the paste without ferrock had normal consistency of 28%. All of the pastes containing ferrock based cement showed normal consistency equal and higher than the control paste. For 5% replacement the normal consistency was similar with control paste. Starting from 10% replacement the normal consistency had shown a slight increment by 0.5% intervals and it increases continuously to 29.5% at 20% replacement.

Table 4.1 Normal consistency of blended cement pastes containing ferrock

Mix' s	Weight of OPC (g)	Weight of ferrock (g)	Weight of water (ml)	Consistency (%) (ASTM C 187)
Mix 0%	500	0	140.00	28.00
WMix 5%	475	25	140.00	28.00
WMix 10%	450	50	142.50	28.50
WMix 15%	425	75	145.00	29.00
WMix 20%	400	100	147.50	29.50
WOMix 5%	475	25	140	28.00
WOMix 10%	450	50	142.5	28.50
WOMix 15%	425	75	145	29.00
WOMix 20%	400	100	147.5	29.50

The findings on the consistency of the blended pastes conformed to the usual range of water to cement ratio for normal consistency which is between 26% and 33%. The increment on water requirement is due to the higher surface area of ferrock cements as compared to that of cement.

4.2.2 Coarse aggregate test

The coarse aggregate taken from the site was washed and dried in air to make it free from silt and clay and deleterious materials based on the quality requirement confirmation as in standard all test on aggregate were done (see appendix 1 B). The size of coarse aggregate used for the study was nominal aggregate size of 25mm. To evaluate the properties of coarse aggregate the following experimental test were conducted specific gravity, unit weight, water Absorption, moisture content and fineness modulus analysis.

Table 4.2 Physical property of natural coarse aggregate used for the research

Physical property	**Limiting value**
Max sieve size	25mm
Unit weight	1613.09 Kg/m^3
Specific gravity	2.8
Water Absorption	0.69

Therefore, according to the result, the coarse aggregate fulfils the gradation standard and other properties of ASTM C33.

The gradation curve of coarse aggregate is given in figure 4.1 below, which the percent finer is within the range provided by the (ASTM C33) standard.

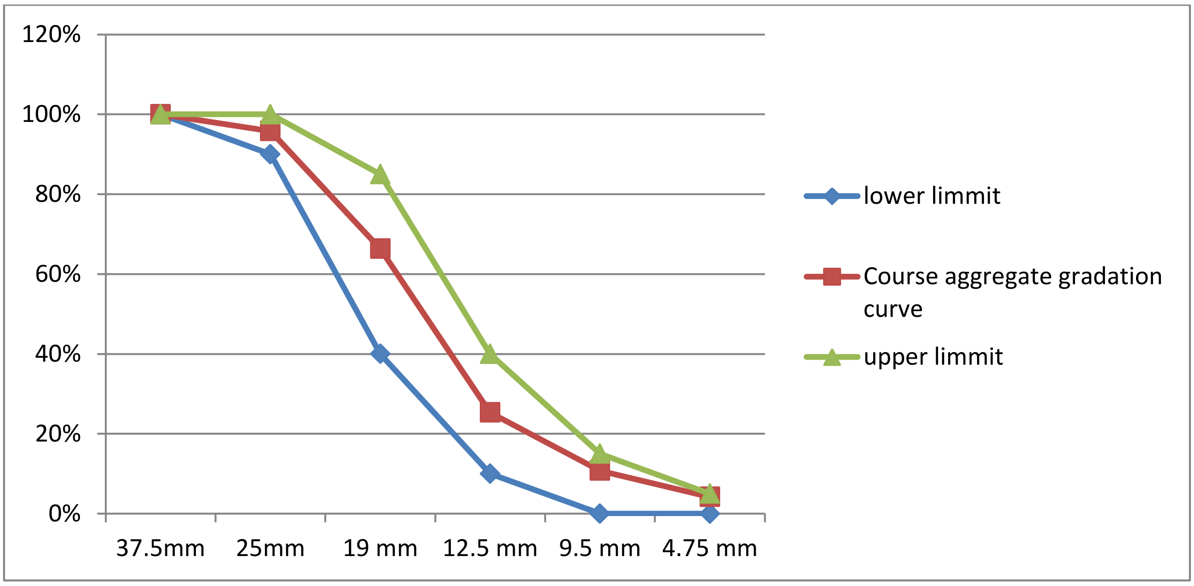


Figure 4.1 Course aggregate gradation curve

4.2.3 Fine aggregate test

According to ASTM C33, aggregates which are less than 4.75mm are designated as sand and retained by 0.75mm. For this study, locally available well graded river sand from Awash basin was used as a fine aggregate. Since, the aggregate is extracted from river; it's full of dust film on their surface. For this reason, the fine aggregates were washed thoroughly and dried to saturated surface dry (SSD) state before any test was carried out. In addition to this, all fine aggregate which retain on 9.5mm sieve size were no longer relevant, and all the passing fine aggregate were used for experimentation. Various fine aggregate tests were performed to investigate the quality of the fine aggregate in accordance with ASTM standard (see appendix 1 C).

Table 4.3 The physical properties of sand for the research work

Physical property	Limiting value
Bulk specific gravity	2.66
Apparent specific gravity	2.705

Water Absorption	1.01%
Unit Weight	1591.25 Kg/m^3
Max sieve size	4.75mm
Silt content	2.4
Free moisture content	2.83%
Finesse modulus	2.8%

Therefore, according to the result the sand fulfils the gradation standard and other properties of ASTM C33.

The gradation curve of coarse aggregate is given in figure 4.2 below

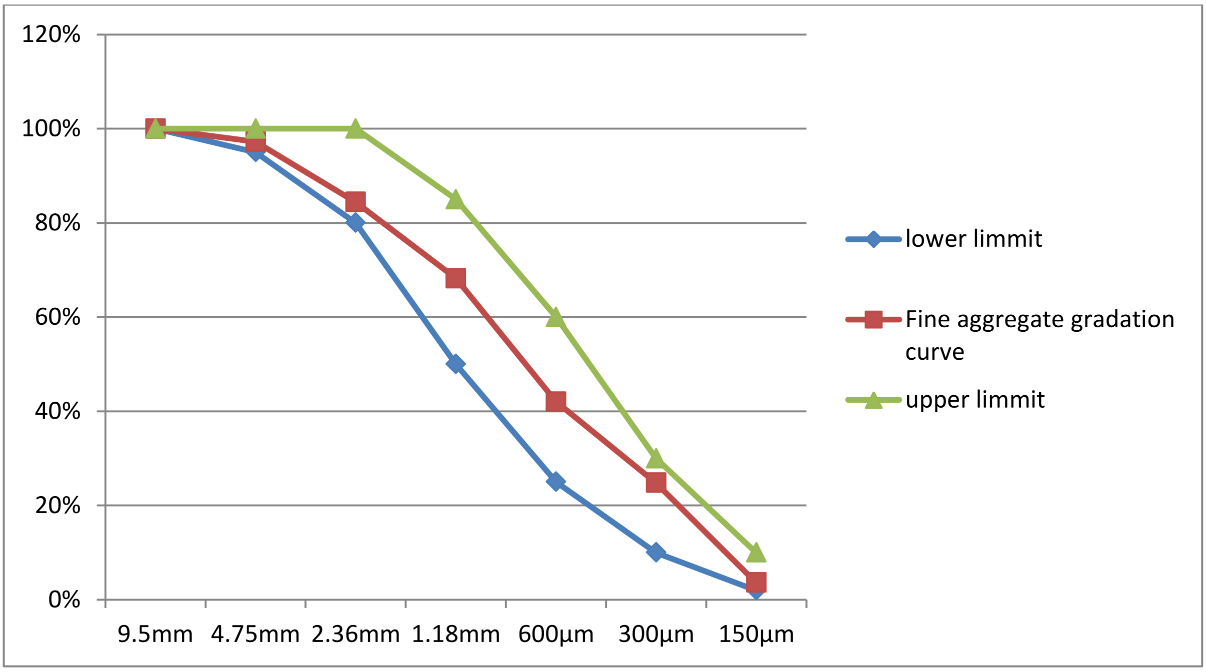


Figure 4.2 Fine aggregate gradation curves

4.3 Properties of Fresh Concrete

4.3.1 Workability of concrete containing ferrock

The ability of fresh concrete to be mixed, transported, easily flowed, and placed is referred to as workability (ASTM C143). In this experimental investigation, the workability of ferrock based and conventional concrete was investigated. In this work, the slump cone test was used to investigate the level of workability. The slump values of ferrock based and C25 control concrete is illustrated in Table 4.8.

The results of the workability test given the slump values for the various mixing batches are explained in Figure 4.3. The degree of workability of concrete batches prepared from different percentage replacement of cement had different slump values ranging from a minimum of low 75 mm to a maximum of 87 mm. Table 4.4 shows the results of the slump test for all mixes. The result of the workability of the concrete mix on the samples at 0%, 5%, 10%, 15% and 20% of replaced cement with ferrock are shown below.

Table 4.4 results of the slump test for all mixes

Concrete grade	Slump value (mm)
C-25	87
	85
	77
	77
	75
	84
	78
	77
	75

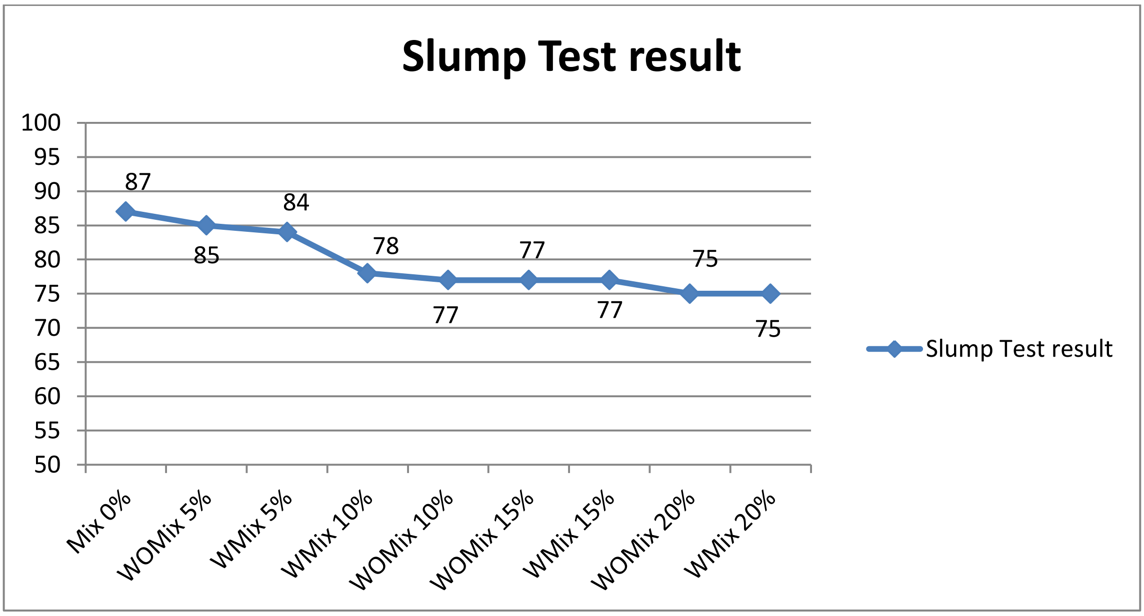


Figure 4.3 Slump values for all the mixes

From the results it can be seen in figure 4.3 as the percentage replacement of OPC with ferrock cement increases, the workability of concrete decrease. Replacing cement by an equal mass of ferrock cement causes an increase in volume since the density of cement is higher than that of ferrock. This therefore increases the water demand and as the ferrock cement content increases the workability reduces since the quantity of water remains the same for all mixes. According to the mix design the slump of the concrete mix is 75-100 mm so the result of the slump of all the nine mixes as shown in figure 4.1 above are acceptable. Therefore the overall results of the concrete mix when the percentage of ferrock cement increase shows reduction in workability of the concrete. This is due to the specific surface of ferrock cement is greater than cement.

4.4 Durability of Hardened Concrete

4.4.1 Water absorption capacity

The water absorption by immersion test is done based on ASTM C 1585 procedure. Moisture penetration is one of the factors affecting the durability of concrete. Concrete as a porous material which can allow water to migrate through it, corroding steel reinforcement, bringing in harmful chemicals, So it is a predominant factor to be determined to assess the quality of concrete. For water absorption test, cube specimen of size of 150mm*150mm*150mm were casted and immersed in water curing for 28 days. The specimens are oven dried for 24 hours at the temperature of 105 degree Celsius until the mass becomes constant and again weighed at room temperature. After final drying, the samples were immersed in water for three days then the final surface dried mass was measured. After having the final mass of oven dried and surface dried mass, the percentage of water absorption after immersion is calculated as:

$$\text{Absorption after immersion in } \% = \frac{(B-A)}{A} * 100$$ ………………………………... Equation 4.2

Where: A - Mass of oven dried sample in air

B - Mass of surface dried sample in air after immersion

Figure 4.4 Water absorption test

Table 4.5 Result for water absorption test

Mix' s	Mass of oven dried sample in air	Mass of surface dried sample in air after immersion	Absorption after immersion in %
Mix 0%	8.105	8.682	6.65%
WMix 5%	8.255	8.790	6.09%
WMix 10%	7.995	8.430	5.16%
WMix 15%	8.205	8.749	6.22%
WMix 20%	8.3	8.885	6.58%
WOMix 5%	8.275	8.851	6.51%
WOMix 10%	7.945	8.546	7.03%
WOMix 15%	8.195	8.845	7.35%
WOMix 20%	8.115	8.812	7.91%

The water absorption capacity of concrete cubes tested at the age of 28 days curing for the various mixing batches is shown in Figure 4.5 below. Water absorption of concrete batches prepared from 0%, 5%, 10%, 15% and 20% replacement of cement with ferrock cement containing oxalic acid had different water absorption values ranging from a maximum of 6.58% for 20% replacement to a minimum of 5.16% for 10% replacement of ferrock containing oxalic acid, ferrock cement concretes without oxalic acid showed a maximum of 7.91% for 20% replacement and a minimum of 6.51% for 5% replacement respectively. In first scenarios ferrock cement containing oxalic acid as the percentage replacement increases from 10% to 20% the water absorption value increased, in the second scenario the increase in water absorption value was observed as the percentage replacement is increased from 0% to 20%.

More water absorption means more capillaries inside the material or more is the porous the material which will lead to higher absorption of water and less strength. The experimental result shows that the 10 % replacement of cement with ferrock cement containing oxalic acid performs well when compared with conventional concrete.

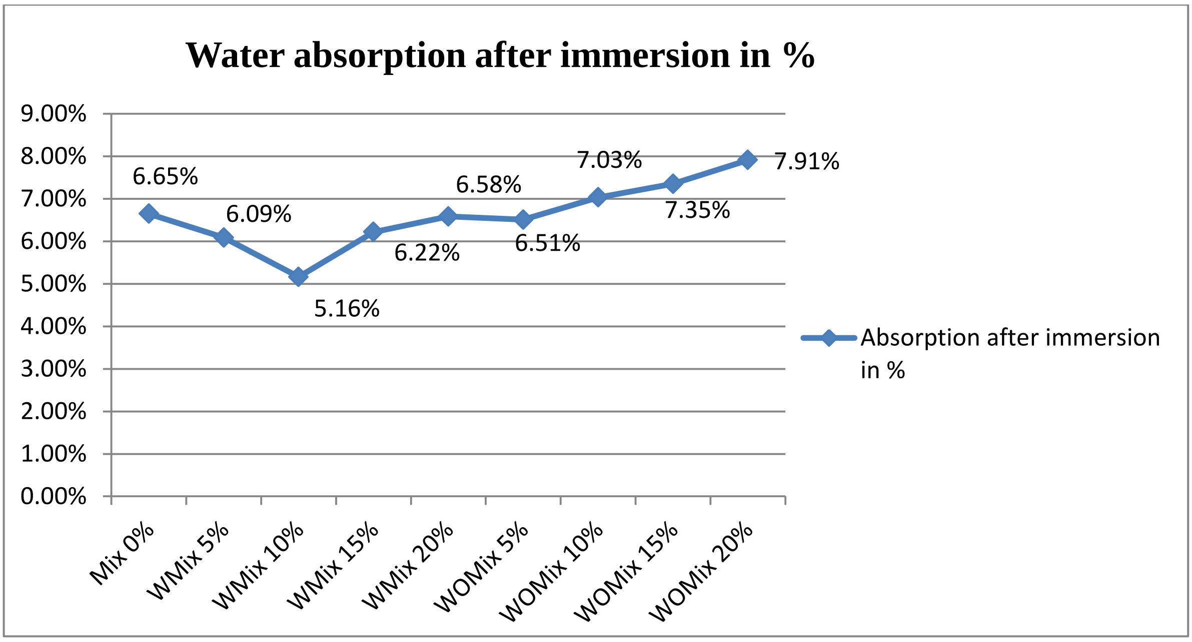


Figure 4.5 test result for water absorption of all mixes

4.4.2 Sulfate attack resistance

Mass loss of concrete cubes tested after 28 days immersion in 5% sodium sulfate solution in dome in accordance with ASTM C 1012. For the control mix, ferrock cement containing oxalic acid and ferrock cement without oxalic acid are shown in Table 4.6 and Figure 4.7.

Figure 4.6 sodium sulfate attack resisrance test

Table 4.6 mass loss in sulfate attack resistance of all mixes

Concrete mix's	Weight before immersion (Kg)	Weight after immersion (Kg)	Mass loss (%)
Mix 0%	8.012	7.983	0.362%
WMix 5%	8.215	8.201	0.170%
WMix 10%	8.305	8.294	0.132%
WMix 15%	8.295	8.281	0.169%
WMix 20%	8.351	8.328	0.275%
WOMix 5%	8.196	8.18	0.195%
WOMix 10%	8.234	8.215	0.231%
WOMix 15%	8.312	8.286	0.313%
WOMix 20%	8.267	8.232	0.423%

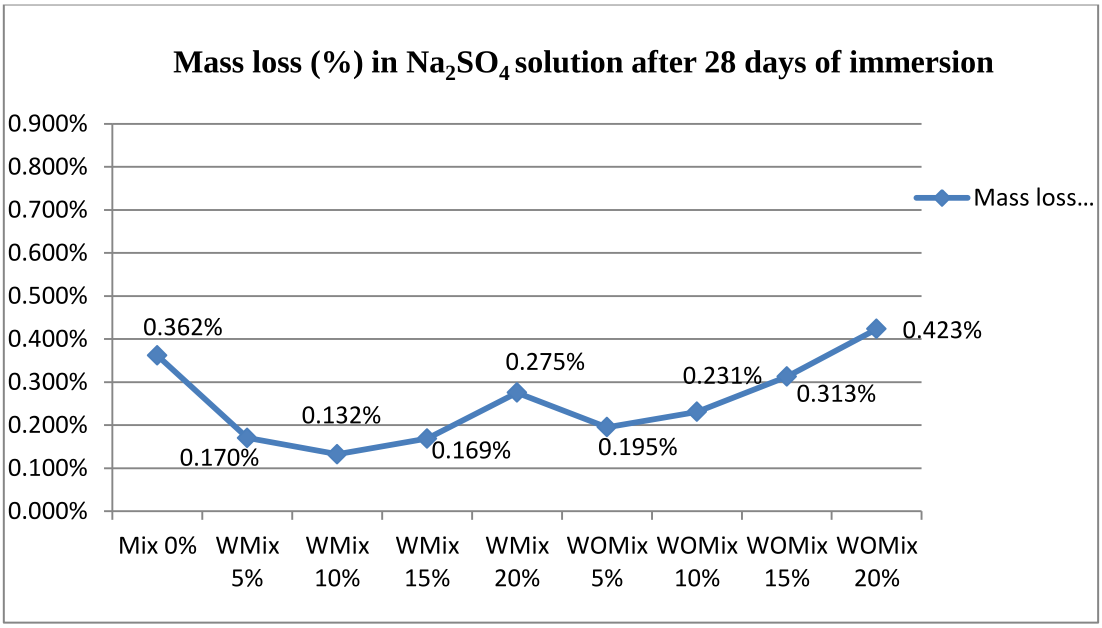


Figure 4.7 Mass loss (%) in Na_2SO_4 solution after 28 days of immersion

The cubes were immersed in a 5% Na_2SO_4 concentrated solution for 28 days. Mass loss of concrete batches prepared from 0%, 5%, 10%, 15% and 20% replacement of cement with ferrock cement displayed mass change values ranging from 0.132 % to 0.423%. Ferrock cement containing oxalic acid showed a better sulfate resistance than those ferrock mix's that do not contain oxalic acid and the control mix. The control C-25 concrete exhibited a mass loss of 0.362%, all ferrock cement Concretes containing oxalic acid showed a better durability against Na_2SO_4 sulfate attack from both the control concrete and ferrock cement concretes without oxalic with a mass loss ranging from 0.132% up to 0.275%. From the mix's containing oxalic acid 10% replacement of cement with ferrock showed the least mass loss which is 0.132%, this implies that it is having high hardened density of concrete and therefore slowed down the process of deterioration by sodium sulfate attack making it the most durable of all the 9 mix's. As the present replacement of cement with ferrock cement containing oxalic acid increases from 10% the durability against sulfate attack starts to gradually decrease compared to the 10% replacement, but as per the study replacement up to 20% showed a better performance under Na_2SO_4 sulfate attack than the control C-25 concrete. This result indicated that the high hardened density of ferrock concrete was very effective in resisting sodium sulfate attack.

Ferrock cement concrete without oxalic acid showed a relatively lower resistance to sulfate attack having a mass loss ranging from 0.195% to 0.423%. 5% replacement showed a better resistance to sulfate attack than 20% replacement of cement with ferrock cement containing oxalic acid and also from 10%, 15% & 20% replacement of cement with ferrock cement concrete without oxalic acid. As the present replacement of cement with ferrock cement concrete without oxalic acid increases from 5% to 20% the concrete durability against sulfate attack gradually reduces. This implies that concrete with partial replacement of cement with ferrock cement concrete without oxalic acid exhibit lower hardened density of concrete and therefore fastened the process of deterioration by sodium sulfate attack.

The reason behind the improvement against sulphate attack is that, sulphate salt attacks either C_3A-calcium hydroxide or mono sulfo almunate (Afm). Then it form ettringite which is expansive and causes crack. Once the salt have consumed all the CH, then it starts attacking or decalcifies the calcium silicate hydrate (CSH) which is the back bone of concrete strength. One of the best methods to stop this effect is reducing C_3A of cement, what we are doing here by taking out cement and replacing by ferrock. The other method is reducing the w/c ratio. In higher strength concrete the water-cement ratio is lower that is why weight loss is lesser in High Strength Concrete than Normal Strength Concrete.

4.5 Properties of Hardened concrete

4.5.1 Compressive Strength

The 7th and 28th day's compressive strengths were determined with the measurement of deformation with load.

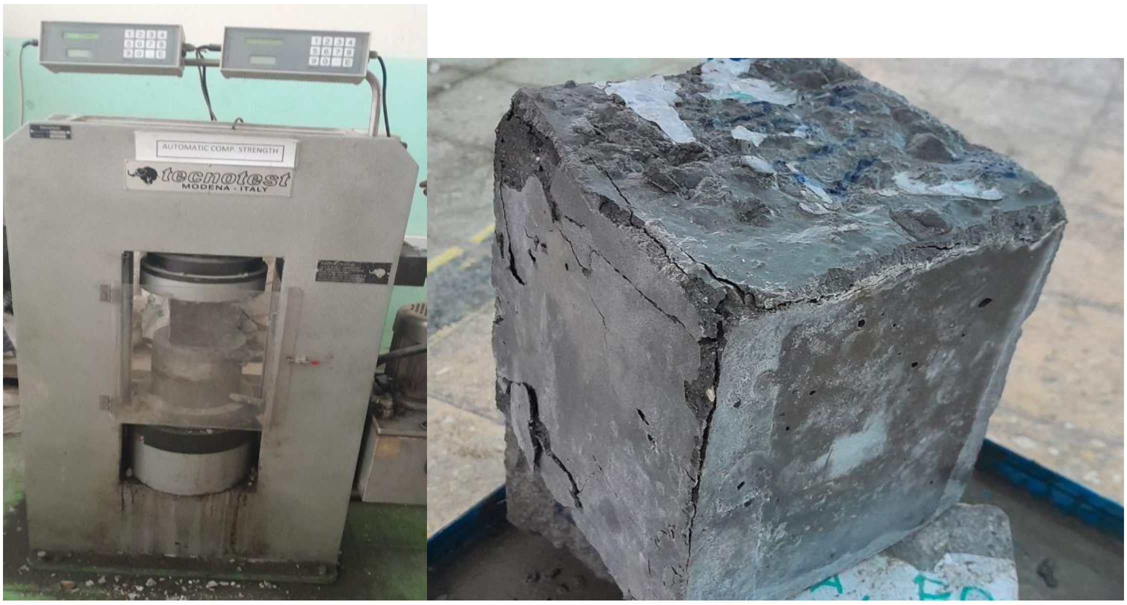


Figure 4.8 a) Compressive test machine b) Cube after compressive strength test

The compressive strength representing the mean of three specimens of the 7 and 28 days of the specimens and the control mix is presented in Table 4.7 and 4.8; the raw data is attached in Appendix 3 A.

Table 4.7 Average compressive strength test values of ferrock cement concrete in 7 days of water curing

7 days compressive strength of Ferrock concrete		
Mix' s	Avg. load (KN)	Average Compressive strength (MPa)
Mix 0%	478.3	21.26
WOMix 5%	455.5	20.31
WOMix 10%	462.3	20.55
WOMix 15%	432.7	19.23
WOMix 20%	407.7	18.12
WMix 5%	502.3	22.33
WMix 10%	556.7	24.74
WMix 15%	474.0	21.07
WMix 20%	432.3	19.21

Table 4.8 Average compressive strength test values of ferrock cement concrete in 28 days of water curing

28 days compressive strength of Ferrock concrete		
Mix' s	Avg. Load (KN)	Average Compressive strength (MPa)
Mix 0%	702.3	31.23
WOMix 5%	650.3	28.90
WOMix 10%	630.0	28.00
WOMix 15%	597.7	26.56
WOMix 20%	559.3	24.86
WMix 5%	726.3	32.28
WMix 10%	870.7	38.70
WMix 15%	696.7	30.96
WMix 20%	642.7	28.56

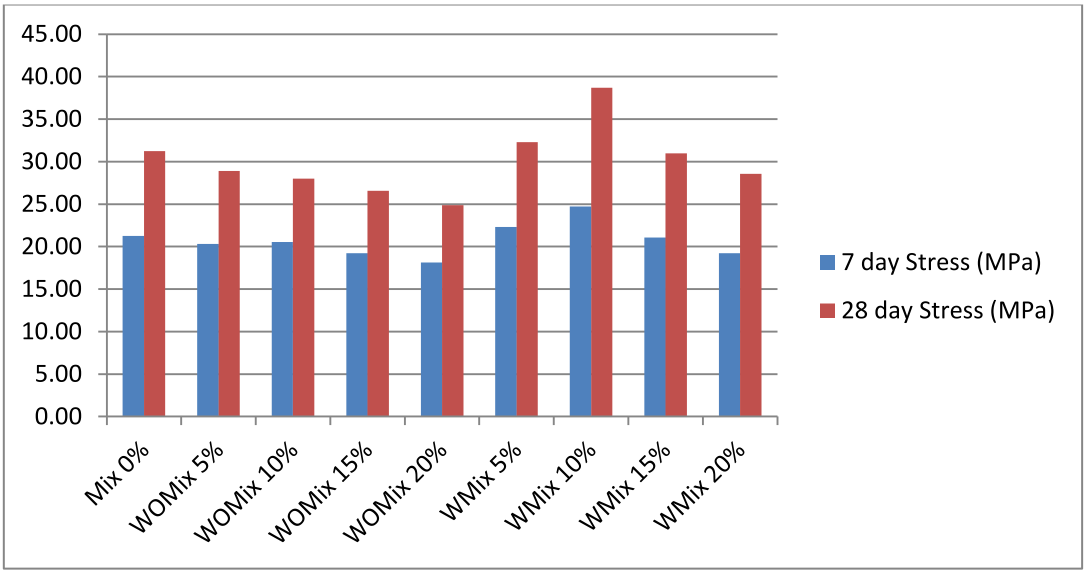


Figure 4.9 Average compressive strength test values of all mixes in 7 and 28 days of water curing

On seven days of curing, the control mix with 21.26MPa performed better than all ferrock cement based except the 5% and 10% mix of ferrock cement containing oxalic acid exhibiting 22.33MPa and 24.74MPa strength respectively, with a 4.89% and 16.37% increase in strength from the control mix respectively. 5 and 10% ferrock cement replacement containing oxalic acid exhibited more compressive strength than the control mix on 28 days of curing; 5% replacement showed a compressive strength of 32.28MPa that shows a strength increase of 3.36%; 10% replacement showed a better compressive strength than all the nine mixes with 38.7MPa that shows a strength increase of 23.84%. However, 15% and 20% replacement of ferrock cement containing oxalic acid showed a decrease in strength compared to the control mix with 0.86% and 8.55% decrease in strength respectively and also 5 to 20% of ferrock cement replacement without oxalic acid exhibited a gradual decrease on the increased use of ferrock from 5% to 20 % (figure 4.9), with a percentage decrease of 7.46%, 10.34%, 14.95 and 20.39% respectively. The findings are in line with the study of (Nadir et al., 2022;Vijayan et al., 2020) and (Shivani et al., 2022), who found that up to 12% replacement of conventional ferrock with OPC performs better than the control mix on 7, 14 and 28 of curing. However, Karthika et al., (2021) elucidated in their study that SCMs with 15% and more ferrock replacement resulted in decreasing compressive strength, as suggested by this study also. Pozzolanic-ferrock-based SCMs tend to achieve compressive strength on more curing age with the increased formulation of C-S-H gel and $FeCO_3$. But the excessive presence of silica in pozzolans starts converting into $Si(OH)_4$ on hydration and results in swelling silica-hydrated compounds, which cause swelling or cracking and reduction in strength (Hadži-Nikolova et al., 2019).

4.5.2 Flexural Strength

Beam samples measuring 500*100*100mm were molded and stored in water for 28days before the test for flexural strength. The Flexural test ASTM D6272 measures the force required to bend a plastic beam under a four point loading system. Three similar samples were prepared for each mix proportion. The flexural tensile strength tests of the fabricated concrete specimens were carried out using the two points loading which is also known as four point loading. It is a method used for testing the flexural tensile strength. This method is preferred over centre point loading for the different advantages it possesses. In this test the concrete beam to be tested is supported at its ends and loaded at its interior location by gradually increasing load to failure. The mean flexural tensile strength of 7 and 28 days of the two mix series along with the control concrete are presented in Table 4.9 and 4.10 along with the relative flexural strength loss and gain to that of the control mix. The raw data is presented in Appendix 3 B.

Figure 4.10 The flexural tensile strength tests machine and tested sample

The calculation of the flexural stress is as follows:

$C = D/2$ cm …………………………………………………………………. Equation 4.3

$M = PL/3$ Nm ………………………………………………………………. Equation 4.4

$I = bd^3 /12$ m^4 …………………………………………………………… Equation 4.5

$\sigma = Mc/I$ MPa …………………………………………………………… Equation 4.6

Where:

P = Failure Load

σ = Bending strength

M = Maximum Moment

L = span of specimen

I = Moment of Inertia

D = depth of specimen

C = Centroidal depth

W = width of specimen

Table 4.9 mean flexural strength of all the mix series after 7 days of curing

Mix' s	Average flexural strength at 7 day		
	Avg. Load(KN)	Mean Flexural strength (Mpa)	Gain/Loss (%)
Mix 0%	10.39	3.118	0.00
WOMix 5%	10.09	3.027	-2.92
WOMix 10%	9.74	2.922	-6.30
WOMix 15%	9.28	2.784	-10.73
WOMix 20%	8.80	2.640	-15.34
WMix 5%	10.62	3.188	2.24
WMix 10%	10.99	3.299	5.79
WMix 15%	10.31	3.093	-0.80
WMix 20%	9.69	2.908	-6.76

Table 4.10 mean flexural strength of all the mix series after 28 days of curing

Mix' s	Avarage flexural strength at 28 day		
	Avg. Load(KN)	Mean Flexural strength (Mpa)	Gain/Loss (%)
Mix 0%	12.89	3.867	0.00
WOMix 5%	12.21	3.664	-5.24
WOMix 10%	11.31	3.393	-12.25
WOMix 15%	10.78	3.236	-19.49
WOMix 20%	10.31	3.093	-20.01
WMix 5%	13.70	4.110	6.29
WMix 10%	14.06	4.219	9.10
WMix 15%	12.25	3.675	-4.97
WMix 20%	11.32	3.397	-12.15

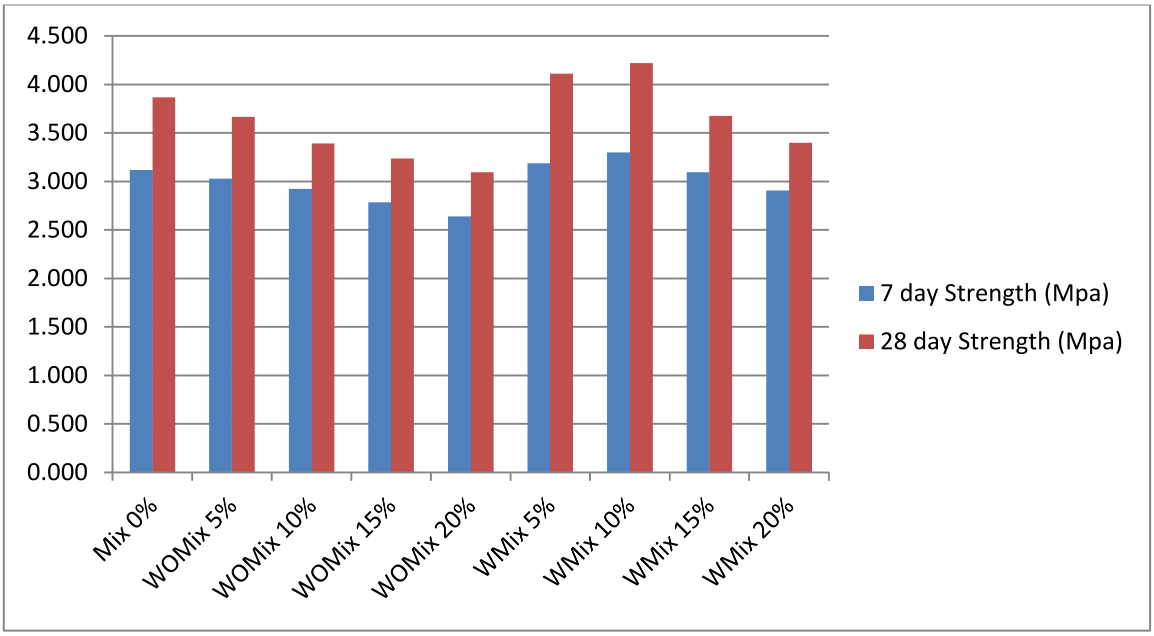


Figure 4.11 mean flexural strength of all the mix series after 7 and 28 days of curing

The samples tested after 7 and 28 days of curing, all ferrock cement concretes without oxalic acid showed a decrease in flexural strength compared to the control C-25 concrete. The flexural strength reduced as the present of replacement is increased from 5% to 20%.

After 7 days of curing, the rate of flexural strength development of 0%, 5%, 10%, 15% and 20% of ferrock based concretes with oxalic acid are 3.118MPa, 3.188MPa, 3.299MPa, 3.093Mpa and 2.908MPa respectively. This indicates the rate of flexural strength development at 5% and 10% ferrock cement concretes containing oxalic acid were improved by 2.24% and 5.79% from the control concrete respectively. Whereas, for 15% and 20% replacement the rate of flexural strength development were lowered by 0.8% and 6.76% from control concrete respectively. Therefore, the experimental investigation on flexural strength shown that, the strength of the concrete has increased as the replacement percentage of the ferrock cement containing oxalic acid increased up to 10% by weight of cement. The flexural strength had shown a reduction pattern as the ferrock cement content of the concrete increases beyond 10%.

The 28 days flexural strength of ferrock based concretes containing oxalic acid showed a better flexural strength at 5% and 10% replacement of cement, were improvement of 6.29% and 9.1% from the control C-25 concrete respectively. According to the study conducted percentage of replacement of cement increases from 10% to 20% the flexural strength showed a decrease from the control concrete. The reason in the reduction of flexural strength is that the reduction of cement loses the binding property due to the addition of ferrock cement more than 10% and as cast iron contains carbon to some extent as the present of replacement increases then it becomes brittle leading to loss of flexural strength in concrete.

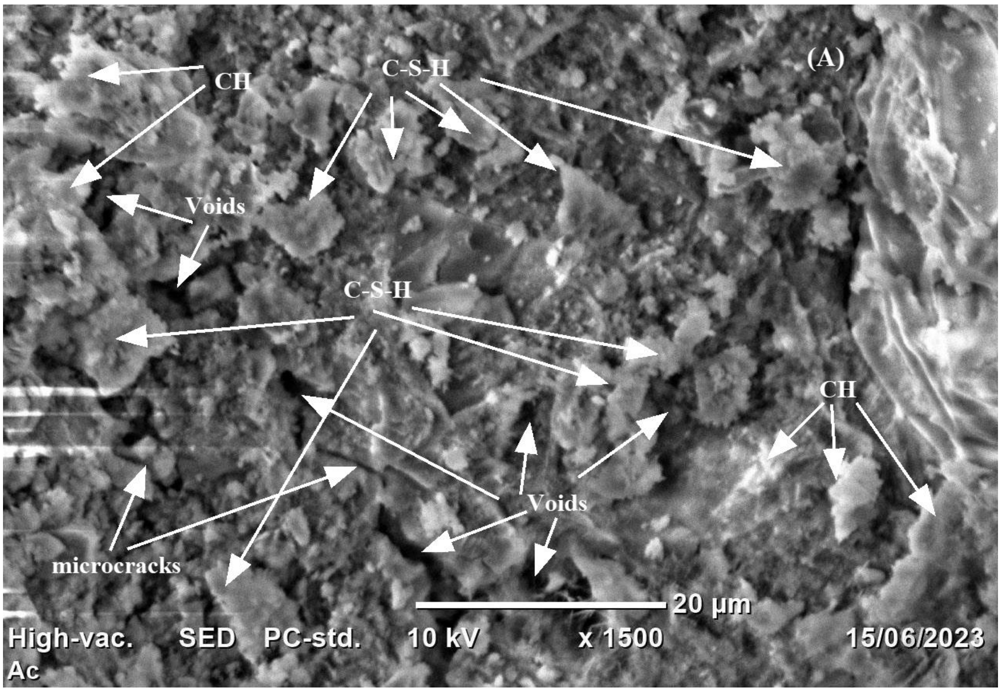
4.5.3 Result of Scanning Electron Microscope (SEM)

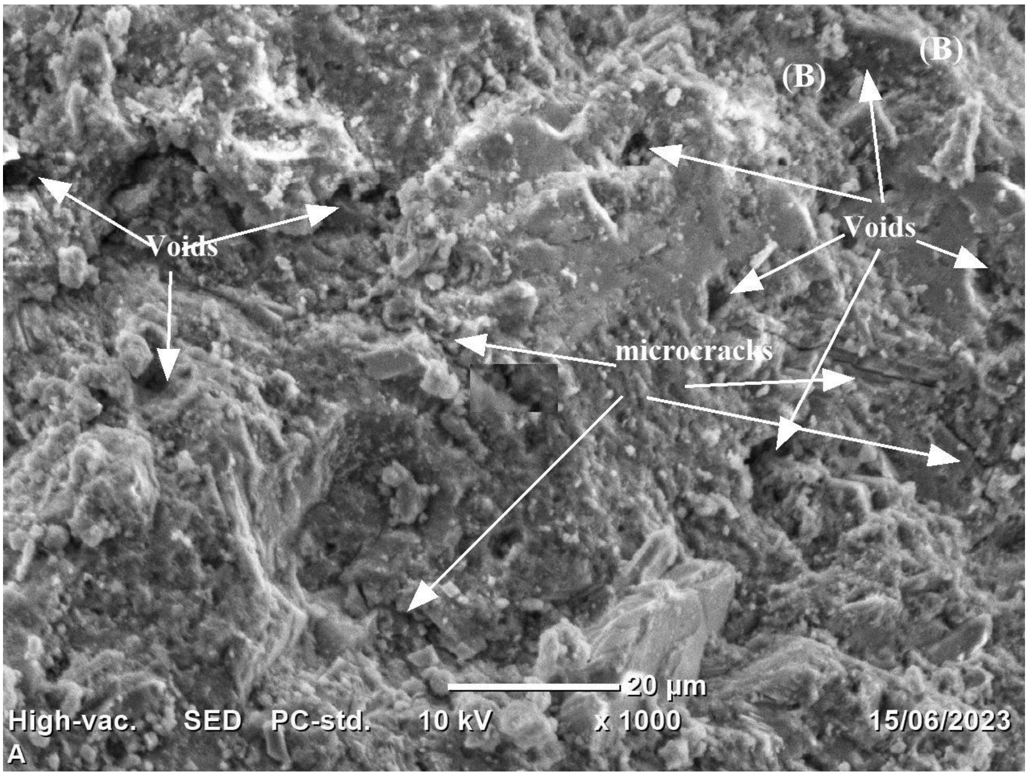
Scanning electron microscopy is used to investigate the morphology of shape, size, and texture of the control concrete, 10% replaced cement with ferrock based concretes with and without oxalic acid are conducted and the taste results are discussed as follows. In SEM images, light grey irregular shape areas show calcium hydroxide crystals, dark gray areas represent calcium silicate hydrate, and black areas indicate pores and cracks (Scrivener, 2004).

Shape featured in Figure 4.12 (A), named calcium hydroxide (CH), the outer shapes are irregular, and it is somewhat brighter appearance than the C-S-H. Figure 4.12 (A) indicates two of them, and there are several others. Calcium hydroxide is an important product in cement paste. It can be notable and distinguished from other products in cement pastes by a gray level very little brighter than that of C– S–H gel. Even so, it requires sometimes close examination to be separated from other hydration products.

Pore space and micro cracks usually present in significant contents in the cement paste, and it can be detected by SEM images. The w/c ratio and degree of hydration are greatly affecting the total contents of pore spaces. Figure 4.12 (A); (B); (C) shows an example of such pores and micro cracks.

Mehta and Monteiro (2014) noted that C-S-H formed by pozzolanic reactions at a later age is characterized by micro-porous and low density features, which cause low grey level (dark colour). This concept is further supported by the SEM images shown in Figure 4.12 (B) and (C). The benefit of using mineral admixture is a physical effect of pore size refinement and filling up capillary pores and crack spaces, thus improving the microstructure of cement paste. The SEM images of the Ferrock containing oxalic acid cement paste samples presented in figure 4.13 also support this suggestion. As seen from the images, when compared to the conventional cement paste as in Figure 4.12 (A), the cement paste with Ferrock containing oxalic acid based additives in Figure 4.12 (C) have much less pores areas and smaller crack widths. This is attributes to the later production of C-S-H caused by pozolanic reactions filling up pores and led to reduce the width and number of cracks, increase the homogeneity of the matrix producing more denser area, which leads to a stronger and durable concrete. The SEM image of 10% Ferrock without oxalic acid based concrete shown in figure 4.12 (B) and 4.14 shows that there are microcracks and pores larger in number as well as length than the control and Ferrock containing oxalic acid leading to reduced strength and durability.





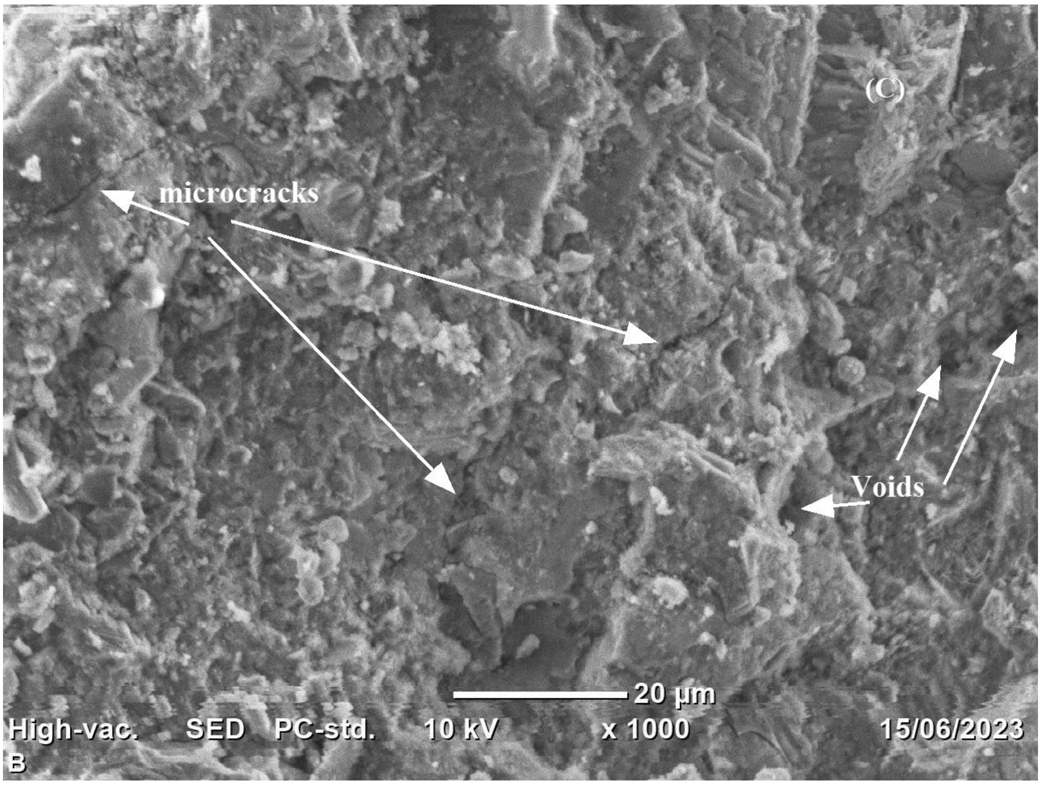


Figure 4.12 SEM image of A) C-25 Control concrete; B) Ferrock without oxalic acid; C) ferrock with oxalic acid

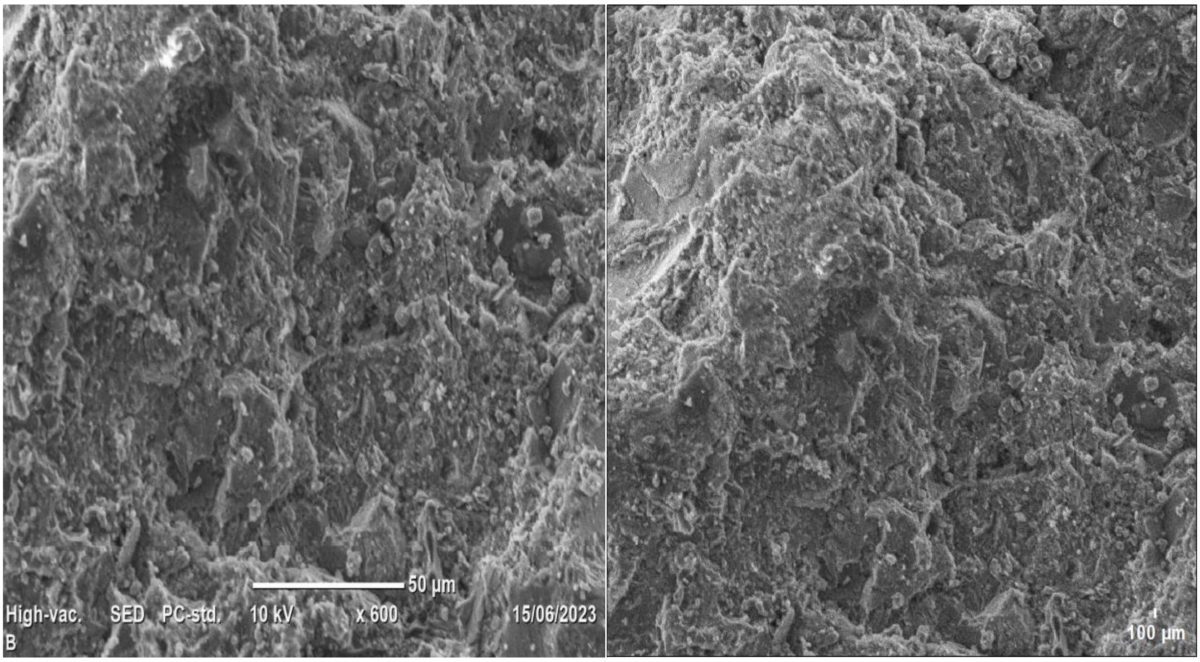


Figure 4.13 SEM image of Ferrock based concrete with oxalic acid

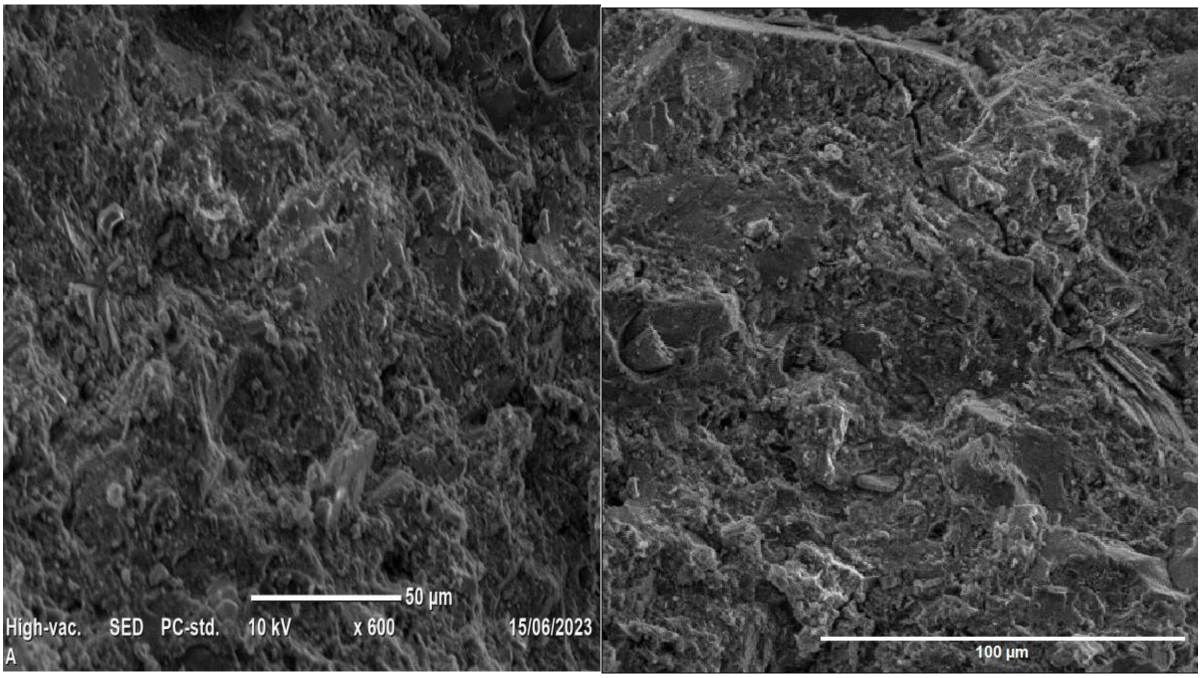


Figure 4.14 SEM image of Ferrock based concrete without oxalic acid

4.6 Cost Analyses and environmental assessment

4.6.1 Cost analysis

In particular, workability, strength, and affordability should be taken into consideration while selecting materials for use in concrete production. The condition relating to the economy of the mixture is one of those three requirements that are fundamental to the price of the concrete. The effect of replacement of cement by ferrock on the cost of concrete, which is expressed by cost per cubic meter of concrete, is assessed based on the material prices collected from most common sources and suppliers in Adama City.

Improved probabilistic socioeconomic forecasts, climate models, damage functions, and discounting techniques that collectively reflect theoretically coherent risk valuation have been shown to significantly enhance estimates of the carbon tax of CO_2, according to a research by Rennert et al,. (2022) at a near-term risk-free discount rate of 2%, the recommended mean carbon tax of CO_2 estimate is $185 (10141.7 Birr) per tonne of CO_2, which is 3.6 times higher than the US government's current estimate of $51 (2795.82 Birr) per tCO_2 (Rennert et al., 2022). According to Hendriks et al. (2004) for every 1kg of cement produced, 0.9kg of CO_2 is evolved, and this equates to the evolution of about 3.24 billion tons of CO_2/year for the current projected 3.6 billion produced annually, and these figures don’t take into account the emissions from the quarrying and transportation of raw materials and the transport and delivery of produced cement (Hendriks et al., 2004).

Ferrock absorbs 8-11 % of CO_2 from the environment, making it a greener, environmentally friendly material. Therefore, using 5 to 20% modified ferrock-based SCMs will lead to lower global warming potential making it sustainable.

The cost comparison only considers direct cost of material and transportation, also the carbon tax of CO_2 is used for comparison. Other costs such as labor cost, equipment cost, profit, maintenance, and overhead costs are not included here. The unit cost of cement was taken as the average cost of Dangote OPC and National cement OPC, which are mostly, used cement in Adama City and the cost of ferrock waste was determined with respect its different ingredients. Due to the fluctuation of the current market, the price of ingredients was collected between April and May by interviewing local suppliers informally as presented in Tables below.

Table 4.11 Social cost of CO_2 for cement and ferrock

Ingredients	Cement	Ferrock
CO_2 emission/100Kg	90	-10
CO_2 emission/1Kg	0.9	-0.1
SC of CO_2 /100Kg	912.78	-101.42
SC of CO_2 /1Kg	9.1278	-1.0142

Table 4.12 Cost of ingredients from different sources and suppliers

Ingredients	price Birr	Average Birr	Unit Price/Kg
Cement (per 100kg)	1,885.00	1,842.50	18.43
	1,800.00		
Ferrock W/O oxalic acid	250.00	250.00	2.50
Ferrock with oxalic acid	967.00	967.00	9.67
Coarse aggregate (per m^3)	1,700.00	1,750.00	1.08
	1,800.00		
Sand (per m^3)	2,250.00	2,275.00	1.43
	2,300.00		
Tap water (per 100kg)	150.00	150.00	1.5

Making use of Table 21 in APPENDIX 4 shows the partial replacement of cement with ferrock containing oxalic acid up to 20% can save cost of concrete up to 12.5% as compared to the control mix, as observed from the table above partial replacement of cement with ferrock without oxalic acid up to 20% can save cost of concrete up to 18.1% as compared to the control mix. As 10% replacement of cement with ferrock containing oxalic acid showed better performance from durability as well as strength aspect, it can save up to 5.9% cost making it economical as well. According to cost analysis as the percentage replacement rate of ferrock increases the cost is decreasing.

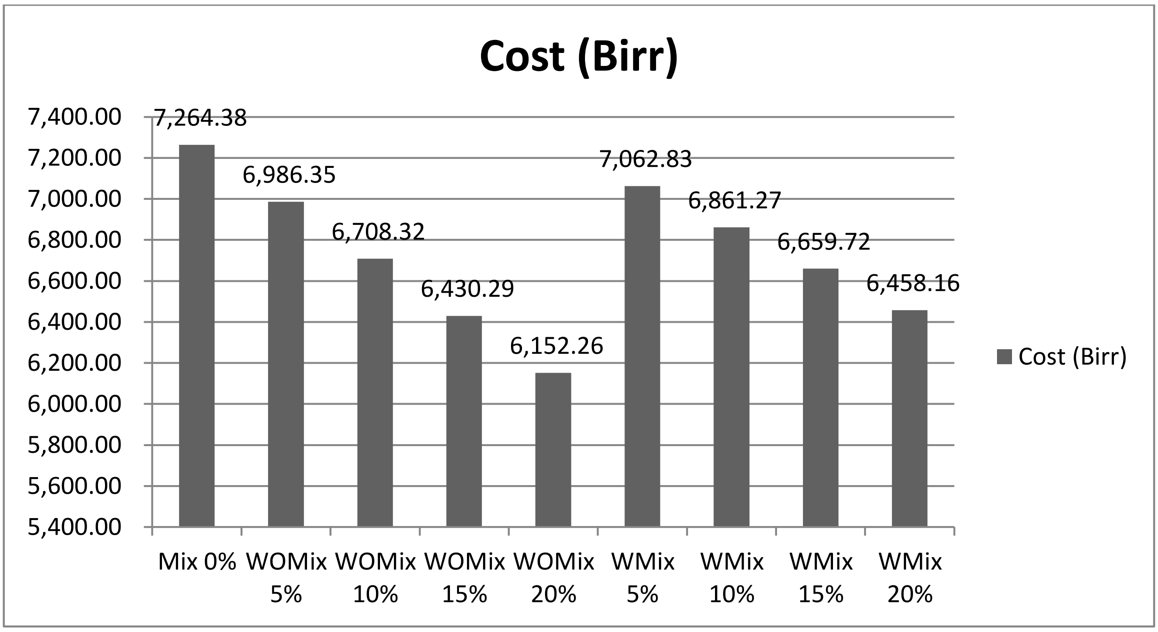


Figure 4.15 Cost comparison of concrete containing ferrock cement with conventional concrete

4.7 Environmental assessment

The iron powder/ dust is hazardous and harmful to the environment, can cause an explosion and is generally disposed-off in landfilling, costing huge disposal costs to steel mills; however, its use as an alternative to cement can give some environmental benefits though making slightly lesser cost-effective/ economical in comparison to OPC (Nadir et al., 2022; García et al., 2017).

From the carbonation depth test, it is evident that the ferrock blocks absorbs considerable amount of CO_2 from the atmosphere and it is fully carbonated, as well as it also reduces the amount of CO_2 emitted from the construction industry which is currently 70%. Ferrock, being

Environmental friendly and all the raw materials used are from scratch, is an efficient concreting technology both in terms of strength and environmental efficiency. The incremental addition of oxalic acid increases the production of iron carbonate which respectively reflects in increased strength (Prashanth et al., 2019).

Stone and Widera (2016) introduced ferrock as a novel material as low energy embodied, CO_2 negative, environmentally friendly material which absorbs around 9-12% CO_2 of its weight of use from the environment (Vijayan et al., 2020; Sumanta et al., 2014; Widera & Stone, 2016). The study by Garcia et al. (2017) elucidated that ferrock is CO_2 negative, either absorbing CO_2 from the environment or absorbing CO_2 produced during hydration of OPC if ferrock is used as SCM with cement concrete (Nadir et al., 2022; García et al., 2017). They have estimated/ compared the energy use in MJ/FU (mega joules per fibrin unit), use of water in L/FU (litres per fibrin unit) and global warming potential/ emission of CO_2 in Kg CO_2 equivalent per fibrin unit for OPC and ferrock (Nadir et al., 2022; García et al., 2017), they assumed the production of ferrock as a by-product obtained during shot blasting and cleaning of scrap iron in steel mills; therefore, CO_2 emission or energy and water used during this process are actually consumed by production of steel, not by the production of ferrock. It is suggested that the energy used by cement production is 5887 MJ/FU, which is ten times higher than the energy used by the production of ferrock with 557 MJ/FU. 10100 litres/ FU of water is used by cement which is 45 times higher than the use of water by ferrock production (220 litres/ FU). The cement is estimated to contribute 1040 Kg CO_2 -eq/FU (emission of 1 ton of CO_2 / ton of OPC). In contrast, ferrock is estimated to consume/ absorb 50 Kg CO_2 -eq/FU from the environment for carbonation of iron powder during the formation process of $FeCO_3$, creating a negative balance and resulting in almost 21 times lesser contribution to global warming potential (Nadir et al., 2022; García et al., 2017). The ferrock's contribution to the absorption of CO_2 from the environment/ hydration process of OPC, if used as an SCM, suggests it as a greener, environmentally friendly material which exhibits at par engineering properties to OPC. However, its economic use is still a question mark on its large-scale use due to less production from steel mills and transportation costs from steel mills to the point of sales/ use. Therefore, using ferrock as an SCM is highly recommended near steel mills where easy supply with lesser transportation cost is feasible.

CHAPTER 5

5 COCLUSION AND RECOMMENDATION

5.1 Conclusion

The study's results, which were highly intriguing and encouraging and were strongly supported by recent research, clarified ferrock as a feasible and sustainable SCM. Based on the investigations the following conclusions are made:-

- The workability of concrete decreased as the percentage replacement cement with ferrock increased as the quantity of water remains the same for all mixes and this is due to the specific surface of ferrock cement is greater than cement, these therefore increases the water demand as the ferrock cement content increases.
- The water absorption was least at 10% replacements using ferrock cement containing oxalic acid. Due to the filling effect of ferrock, fewer conductivity voids were made at these percentage replacements. The water absorption showed an increasing pattern using ferrock without oxalic acid from 7.03% to 7.91% with 10%-20% replacement of cement compared to all the specimens.
- The sulfate attack resistance test result using mass loss of the concrete specimens exposed to 5% sodium sulphate attack was smaller in all percentage replacements relative to the control concrete samples, except for 20% replacement of ferrock without oxalic acid with a 0.423% mass loss.
- The performance under compressive strength test of the control concrete was observed better in the first 7 days of curing except for the 5 and 10% replacement of cement with ferrock cement containing oxalic acid mix of all mixes. After 28 days of curing the 5-10% ferrock cement containing oxalic acid exhibited 3.37 to 23.91% more compressive strength than the control mix. The 10% ferrock containing oxalic acid exhibited the maximum compressive strength of 38.7MPa (23.91% increase) on 28 days of curing. Replacement of 15 and 20% ferrock cement containing oxalic acid exhibited a gradually decreasing trend of 0.87%-8.54% in compressive strength. 5% replacement with ferrock without oxalic acid showed a better 28 days compressive strength that the 20% replacement with ferrock containing oxalic acid. The maximum decrease in compressive strength of 20.39% was observed in 20% ferrock cement without oxalic acid, followed by

a 14.94% decrease in 15% replacement of cement with ferrock cement without oxalic acid.

- The flexural strength performance for the 5 and 10% replacement of cement with ferrock cement containing oxalic acid mix of all mixes showed a percentage increase of 2.24% and 5.79% respectively from the control concrete. The 28 days flexural strength was enhanced at 5% and 10% replacements with ferrock cement containing oxalic acid. It is increased by 6.25% and 9.1% at 5% and 10% replacements respectively. Replacement of 15 and 20% ferrock cement containing oxalic acid exhibited a gradually decreasing trend of 4.97% to 12.15% in flexural strength. Replacement of cement using ferrock without oxalic acid showed a decreasing pattern of 5.25% to 20.01% as the percentage of replacement was increased from 5 to 20%.
- When oxalic acid is not used, the reaction between the iron oxide and the fly ash is slower, which resulted in a weaker and less durable material. Here are some of the effects of oxalic acid on ferrock:
  - ✓ Increased strength: Oxalic acid helps to speed up the hydration reaction, which results in a stronger material.
  - ✓ Increased durability: Oxalic acid helps to make the concrete less permeable and more durable to sulfate attack.

  Overall, oxalic acid is a beneficial additive that can improve the properties of ferrock based concrete. If you are considering using ferrock, it is important to use oxalic acid as directed.
- As concluded by microstructure study using SEM the use of 10% Ferrock containing oxalic acid led to reduce the width and number of cracks, increase the homogeneity of the matrix producing more denser area, which leads to a stronger and durable concrete. As compared to the control concrete and 10% Ferrock without oxalic acid based concrete.
- The cost analysis shows that partial replacement of cement with ferrock that contains oxalic acid up to 20% can reduce the cost of concrete by as much as 12.5% when compared to the control mix. Similarly, partial replacement of cement with ferrock without oxalic acid up to 20% can reduce the cost of concrete by as much as 18.1% when compared to the control mix. In general, the use of ferrock for partial cement replacement could help to overcome the limitations and problems on the cost, energy, and demand of cement in addition to the environmental benefit.

5.2 Recommendation

Based on the insights gained from the study, the incorporation of ferrock in cement improves the performance of concrete. This research mainly studied the influence of ferrock based Cement on different properties of concrete such as workability, durability, compressive and flexural strength. Issues which are not addressed in this research and areas for future works are also forwarded as recommendations as bellow.

  - Further investigation on-resistance of ferrock based concrete to alkali-silica reactions; aggressive environment, freeze and thaw cycles and resistance to high temperatures are needed.
  - The reaction between ferrock and ordinary Portland cement when mixed with water shall be checked using advanced technologies like X-ray diffraction analysis (XRD).
  - The effect of the partial replacement of cement with ferrrock cement incorporating other admixtures other than oxalic acid should be studied since it causes an increase in the initial cost of ferrock based concrete.
  - The strength and durability of ferrock cements without oxalic acid at a longer curing age of 56 days and above need to be studied as they are more economical if they can attain the required strength.

- A much more extensive field study on a concrete structure made with ferrock cement concrete mixture should be conducted and changes in elastic modulus and mechanical properties should be investigated.
- Ferrock cement containing oxalic acid as investigated in this research can be used as a cement replacing material with economical, strength, durability and environmental advantages, Therefore concerned bodies should be made aware about this potential cement replacing material and promote its standardized production and usage.
- Due to lower to no production from steel mills the economic viability of using ferrock on a broad scale is still in doubt in developing countries.

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APPENDICES

Appendix 1: Physical Property Test Results for Cement and Aggregates

A. Consistency Taste for Blended cement paste

The normal consistency of hydraulic cement was checked to know the amount of water required to make a neat paste of satisfactory workability. The result of all blended cement pastes are presented below:

Table 1 Trial of normal consistency of blended cement

mix's	Wt. of blended Powder (g)	Wt. of water (ml)	W/C	Penetration Depth (mm)
Mix 0%	500	130	0.26	6
	500	140	0.28	10
WOMix 5%	500	130	0.26	5
	500	140	0.28	10
WOMix 10%	500	140	0.28	8
	500	142.5	0.285	9.5
WOMix 15%	500	142.5	0.285	8
	500	145	0.29	10
WOMix 20%	500	145	0.29	8.5
	500	147.5	0.295	10
WMix 5%	500	130	0.26	5
	500	140	0.28	10
WMix 10%	500	140	0.28	8
	500	142.5	0.285	9.5
WMix 15%	500	142.5	0.285	8
	500	145	0.29	10
WMix 20%	500	145	0.29	8.5
	500	147.5	0.295	10

B. Coarse Aggregate

The following tests were conducted for coarse aggregate as per ASTM C 33 standards.

1. Moisture content test

According to ASTM C 566, moisture content test is the test that shows the amount of water or moisture in coarse aggregate. The following data are the samples weights are taken to the calculation.

- Weight of the original sample (OS) = 1000g
- Weight of the oven dry sample (ODS) = 987g

$$\text{Moisture Content} = \frac{\text{OS} - \text{ODS}}{\text{ODS}} * 100$$

$$= \frac{1000-987}{987} * 100 = 1.32$$

Therefore the result shows that we must account the water that is greater than that of the water absorption of the material.

2. Gradation test

Gradation test was performed as per ASTM C136. Aggregates having a particle size larger than 4.75 mm are considered as coarse aggregate and 25 mm nominal maximum aggregate size was taken to conduct this study.

Table 2 Sieve analysis for coarse aggregate

Sieve size (mm)	Weight Retain(gm.)	Weight Retained (%)	Cumulative Retained (%)	Cumulative Passing (%)	Cumulative passing (%)
37.5mm	0	0	0	100	100
25mm	210	4.2	4.2	95.8	90-100
19 mm	1682.5	33.65	33.65	66.35	40-85
12.5 mm	2050.5	41.01	74.66	25.34	10--40
9.5 mm	728	14.56	89.22	10.78	0-15
4.75 mm	329	6.58	95.8	4.2	0-5
Total	**5000**				

Therefor according to the ASTM C136 standard the gradation test for coarse aggregate was satisfied for the requirement.

3. **Unit weight test**

Unit weight also known as bulk density and conducted according to ASTM C 29. It is the weight of aggregate in a given volume of graded aggregate. It includes the aggregate and the void space between the aggregate and the unit weight for normal weight concrete ranges from 1120 to 1920 kg/m^3.

$$\text{Weight of the container WC} = 4.734\text{kg}$$

$$\text{Mass of container + mass of the sample (WC + WS)} = 6.952\text{kg}$$

$$\text{Volume of the container (VC)} = 0.001375\text{m}^2$$

$$\text{unit weight} = \frac{[(\text{WC} + \text{WS}) - \text{WC}]}{\text{VC}}$$

$$= \frac{6.952-4.734}{0.001375} = 1613.09\ \text{Kg/m}^3$$

4. **Specific gravity and absorption test**

According to ASTM C 127, specific gravity is the ratio of the mass of a unit volume of material to the mass of the same volume of water at stated temperature while water absorption is the increase in the weight of aggregate due to water in the pore of materials. Due to the time that this research is under taken was summer time there was must to identify the water absorption and moisture content carefully.

$$\text{Oven dry weight (OW)} = 4966\text{gm}$$

$$\text{Weight of saturated surface dry sample on air (SSD in air)} = 5000\ \text{gm}$$

$$\text{weight of saturated surface dry sample in waater (SSD in water)} = 3215\text{gm}$$

$$\text{Bulk specific gravity (SSD)} = \frac{(\text{SSD in air})}{(\text{SSD in air}) - (\text{SSD in water})}$$

$$= \frac{5000}{5000 - 3215} = 2.8$$

$$\text{Absorption, \%} = \frac{(5000 - 4966)}{4966} * 100 = 0.69$$

Therefore, both the bulk specific gravity and absorption are within the range between 2.4 and 3.0 and 0.5% and 4% respectively. It can be used for concreting.

C. Taste for Fine Aggregate

1. Moisture content test

According to ASTM C 566 covers the determination of the percentage of evaporable moisture in a sample of aggregate by drying both surface moisture and moisture in the pores of the aggregate.

- Weight of the original sample (OS) = 2000 g
- Weight of the oven dry sample (ODS) = 1944.9 g

$$\text{Moisture Content} = \frac{\text{OS} - \text{ODS}}{\text{ODS}} * 100 = \frac{2000 - 1944.9}{1944.9} * 100 = 2.83\%$$

Since the weather condition is rainy it's expected that the sand has moisture content so it's must to adjust the amount of water that is added to the concrete.

2. Gradation test

Gradation test was performed as per ASTM C136. Aggregates having a particle size smaller than 4.75 mm can be considered as fine aggregate. Weight of sample taken = 500gm

Table 3 Sieve analysis results of fine aggregate

Sieve Size	Weight Retain (gm.)	Weight Retained (%)	Cumulative Retained (%)	Cumulative Passing (%)	Cumulative Passing (%)
9.5mm	0	0	0	100%	100
4.75mm	14	2.8	2.8	97.20%	95-100
2.36mm	64	12.8	15.6	84.40%	80-100
1.18mm	81	16.2	31.8	68.20%	50-85
600μm	131	26.2	58	42.00%	25-60
300μm	86	17.2	75.2	24.80%	10--30
150μm	106	21.2	96.4	3.60%	2--10
Pan	18	3.6	-	-	-
Total	**500**		279.8	-	-
			FM = 2.80		

$$\text{finess} = \sum \text{Cummulative \% of } \frac{\text{retained}}{100} = \frac{279.8}{100} = 2.8$$

3. Unit weight test

Unit weight also known as bulk density and conducted according to ASTM C 29; the unit weight of the fine aggregates is between 1280 to 1920 kg/m which is helps to determine the weight of sand in a given volume of graded sand.

Description	**Variable**	**Weight Kg)**
Weight of sample + measure	A	6.922
Weight of measure	B	4.734
Volume of measure(m^3)	C	0.001375

$$\text{Unit weight} = \frac{A - B}{C} = \frac{6.922 - 4.734}{0.001375} = 1591.25\ \text{Kg/m}^3$$

4. Specific gravity test

According to ASTM C 128, the bulk specific gravity of fine aggregates ranges between 2.6 to 2.8. Consequently, a sample having a bulk specific gravity of 2.66 is suitable for concrete production. Due to the time that this research is under taken was rainy time it was must to identify the water absorption and moisture content carefully.

$$\text{Weight of the sample, SSD} = 500\text{g}$$

$$\text{Weight of pyconometer} + \text{water} = 1590\text{g}$$

$$\text{Weight of pyconometer} + \text{water} + \text{sand} = 1902\text{g}$$

Weight of oven dried sample on air = 495 g

$$\text{Bulk specific gravity (SSD)} = \frac{500}{(500 + 1590 - 1902)} = 2.66$$

$$\text{Apparent specific gravity} = \frac{495}{(495 + 1590 - 1902)} = 2.705$$

5. Absorption test

According to ASTM C 128 to test the increase in weight of aggregate due to water in the pore of the material so the water absorption of the material must be tested. Absorption is a measure of the total pore volume accessible to water. It’s also useful for mix design moisture adjustment. The absorption of 1.01% is well within the maximum limit of 4%.

Weight of SSD = 500 g

Weight of oven dried sample on air = 495 g

$$\text{Absorption, \%} = \frac{(500 - 495)}{495} * 100 = 1.01\%$$

2. Silt content

The silt content of sand was determined according to ASTM C 117; it covers the determination of the amount of material finer than a 75-µm (No. 200) sieve in aggregate by washing and testing the amount of the dust that is found on the material.

ASTM C 33, “Concrete Aggregates,” limits the percentage of material finer than a 75µm (No.200) sieve to 3% for fine aggregate subject to abrasion, 5% for fine aggregate used in any other concrete.

In this research the sand that used was Awash basin sand. Sample calculation for trial 1

$$\text{Deposit of clean sand (A)} = 300 \text{ ml}$$

$$\text{silt deposited above the sand (B)} = 7.5 \text{ ml}$$

$$\text{Silt content} = \frac{\text{silt deposited above the sand (A)}}{\text{Deposit of clean sand (B)}} * 100 \ = 2.5\%$$

Item	Trial 1	Trial 2	Trial 3	Average
A	7.5	8.1	6	7.2
B	300	300	300	300
Silt content(%) =(A/B)*100	2.5	2.7	2	**2.4**

Therefore the average silt content of the sample is 2.4%.

Appendix 2: Mix Design

Concrete mix design (Mixture proportioning) refers to the process of determining the quantities of concrete ingredients, to achieve the specified characteristics of the concrete both in the fresh and hardened state. Before the proportioning of a concrete mixture, material characteristics should have to be tested and mixture characteristics and type are selected based on the intended use of the concrete. Concrete mix design can be calculated both in weight and volume method. But, in this paper weighing method of mix design is selected. .

According to ACI 301-99 (ACI 301-99, 1999) performance and design requirement to provide workability and consistency, average compressive strength provides an average adequate compressive strength. The required average compressive strength f'_{cr} was calculated for the specified class of concrete in accordance with one of the following:

Table 4 Average compressive strength conversion

Specific compressive strength f'c, Mpa	Required average compressive strength f'c, Mpa
Less than 21	f'c + 7
21 to 35	f'c + 8.5
Over 35	1.1 f'c + 5

Where: f'c = specified strength (MPa)

The specified compressive strength, f'c, MPa is 25 and required average compressive strength f'c, MPa be = 25MPa + 8.5 = 33.5 MPa. Target mean strength for C-25 grade concrete is 33.5 N/mm^2, and ACI 211-1-81 Table A-1.5.3.4(a) Water to cement ratio was 0.491. Slump of concrete was supposed 75-100 mm. Standard cast iron molds of size 150mm*150mm*150mm were used in the preparation of cubes for compressive strength and permeability tests and rectangular beam size of 100mm*100mm*500mm were used for flexural strength test. The molds have been cleaned to remove dust particles and applied with burned oil on all sides before the concrete is poured into the mold.

1. **Slump selection**

From table 3 (ACI-2111_91), maximum slump = 100 mm and minimum slump= 75mm.

2. **Maximum size of aggregate selection**

- 25 mm maximum Nominal aggregate size was used
- sand or fine aggregates = 4.75mm

3. **Estimation of mixing water and air content**

Assume non air entrained concrete

Table 5 Approximate Mixing Water and Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregates (ACI-2111_91)

NON AIR ENTRAINED CONCRETE								
Slump (mm)	9.5mm	12.5mm	19mm	25mm	37.5mm	50mm	75mm	150mm
25 to 50	207	199	190	179	166	154	130	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	-
more than 175	-	-	-	-	-	-	-	-
Approximate amount of entrapped air in non-air entrained concrete (%)								
Slump (mm)	9.5mm	12.5mm	19mm	25mm	37.5mm	50mm	75mm	150mm
All	3.0	2.5	2.0	1.5	1.0	0.5	0.3	0.2

From table 4 of ACI standards, for non-air entrained and slump of 75-100, the water in 1m³ of concrete is 193 Kg

4. **Water to cement ratio selection**

From ACI 211-1-81 Table A-1.5.3.4(a) Water / Cement Ratio is taken as 0.491 The ACI table below cannot provide the exact value of the water-cement ratio for a 33.5 MPa mean strength. This can be calculated via interpolating the above and below values follows: 33.5 MPa is found between 35 and 30 MPa.

By interpolation we obtain w/c= 0.491, Hence, the minimum water cement ratio is 0.491

Table 6 Average compressive strength with water cement ratio

Compressive strength at 28 days (Mpa)	Water Cement ratio
45	0.38
40	0.42
35	0.47
30	0.54
25	0.61
20	0.69
15	0.79

5. **Calculation of cement content:**

For slump of 75-100mm

Water content=193 Kg/m³

Water/cement = 0.491

Cement content = water content / (w/c) = 193/0.491 = 393.07 Kg/m^3

6. **Estimation of coarse aggregates content**

Volume of coarse aggregate per unit volume of concrete for different fineness moduli of fine aggregate (ACI-2111_91)

Table 7 Volume of coarse aggregate per unit volume of concrete

Nominal maximum size of aggregate (mm)	2.40	2.60	2.80	3.00
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72
75	0.82	0.80	0.78	0.76
150	0.87	0.85	0.83	0.81

The quantity of coarse aggregate estimated from ACI 211-1-81 Table A- 1.5.3.6 for finesse modules of 2.8 and 25mm Nominal size of coarse aggregate, the table indicates the volume of Coarse aggregate to be used is 0.67.

Mass of coarse aggregate = bulk volume * bulk density of coarse aggregate

=1613.09*0.67 = 1080.77 Kg/m^3

7. **Determining the solid volume of coarse aggregate.**

$$\text{Solid volume of coarse aggregate} = \frac{\text{Weight of coarse aggregate}}{\text{Specific gravity}}$$

$$= \frac{1080.77}{2.8} = 385.99\text{Kg/m}^3$$

8. **Calculating the solid volume of cement, water, and air**

$$\text{Volume of cement (VC)} = \frac{\text{Weight of cement}}{\text{Specific gravity of cement}}$$

$$= \frac{393.07}{3.15} = 124.78\ \text{Kg/m}^3$$

$$\text{Volume of water (VW)} = 193\text{Kg/m}^3$$

$$\text{Volume of Air (VA)} = 1.5\% = 15\text{Kg/m}^3$$

9. **Calculating solid volume of sand**

Solid volume of sand = 1000 - (VCA+VC+VW+VA)

= 1000 – (385.99 + 124.78 + 193 + 15)

= 1000 – 718.77 = 281.23Kg/m^3

Solid weight of sand= dry volume of sand x specific gravity

= 281.23 kg/m^3*2.705

= 760.73 kg/m^3

10. **Adjustments for moisture in the aggregate**

Fine aggregate adsorption =2.83% and coarse aggregate absorption = 1.32%

Water absorbed by coarse aggregate = 1,080.77 kg/m^3 x 0.0132 =14.27 kg/m^3

Water supplied by fine aggregate =760.73 kg/m^3x 0.0283 = 21.53 kg/m^3

Amount of water needed =193 kg/m^3 + 14.27 kg/m^3 – 21.53 kg/m^3

= 185.74 kg/m^3

Amount of Cement = 393.07 kg/m^3

Amount of Fine aggregate = 760.73 kg/m^3 + 21.53 kg/m^3 = 782.26 kg/m^3

Amount of Coarse aggregate = 1080.77 kg/m^3 – 14.27 kg/m^3 = 1066.5 kg/m^3

Hence the estimated batch weight for 1m^3 of concrete is given in the table below

Table 8 The estimated ingredients for a meter cube of concrete

Water	185.74 kg/m^3
Cement	393.07 kg/m^3
Fine Aggregate	782.26 kg/m^3
Coarse Aggregate	1066.5 kg/m^3

Table 9 Mix Ratio for C-25 Concrete grade

Ingredients	Cement	Fine Aggregate	Coarse Aggregate
Amount in m^3	393.07	782.26	1066.5
Ratio	1.00	1.99	2.71

The proportion of ingredients for the nine types of trial mix in 54 cubes and 54 beams are calculated below but before we proceed with the required quantity of each ingredient let us calculate the total required volume of fresh concrete:

Volume of trial mix equals:

$$= [(0.15 * 0.15 * 0.15) + (0.1 * 0.1 * 0.5)] * 9 * 3 * 2 + 15\% \text{ wastage} + 5\% \text{ shrinkage}$$

$$= 0.5427 \text{ m}^3$$

Appendix 3: Hardened Concrete Properties and Durability Taste Results

A. Compressive strength test

1. Compressive strength at 7 and 28 days of water curing

Table 15 Compressive strength at 7 days of curing

7 days compressive strength of Ferrock based concrete				
Mix' s	Age	load (KN)	Stress (MPa)	weight (Kg)
Mix 0%	7	480	21.33	8.005
		486	21.6	8.012
		469	20.84	8.096
Average		**478.33**	**21.26**	**8.04**
WOMix 5%	7	460	20.44	7.995
		456	20.27	8.072
		455	20.22	8.108
Average		**455.5**	**20.31**	**8.06**
WOMix 10%	7	455	20.22	8.156
		470	20.89	8.132
		462	20.53	8.192
Average		**462.33**	**20.55**	**8.16**
WOMix 15%	7	442	19.64	8.204
		426	18.93	8.055
		430	19.11	8.145
Average		**432.67**	**19.23**	**8.13**
WOMix 20%	7	416	18.49	8.228
		401	17.82	8.264
		406	18.04	8.312
Average		**407.67**	**18.12**	**8.27**
WMix 5%	7	512	22.76	8.075
		494	21.96	8.108
		501	22.27	8.035
Average		**502.33**	**22.33**	**8.07**
WMix 10%	7	552	24.53	8.09
		540	24	8.18
		578	25.69	8.045
Average		**556.67**	**24.74**	**8.11**
WMix 15%	7	462	20.53	8.156
		477	21.2	8.216
		483	21.47	8.115
Average		**474**	**21.07**	**8.16**

WMix 20%	7	436	19.38	8.14
		420	18.67	8.288
		441	19.6	8.252
Average		**432.33**	**19.21**	**8.23**

Table 16 Compressive strength at 28 days of curing

28 days compressive strength of Ferrock based concrete				
Mix' s	Age	load (KN)	Stress (MPa)	weight (Kg)
Mix 0%	28	700	31.16	7.994
		701	31.16	8.024
		706	31.38	8.015
Average		**702.33**	**31.23**	**8.01**
WOMix 5%	28	646	28.71	7.995
		655	29.11	8.005
		650	28.89	8.072
Average		**650.33**	**28.90**	**8.02**
WOMix 10%	28	636	28.27	8.030
		630	28.00	8.120
		624	27.73	8.075
Average		**630.00**	**28.00**	**8.08**
WOMix 15%	28	602	26.76	8.156
		594	26.40	8.252
		597	26.53	8.180
Average		**597.67**	**26.56**	**8.20**
WOMix 20%	28	570	25.33	8.192
		551	24.49	8.125
		557	24.76	8.336
Average		**559.33**	**24.86**	**8.22**
WMix 5%	28	719	31.96	8.144
		732	32.53	8.216
		728	32.36	8.180
Average		**726.33**	**32.28**	**8.18**
WMix 10%	28	854	37.96	8.216
		886	39.38	8.252
		872	38.76	8.168
Average		**870.67**	**38.70**	**8.21**

WMix 15%	28	690	30.66	8.045
		698	31.02	8.228
		702	31.20	8.312
Average		**696.67**	**30.96**	**8.20**
WMix 20%	28	636	28.27	8.345
		650	28.89	8.036
		642	28.53	8.276
Average		**642.67**	**28.56**	**8.22**

B. Flexural strength

Table 17 Flexural strength at 7 days of water curing

Mix' s	Dimension (mm)			P(KN)	M (Nm)	I (m4)	C (cm)	σ (Mpa)
	L	W	H					
Mix 0%	500	100	100	10.41	1041.34	8.33E-06	5.00	3.125
	500	100	100	10.31	1031.34	8.33E-06	5.00	3.095
	500	100	100	10.45	1044.67	8.33E-06	5.00	3.135
Average				**10.39**	1039.12	8.33E-06	5.00	**3.118**
WOMix 5%	500	100	100	10.05	1004.68	8.33E-06	5.00	3.015
	500	100	100	10.27	1027.01	8.33E-06	5.00	3.082
	500	100	100	9.95	994.69	8.33E-06	5.00	2.985
Average				**10.09**	1008.79	8.33E-06	5.00	**3.027**
WOMix 10%	500	100	100	9.81	981.36	8.33E-06	5.00	2.945
	500	100	100	9.75	975.00	8.33E-06	5.00	2.926
	500	100	100	9.65	964.69	8.33E-06	5.00	2.895
Average				**9.74**	973.68	8.33E-06	5.00	**2.922**
WOMix 15%	500	100	100	9.21	921.38	8.33E-06	5.00	2.765
	500	100	100	9.33	933.37	8.33E-06	5.00	2.801
	500	100	100	9.28	928.04	8.33E-06	5.00	2.785
Average				**9.28**	927.60	8.33E-06	5.00	**2.784**
WOMix 20%	500	100	100	8.71	871.00	8.33E-06	5.00	2.613
	500	100	100	8.78	878.06	8.33E-06	5.00	2.635
	500	100	100	8.90	890.38	8.33E-06	5.00	2.672
Average				**8.80**	879.81	8.33E-06	5.00	**2.640**
WMix 5%	500	100	100	10.53	1053.00	8.33E-06	5.00	3.160
	500	100	100	10.70	1069.66	8.33E-06	5.00	3.210
	500	100	100	10.65	1064.66	8.33E-06	5.00	3.195
Average				**10.62**	1062.44	8.33E-06	5.00	**3.188**
WMix 10%	500	100	100	11.24	1124.00	8.33E-06	5.00	3.373

	500	100	100	10.96	1096.00	8.33E-06	5.00	3.289
	500	100	100	10.78	1078.00	8.33E-06	5.00	3.235
Average				**10.99**	1099.33	8.33E-06	5.00	**3.299**
WMix 15%	500	100	100	10.32	1032.00	8.33E-06	5.00	3.095
	500	100	100	10.20	1019.68	8.33E-06	5.00	3.060
	500	100	100	10.41	1041.34	8.33E-06	5.00	3.125
Average				**10.310047**	1031.00	8.33E-06	5.00	**3.093**
WMix 20%	500	100	100	9.72	972.00	8.33E-06	5.00	2.917
	500	100	100	9.51	951.37	8.33E-06	5.00	2.855
	500	100	100	9.84	984.00	8.33E-06	5.00	2.951
Average				**9.69**	969.12	8.33E-06	5.00	**2.908**

Table 18 Flexural strength at 28 days of water curing

Mix' s	Dimension (mm)			P(KN)	M (Nm)	I (m4)	C (cm)	σ (Mpa)
	L	W	H					
Mix 0%	500	100	100	12.999	1299.92	8.33E-06	5.00	3.901
	500	100	100	12.82	1282.00	8.33E-06	5.00	3.847
	500	100	100	12.84	1283.59	8.33E-06	5.00	3.852
Average				**12.89**	1288.51	8.33E-06	5.00	**3.867**
WOMix 5%	500	100	100	12.18	1217.95	8.33E-06	5.00	3.655
	500	100	100	12.11	1211.28	8.33E-06	5.00	3.635
	500	100	100	12.34	1233.61	8.33E-06	5.00	3.702
Average				**12.21**	1220.95	8.33E-06	5.00	**3.664**
WOMix 10%	500	100	100	11.38	1137.97	8.33E-06	5.00	3.415
	500	100	100	11.26	1126.00	8.33E-06	5.00	3.377
	500	100	100	11.29	1128.64	8.33E-06	5.00	3.387
Average				**11.31**	1130.87	8.33E-06	5.00	**3.393**
WOMix 15%	500	100	100	10.63	1063.00	8.33E-06	5.00	3.190
	500	100	100	10.83	1082.99	8.33E-06	5.00	3.250
	500	100	100	10.89	1088.99	8.33E-06	5.00	3.268
Average				**10.78**	1078.33	8.33E-06	5.00	**3.236**
WOMix 20%	500	100	100	10.31	1031.34	8.33E-06	5.00	3.095
	500	100	100	10.23	1022.68	8.33E-06	5.00	3.069
	500	100	100	10.38	1038.00	8.33E-06	5.00	3.115
Average				**10.31**	1030.67	8.33E-06	5.00	**3.093**
WMix 5%	500	100	100	13.679	1367.9	8.33E-06	5.00	4.105
	500	100	100	13.796	1379.6	8.33E-06	5.00	4.14
	500	100	100	13.612	1361.2	8.33E-06	5.00	4.085
Average				**13.70**	1369.57	8.33E-06	5.00	**4.110**
WMix 10%	500	100	100	13.98	1397.89	8.33E-06	5.00	4.195
	500	100	100	14.19	1419.00	8.33E-06	5.00	4.256

	500	100	100	14.01	1401.22	8.33E-06	5.00	4.205
Average				**14.06**	1406.04	8.33E-06	5.00	**4.219**
WMix 15%	500	100	100	12.32	1232.28	8.33E-06	5.00	3.698
	500	100	100	12.14	1214.00	8.33E-06	5.00	3.641
	500	100	100	12.28	1227.94	8.33E-06	5.00	3.685
Average				**12.25**	1224.74	8.33E-06	5.00	**3.675**
WMix 20%	500	100	100	11.413	1141.31	8.33E-06	5.00	3.425
	500	100	100	11.26	1126.00	8.33E-06	5.00	3.377
	500	100	100	11.29	1129.31	8.33E-06	5.00	3.389
Average				**11.32**	1132.20	8.33E-06	5.00	**3.397**

C. Durability Taste

Table 19 Water absorption results

Concrete mix's	Mass of oven dried sample in air	Mass of surface dried sample in air after immersion	Absorption after immersion in %
Mix 0%	8.099	8.642	6.28
	8.111	8.722	7.01
Average	8.105	8.682	**6.65**
WMix 5%	8.215	8.870	7.38
	8.295	8.710	4.76
Average	8.255	8.790	**6.09**
WMix 10%	8.035	8.470	5.14
	7.955	8.390	5.18
Average	7.995	8.430	**5.16**
WMix 15%	8.165	8.669	5.81
	8.245	8.829	6.61
Average	8.205	8.749	**6.22**
WMix 20%	8.345	8.840	5.60
	8.255	8.930	7.56
Average	8.300	8.885	**6.58**
WOMix 5%	8.230	8.806	6.54
	8.320	8.896	6.47
Average	8.275	8.851	**6.51**

WOMix 10%	7.980	8.575	6.94
	7.910	8.516	7.12
Average	7.945	8.546	**7.03**
WOMix 15%	8.165	8.815	7.37
	8.225	8.875	7.32
Average	8.195	8.845	**7.35**
WOMix 20%	8.075	8.777	8.00
	8.155	8.847	7.82
Average	8.115	8.812	**7.91**

Table 20 Sulfate attack resistance mass loss and compressive strength loss test results

Concrete mix's	Weight before immersion (Kg)	Weight after immersion (Kg)	Mass loss (%)
Mix 0%	7.976	7.949	0.339
	8.048	8.017	0.385
Average	8.012	7.983	**0.362**
WMix 5%	8.190	8.180	0.122
	8.240	8.222	0.218
Average	8.215	8.201	**0.170**
WMix 10%	8.250	8.242	0.097
	8.360	8.346	0.167
Average	8.305	8.294	**0.132**
WMix 15%	8.280	8.271	0.109
	8.310	8.291	0.229
Average	8.295	8.281	**0.169**
WMix 20%	8.326	8.305	0.252
	8.375	8.350	0.299
Average	8.351	8.328	**0.275**
WOMix 5%	8.180	8.169	0.134
	8.212	8.191	0.256
Average	8.196	8.180	**0.195**
WOMix 10%	8.231	8.206	0.304

	8.237	8.224	0.158
Average	8.234	8.215	**0.231**
WOMix 15%	8.310	8.288	0.265
	8.314	8.284	0.361
Average	8.312	8.286	**0.313**
WOMix 20%	8.260	8.234	0.315
	8.274	8.230	0.532
Average	8.267	8.232	**0.423**

Appendix 4: Economical Analysis

Table 21 Material and carbon tax of CO_2 cost per cubic meter concrete

Mixes	Ingredients	Quantity	Unit weight	Price per M^3	Gain/Loss
Per m^3	Cement	393.07	18.43	7,242.31	
	Sand	782.26	1.43	1,118.39	
	Coarse aggregate	1066.5	1.08	1,157.02	
	Water	185.74	1.5	278.61	
	Cement CO_2 emission	393.07	9.1278	3,587.86	
	Total Price			**13,384.20**	
Mix 0%	Cement	213.32	18.43	3,930.40	0
	Sand	425.08	1.43	607.73	
	Coarse aggregate	578.79	1.08	627.91	
	Water	100.80	1.5	151.20	
	Cement CO_2 emission	213.32	9.1278	1,947.13	
	Total Price			**7,264.38**	
WOMix 5%	Cement	202.65	18.43	3,733.88	- 0.040
	Sand	425.08	1.43	607.73	
	Coarse aggregate	578.79	1.08	627.91	
	Ferrock 5%	10.67	2.50	26.66	
	Water	100.80	1.5	151.20	
	Cement CO_2 emission	202.65	9.1278	1,849.78	
	Ferrock CO_2 emission	10.67	-1.0142	- 10.82	
	Total Price			**6,986.35**	
WOMix 10%	Cement	191.99	18.43	3,537.36	- 0.083
	Sand	425.08	1.43	607.73	
	Coarse aggregate	578.79	1.08	627.91	
	Ferrock 10%	21.33	2.50	53.33	
	Water	100.80	1.5	151.20	
	Cement CO_2 emission	191.99	9.1278	1,752.42	
	Ferrock CO_2 emission	21.33	-1.0142	- 21.63	
	Total Price			**6,708.32**	
WOMix 15%	Cement	181.32	18.43	3,340.84	- 0.130
	Sand	425.08	1.43	607.73	
	Coarse aggregate	578.79	1.08	627.91	
	Ferrock 15%	32.00	2.50	79.99	
	Water	100.8	1.5	151.20	
	Cement CO_2 emission	181.32	9.1278	1,655.06	
	Ferrock CO_2 emission	32.00	-1.0142	- 32.45	
	Total Price			**6,430.29**	
WOMix 20%	Cement	170.66	18.43	3,144.32	- 0.181
	Sand	425.08	1.43	607.73	

	Coarse aggregate	578.79	1.08	627.91	
	Ferrock 20%	42.66	2.50	106.66	
	Water	100.8	1.5	151.20	
	Cement CO_2 emission	170.66	9.1278	1,557.71	
	Ferrock CO_2 emission	42.66	-1.0142	- 43.27	
	Total Price			**6,152.26**	
WMix 5%	Cement	202.65	18.43	3,733.88	-0.029
	Sand	425.08	1.43	607.73	
	Coarse aggregate	578.79	1.08	627.91	
	Ferrock 5%	10.666	9.67	103.14	
	Water	100.8	1.5	151.20	
	Cement CO_2 emission	202.65	9.1278	1,849.78	
	Ferrock CO_2 emission	10.666	-1.0142	- 10.82	
	Total Price			**7,062.83**	
WMix 10%	Cement	191.99	18.43	3,537.36	-0.059
	Sand	425.08	1.43	607.73	
	Coarse aggregate	578.79	1.08	627.91	
	Ferrock 10%	21.332	9.67	206.28	
	Water	100.8	1.5	151.20	
	Cement CO_2 emission	191.99	9.1278	1,752.42	
	Ferrock CO_2 emission	21.332	-1.0142	- 21.63	
	Total Price			**6,861.27**	
WMix 15%	Cement	181.32	18.43	3,340.84	-0.091
	Sand	425.08	1.43	607.73	
	Coarse aggregate	578.79	1.08	627.91	
	Ferrock 15%	31.998	9.67	309.42	
	Water	100.8	1.5	151.20	
	Cement CO_2 emission	181.32	9.1278	1,655.06	
	Ferrock CO_2 emission	31.998	-1.0142	- 32.45	
	Total Price			**6,659.72**	
WMix 20%	Cement	170.66	18.43	3,144.32	-0.125
	Sand	425.08	1.43	607.73	
	Coarse aggregate	578.79	1.08	627.91	
	Ferrock 20%	42.664	9.67	412.56	
	Water	100.8	1.5	151.20	
	Cement CO_2 emission	170.66	9.1278	1,557.71	
	Ferrock CO_2 emission	42.664	-1.0142	- 43.27	
	Total Price			**6,458.16**	