UNIVERSITY OF GHANA, LEGON

DEPARTMENT OF APPLIED NUCLEAR PHYSICS

CORROSION BEHAVIOUR OF IRON STEEL BARS ON THE GHANAIAN MARKET; ELEMENTAL COMPOSITION AND MECHANICAL PROPERTIES PERSPECTIVE

ERIC KWADZO AMESIMEKU

JULY 2018

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THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA, LEGON IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF MPHIL APPLIED NUCLEAR PHYSICS DEGREE.

BY

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JULYY 2018

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DECLARATION

STUDENT`S DECLARATION

I, ERIC KWADZO AMESIMEKU, affirm that this Dissertation with the exception of quotations and references contained in other people's works which I have identified all and duly acknowledged, is entirely my own original work, and it has not been submitted, neither in part nor whole for another degree elsewhere.

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SUPERVISOR`S DECLARATION

I hereby declare that the preparation and presentation of this work was supervised in accordance with the guidelines for supervision of Thesis as laid down by the University of Ghana, Legon.

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ACKNOWLEDGMENTS

With the deepest gratitude I wish to thank Almighty God for blessing me with life and good health in my entire journey to complete this research work.

I wish to express my utmost gratefulness to my project supervisor, Dr. Joseph Bremang Tandoh for his magnificent support, contributions, love and patience to complete this research work. I also wish to thank Dr. Charles Kofi Klutse for generously sharing his wisdom and knowledge in completion of this work.

I am equally grateful for the encouragement and financial support from Priscilla Senam Nanedo and my other mates. Further appreciation goes to the entire Akatsi Senior High Technical School and administrative staff of the school.

Finally, I express my gratitude to my Almighty God, Omnipotent and Omniscient Allah once again, all family members and friends who provided support in diverse ways.

May Almighty God Richly Bless You All.

TABLE OF CONTENTS

CONTENT **PAGE**

CHAPTER THREE

METHODOLOGY

LIST OF TABLES

TABLE **PAGE**

LIST OF FIGURES

FIGURE **PAGE**

LIST OF ABBREVIATION

GSA – Ghana Standard Authority

GAEC– Ghana Atomic Energy Commission

pH – Potential of Hydrogen

NaCl – Sodium Chloride

ARC – Accelerator Research Center

PIXE – Proton Induced X-Ray Emission

FCC – Face Centered Cubic

BCC – Body Centered Cubic

EAF – Electric Arc Furnaces

RC – Reinforced concrete

EMF – Electromotive Force

MIC – Microbiologically Influenced Corrosion

ALWC – Accelerated Low-Water Corrosion

SCC – Stress Corrosion Cracking

EIS – Electrochemical Impedance Spectroscopy

YS – Yield Strength

UTS – Ultimate Tensile Strength

SNICS – Source of Negative Ions by Cesium Sputtering

UHV– Ultra High Voltage

HUTM– Hydraulic Universal Testing Machine

QA – Quality Assurance

QC – Quality Control

ISO – International Organization for Standardization

MMPY – millimeter per year

ABSTRACT

Corrosion is the main problem with structural iron steel bars. Iron steel bars undergo electrochemical reaction with its environment. The iron in the iron steel bar oxidizes to form iron (II) oxides, which is another stable form of iron. This means that the structural integrity of an iron steel bar is likely to weaken as time goes by. The aim of this research is to establish an elemental signature that will relate the mechanical properties of locally and imported 16 mm iron steel bars on the Ghanaian market to their sensitivity to corrosion to their elemental composition. Three iron steel bars brands labeled Local 1 (from Ghana), Foreign 1 (China) and Foreign 2 (Ukraine) were sampled for analyses. The samples were cut into 450 mm and their elemental composition, weight loss and mechanical properties such as ultimate tensile strength, yield strength and percentage elongation were tested at Ghana Standard Authority mechanical laboratory before and after corrosion. The Proton Induced X-ray Emission (PIXE) analytical technique method was used to analyze the samples, and the analyte sample was 16 mm iron steel bar mostly used in all building sites. The following elements, Chlorine, Potassium, Calcium, Titanium, Chromium, Manganese, Iron, Nickel, Copper, and Zinc were found present in all the three brands 16 mm iron steel. After the 60 days of immersion of the samples in 5 % NaCl solution the locally manufactured iron steel bar recorded an ultimate strength of 414.10 Nmm^{-2}, the yield strength of 302.10 Nmm^{-2} and percentage elongation of 36.25 %. The Foreign 1 sample taken from China also had an ultimate tensile strength of 468.60 Nmm^{-2}; the yield strength was 389.70 Nmm^{-2} and a percentage elongation of 22.50 %. The samples taken from Ukraine that was named Foreign 2, had an ultimate tensile strength of 528.60 Nmm^{-2}, yield strength produced was 456.00 Nmm^{-2} and percentage elongation of 25.370 %. The results obtained showed a continuous decrease in mass of the iron steel bar samples with an increase in the immersion days. The overall results indicated that corrosion behavior of iron steel bar depends on the chloride ion concentration in the sample's solution. The corrosion rate of the locally manufactured iron steel immersed in 5 % NaCl solution for 60 days was 0.07 mm per year and sample from China corrosion rate was 0.17 mm per year and the Ukraine sample had 0.16 mm per year. Though the locally manufactured iron steel bar recorded the lowest corrosion rate its yield strength dropped drastically as the immersion time increase. Chromium and Manganese were found to be the main elements that relate mechanical strength to corrosion rate of the iron steel bar.

CHAPTER ONE

INTRODUCTION

1.1 Background

The high demand for accommodation in the country over the past decades has resulted in a boost in the building industry. Ghana's middle-income status might be a catalyst to the rapid development of new buildings in the country. In order for both foreign and local investors to tap into this growing market, there is the need to setup more new structures to accommodate the arrival of businesses into the country. However, to satisfy this high demand for accommodation in the country, some building contractors and designers, base the selection of building materials such as iron steel bars which play a very vital role in the structural safety of buildings just on the cost of the material and not the quality of the material. The main problem with iron steel bar in building structures is corrosion. Corrosion is the degradation of iron steel bar when it comes in contact with its environment.

Recently there have been several reports of instances in the world, where the collapsing of buildings have been attributed to the use of substandard materials. An earthquake in Ecuador which destroyed more than 7000 structures, according to experts, attributed the intense of destruction to the quality of the building materials used [1] and also, the high chloride content in the cement which they believed contributed to the high corrosion rate of the iron steel bar reinforcement. The capital city of Ghana, Accra, also recorded four major buildings that failed to withstand the dead load on its tensile strength and hence killed a total of 19 lives between 2012 and 2014. The issue of Melcom building near Achimota which also collapsed in 2012 and killed 14 innocent people whereas the Grand View Hotel building, which is at Nii-Boi Town, also failed in 2014, recorded four deaths.

In Ghana, the only accredited institute mandated to test the quality of iron rods is the Ghana Standard Authority (GSA). This Authority performs only mechanical property test such as yield strength, ductility, hardness and tensile strength although from literature it has been argued that the elemental composition and corrosion sensitivity of iron steel bars have direct implication on its structural integrity.

This research is focused on three most used brands of iron steel bars that are on the Ghanaian market, to perform a corrosion sensitive test and also to determine the elemental composition of the iron steel bar and their effect on mechanical performance.

Moreover, this research will inform other stakeholders that have handful information in the Ghanaian Construction Industry about the elemental composition and corrosion test effect on mechanical performance of the iron steel bars on the Ghanaian market. . Since corrosion has the possibility of negatively affecting the mechanical properties of steel bars with time, comprehensive information of the actual behaviour of steel bars when exposed to a corrosive environment is a vital tool, which will enable designers putting up lifelong buildings in selecting both the type of steel and environmental location to site such buildings. The mechanical properties of building materials are expected to meet the request of the necessary norms underlying organization codes of practices on which designs are based.

The understanding of the necessary building materials used in construction industries such as iron steel bars, aggregates (sand and stone), cement, wood, plastic etc. their physical properties, workability, performance, availability, aesthetics, and cost are essential in selecting a suitable material for a specific purpose [2]. The understanding of the physical properties of these building materials is important, to ensuring the long life span and quality of the buildings that are made with these materials. A summary of the corrosion parameters measured and used for this study is discussed below.

1.2 Corrosion Rate

Corrosion rate is the speed at which a given metal deteriorate in its environment. It is the amount of corrosion loss per period in weight. The elemental compositions of the metal and its environment have direct impact on the corrosion rate. Metals easily undergo electro-chemical reaction with their environment, which declines the reliability of the metal's future. Metallic corrosion is a Lewis acid-base reaction while the metal acts as the Lewis acid and the water in the environment acts as Lewis base, it is an electro-chemical process that occurs at the boundary between the metal and its environment. Corrosion can also be defined as an electrochemical reaction involving anodic metal oxidation and cathodic oxidant reduction [3]. The electrochemical theory is pertinent not only to wet corrosion of metals at normal temperature but also to dry oxidation of metals at high temperature [4].

1.2.1 *Potential Hydrogen (pH) of Corrosion Solution*

The pH of the corrosion solution, measures the amount of concentrated hydrogen ions in the solution. A corrosion solution with a high concentration of hydrogen ions indicates that solution has low pH (Acid); metals in environment with high concentration of hydrogen ions have high corrosion rate and weight loss. When the corrosion solution contains a low concentration of hydrogen ions, it implies the pH of the solution is high (base). A solution with a low concentration of hydrogen ions, the corrosion rate and weight loss is low. The high concentration of hydrogen ions also increases the conductivity rate of the ions in the solution and hence increases corrosion rate. Besides, the corrosion rates of metal in aqueous solution depend on both electrodes potential and potential of hydrogen (pH) [5].

1.2.2 *Conductivity*

Conductivity is the ability of the solution to create enabling environment for ions in the solution to conduct electricity. When the solution is able to conduct electricity, it implies the presences of ions in the solution and hence the solutions now acting like an electrolyte. The current is transferred in the electrolyte solutions by ions, however in metals electrons transfer it. The SI unit of conductivity is siemens per meter (Sm^{-1}). The conductivity depends on the temperature of the solution, concentration of ions in the solution, valence of ions and mobility of ions in the solution.

The ions that are transferred within the NaCl solution enable redox reaction to take place. The iron steel bar in the solution loses electron to oxygen. The NaCl in the solution acts as a medium for ions in the water to move to opposite charge and this movement of the ions in the solution accelerates the reaction by increasing the conductivity of water, effectively increasing the concentration of the ions in the water and so increasing the rate of oxidation of the iron steel bar in the NaCl solution. The corrosion of the iron steel bar depends upon the amount of oxygen in the water and onto the iron steel. Contrarily, the dissolved NaCl in the water also reduced the amount of dissolved oxygen present in the water.

1.2.3 *Alloying Elements in Iron Steel bar*

Metals in its pure state normally are not normally fit to be used for construction works, either they are too soft or not malleable. Alloying elements are introduced in metals to amend their chemical and physical state. The addition of these allowing elements enables the modified metals to be used for a particular application. The presence of alloying elements can affect the mechanical properties of metals such as the strength, ductility, electrical conductivity and corrosion resistance.

The introduction of alloying elements like carbon and manganese to raw iron steel improves its mechanical properties by altering the orderly arrangement of the atoms in the lattice level of the metals and blocks the atoms in the metals from sliding over each other.

Thus the presence of other alloying elements such as chromium (Cr), manganese (Mn), nitrogen (N), nickel (Ni), molybdenum (Mo), titanium (Ti), niobium (Nb), zirconium (Zr), copper (Cu), tungsten (W), vanadium (V), and selenium (Se) enhance the corrosion resistant, oxidation resistant and mechanical properties of the iron steel.

1.3 Statement of the Problem

The rampant collapsing of buildings in the Ghana in recent times has become very distressing, resulting in the killing of innocent people. There have been several reports of similar incidents across the capital, from the Melcom shopping mall collapse at Achimota, Accra in 2012 that killed at least 14 people to the Grandview hotel building collapse in Nii Boi town Accra in 2014, which also claimed 4 lives. In a report by the Director of the Institute of Engineers, these catastrophes were attributed to structural failure of the materials used, which could be substandard. He also suggested that the dampness in buildings also contributes to corrosion of iron steel bar in the buildings, which facilitates the structural degradation over time.

Due to the building craze in Ghana, the demand for steel bars has increased astronomically. This high demand has made it lucrative for some manufacturing countries to produce or smuggle possible inferior, cheap steel bars, which do not meet the correct standards onto the Ghanaian market. Corrosion resistance test is also not a mandatory task performed by the GSA for certification of steel bars onto the Ghanaian market. This I believe to be a problem, because the mechanical properties of metals starts to decrease once corrosion sets in, therefore the resistance of iron steel bars to corrosion is an important test parameter which needs to be known by the customers and engineers.

The need to introduce corrosion resistance test in addition to those carried out by GSA is therefore urgent.

1.4 Aim of Study

To determine how elemental composition of iron steel bars are related to their mechanical properties and corrosion of both locally and imported steel bars on the Ghanaian market to its corrosion resistance.

1.5 Specific Objectives

The specific objectives of the research are to:

- Determine the elemental signatures for three (3) major iron steel bar (iron rod) brands on the Ghanaian market using Ion Beam Technique (Proton Induced X-ray Emission).
- Determine the mechanical properties (tensile strength, yield and elongation) of three (3) iron steel bar brands on the Ghanaian market before and after corrosion tests
- Determine the corrosion rate of three (3) iron steel bar brands on the Ghanaian market using a 5 % NaCl media (Sea environmental conditions) to induce corrosion.
- Determine the effect of corrosion on the mechanical properties of three (3) iron steel bars brands after varying the periods of corrosion tests.

1.6 Significance of the Study

The warrant of the quality of building materials is very paramount in order to build strong durable efficient structures [6]. Hence the outcome of this research will be relevant for all stakeholders of the construction industry, and will contribute to enhancing the credibility of the construction industry for upholding good standards in accordance with the Ghana Building Code. Besides, this study will also inform the general public the importance of the corrosion sensitivity test and its effects on the mechanical properties of steel bars with time.

1.7 Scope of the Study

This research adopts the famous "sea spray test" method to access the corrosion rate of metals. 5 % NaCl solution was used to simulate the extreme conditions of seawater concentration (3.5% NaCl). The corrosion test lasted for a period of 60 days, with various intervals of analysis because of time constraints.

The test of mechanical properties of the sample was also limited to tensile strength, yield strength and percentage elongation, because of the availability of these tools at the Ghana Standard Authority laboratory. Only three brands of the iron steel bars were chosen for the mechanical properties test due to cost of analyses at the GSA for each test, and sample. Ion beam Analysis is used to determine elemental composition of the iron steel bar at the Accelerator Research Center (ARC), Ghana Atomic Energy Commission (GAEC).

1.8 Organization of the Dissertation

The dissertation is grouped into five chapters. The first chapter provides information of the background study, which involves introduction, problem statement, objectives, and significance of the study and scope of the study. Chapter two is the literature review and is based on other research findings related to this study.

Sample collection, sample labeling, sample preparation and procedure for conducting the tests are captured in the chapter three. Chapter four contains the results and discussion from this study. Chapter five contains Summary, Conclusions and Recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

It is undeniable fact that, iron steel is the leading backbone of all structures in the building industries in the world. The iron steel elongates the life span of buildings; the ductility nature of iron steel gives buildings all strong kinds of shapes and improves its aesthetic view. The mechanical properties of iron steel in the building enables the designers to modify the existing artifact's ergonomic problem without causing total collapse of entire artifact. This chapter talks about the literature review of the details of iron steel that is, elemental composition, iron steel production, mechanical properties and quality assurance of iron steel bars production.

2.1 Steel

It is a hard metal, which is very strong and bluish-grey in colour. Steel consists of iron, carbon and other alloying elements, such as tungsten, molybdenum, nickel, vanadium, and chromium. Nowadays iron steel bars are mostly one of the major components used in buildings and other industries. The high tensile strength of steel gives exceptional tensile strength to buildings.

Iron is one of the fundamental components of steel. The iron takes two crystal system forms that is, the Face Centered Cubic (FCC) and the Body Centered Cubic (BCC). The type of crystal structure depends on temperature of the iron. The Face Centered Cubic crystal system, contains one iron atom each at the center of the six faces of the cube while in the Body Centered Cubic system has only one iron atom at its center of the cube in its arrangement.

The structural different modifications of iron with its constituent elements, mainly carbon give cast iron and iron steel their kind of exceptional mechanical properties.

The movement of dislocations, which normally occurs in the crystal lattices of iron atoms, is prevented by adding a percentage amount of carbon and other element as hardening agents within the iron.

The percentage quantity of carbon and other alloying elements, reduces the movement of those abnormality within the crystal structure that makeup the pure iron ductile, and hence improves the iron mechanical properties such as tensile strength and yield strength [7].

2.2 Production of Steel

Steel is an alloy, which is made up of iron and carbon. The percentage carbon content in steel ranges from 0.002% to 2.14% by weight for normal iron-carbon alloys [8], and these percentage quantity values change due to the alloying element making up the steel.

Iron is the main major element in the steel, when carbon content in the iron is small; it makes the iron soft, ductile and weak. Also, when the carbon content is too high it makes the alloy brittle and this normally is known as pig iron. When the carbon content is higher than 2.1% in pure iron-carbon alloy, is known as cast iron. Steel is doped with other alloying elements to improve its mechanical properties. The common alloying elements are manganese, nickel, chromium, iron, tungsten, carbon, niobium, boron, cobalt, vanadium, titanium and molybdenum [9]. The presence of any of these elements such as sulfur, silicon, phosphorus, oxygen and nitrogen as additional elements has negative impact on the mechanical properties of the steel. The production of steel in bloomeries and crucibles is known in ancient times [10]. Bloomery is an oven used commonly for producing iron from its oxides. Bloomery was in ancient times the initial smelter capable of smelting iron. The bloom is a bloomery's product and is a spongy mass of iron and slag known as sponge iron, which commonly combined and more forged into wrought iron. Steel production started about 4000 years ago dating from 1800 BC, when pieces of ironware quarried from an archaeological site in Anatolia [11]. The quench-hardened steel, is produced first in the Chinese of the Warring States in (403-221 BC) [12], while in the 1st century AD Chinese of the Han dynasty (202 BC-220 AD) produced steel by melting jointly cast iron with wrought iron, increasing the crucial product of a carbon-intermediate steel [13]. In East Africa 2000 years ago, the Haya people also developed a type of oven that they used to produce carbon steel at a temperature 1802°C [14]. Ancient Merv, in 10th century AD, used carbon that is in a form of charcoal and pure iron in a crucible, by slowly heating and cooling the mixture a crucible steel is produced. Berganesques is a method that is used to produce inferior, inhomogeneous, steel and also the second method Bessemer process that used incomplete decarbonization through recurrent under cold blast forging, these two methods are used in production of steel in 11th century in Song China [15].

Meanwhile, European steel production in 17th century, used blast furnace to produce pig iron from iron ore. The refined pig iron bars produced in refinery furnace are used as raw materials in the steel making [16]. It was realized in 17th century that the best steel came from ore grounds iron in Sweden. Even in the 19th century, the north of Stockholm in Sweden remained the best source of raw material for steel making since the process is the same [17]. Bessemer process in 1855, used pig iron as the raw material and this method began the modern era in steelmaking. The method used by Henry Bessemer, enabled him to produce large quantities of steel inexpensively [18]. Gilchrist Thomas a British metallurgist and inventor improved Bessemer process in 1875. He lined the converter with a basic compound such as burned limestone to remove the impurity that is, phosphorus in the iron ore. Siemens Martin process was another 19th century steelmaking process, which supplemented the Bessemer process.

Today, the common method of recycling scraps metal or pig iron to produce new steel is electric arc furnaces (EAF). This method uses a great deal of electrical energy thus is normally used at places that the supply of electricity is cheap.

2.3 Iron

The element iron has atomic number 26 and chemical symbol Fe. It is one of the metal in transition series. Also, iron is one of the most common chemical elements on earth by mass, which formed the inner and outer core of the earth. The most common fourth element in the earth's crust is the iron, which has its oxidation numbers ranging from −2 to +7 and mostly +2 and +3 is the common oxidation states of iron. Iron is very reactive to oxygen and water; it has lustrous silvery-gray surfaces when fresh, normally iron oxidizes in air to produce hydrated iron oxides (rust). When iron reacts with its environment the iron oxides produced has more volume than the metal and so peel off, exposing the fresh metal surfaces for further corrosion.

Since ancient times iron metal has been in existence. Blast furnaces are used to produce crude iron metal; the iron ore is also reduced by coke to a high content of carbon known as pig iron. To reduce the high carbon content in the pig iron, a further enhancement is made with oxygen to correct percentage to make steel.

Iron in its pure state is very soft and the presence of impurities in its makeup affects its mechanical properties [19].

2.4 Reinforcement of Concrete with Iron steel Bars

Concrete is the mixture of cement, stone, sand and water. It hardens fast but has very weak tensile strength. For concrete structure to withstand the tensile and compressive strength when a force is applied on it, reinforcement steel bar is introduced into the concrete structure. Joseph Monier first practiced this idea in 1867; he is the principal inventor of reinforced concrete [20]. Joseph Monier is the first to know that reinforcing steel bar in concrete improved the concrete structure mechanical properties [21]. The reinforcing structures are intended to oppose the tensile stresses in specific areas of the concrete that might trigger unwanted structural catastrophe. Brickwork constructions, normally used mesh of steel wires or steel bar as tension device in reinforced concrete to reinforce and grasp the concrete in compression [22]. Concrete is reasonably weak in tensile strength but very strong in compression so to balance for this disproportion, reinforcement bar that is iron steel bar is cast into the concrete to carry the tensile loads. Reinforced concrete (RC) is a combined mixture of stone, sand, water and iron steel bar in which concrete's comparatively low tensile strength and ductility are stabilized by the insertion of reinforcement bar having higher tensile strength and ductility [23]. The high tensile strength and ductility reinforcement bar in the concrete also improve the bending and other direct tensile actions of the structure. Reinforced concrete including foundations, walls, beams, slabs, columns, frames are used to build various types of structures in masonry construction.

More so, to design and implement the most well organized floor system in building constructions optimum building structures must be created.

2.5 Carbon

Carbon is also one of the most vital alloying elements in steel; it is a tetravalent element, which has atomic number 6, and C as its chemical symbol. Carbon has three isotopes that are; carbon-12, carbon-13 and carbon-14, which occur naturally and only carbon-14 that is radionuclide has 5,730 years as its half-life [24]. Carbon is known in the earliest civilizations in the form of charcoal and soot. The fourth most abundant element by mass in the universe is Carbon and in the earth's crust is the fifteenth most abundant element. Carbon acted as a hardening agent in iron, by improving the soft nature of iron and hence improving the mechanical aspect of iron steel bar. René Antoine Ferchault de Réaumur first demonstrated that iron is changed into steel through the absorption of carbon in 1722 [25]. Carbon can react with oxygen to produce carbon oxides and at high temperatures the oxygen leaves the metal oxides. This reaction is exothermic which is still used in the steel manufacturing to extract iron, and to regulate the carbon percentage amount in steel.

$$Fe_3O_4 + 4C_{(s)} \rightarrow 3Fe_{(s)} + 4CO_{(g)} \quad \text{.................................} \quad 2.5.1$$

More iron can be smelted when carbon monoxide is recycled:

$$Fe_3O_4 + 4CO_{(g)} \rightarrow 3Fe_{(s)} + 4CO_{2(g)} \quad \text{.................................} \quad 2.5.2$$

Carbon also reacts with other metal elements at high temperatures to produce metallic carbides such as the tungsten carbide, and iron carbide cementite in steel, commonly used for making hard tips of cutting tools.

2.6 Iron-Carbon Phase Diagram

The largest percentage content of alloying elements in steel is iron. Carbon is added to iron to harden it since iron in its natural pure state is very soft. The α-Iron is soft metal the carbon concentration is very small [26]. Similarly, Austenite (γ-iron) is also soft metal but can be soften significantly with more carbon 2.04 % by mass at a temperature of 1146 °C. In stainless steel, Austenite iron is used for making silverware, hospital and other service equipment [27]. Iron is grouped based on the purity and the percentage amount of alloying element mostly carbon. Pig iron, because it contains impurity such as phosphorus, silicon and sulfur. These contaminants in pig iron make it not a saleable product, but rather used as raw material for production of cast iron and steel. The carbon percentage content in pig iron ranges from 3.5 % to 4.5 %. Also, the melting point of pig iron, is in between the range 1420–1470 °C which is lower than its main components iron (1538 °C) and carbon (3550 °C) hence pig iron easily melts out when iron and carbon are heated together [28].

Moreover, when these contaminants in pig iron is well reduced, cast iron is produced with 2-4 % content of carbon and 1- 6 % of silicon with small amounts of manganese. The carbon in cast iron is in the form of cementite, which dominates the mechanical properties of the cast irons and makes the cast iron very hard but unresistant to shock [29]. When 0.8 % carbon mix with iron is cooled gradually from 723 °C to room temperature, another type of cementite and α-iron, is produced which is very malleable and soft known as pearlite because of its appearance. Brittle martensite is produced when the mixture is cooled rapidly [30]. The steel can then be tempered by reheating to a temperature in between, changing the proportions of pearlite and martensite. The end product below 0.8 % carbon content is a pearlite and α-iron mixture, and that above 0.8 % carbon content is a pearlite – cementite mixture [31].

The resistance of iron steel bar against corrosion depends upon its elemental composition. When iron steel is exposed to moisture and oxygen either by carbonation or chloride intrusion trigger the corrosion of steel.

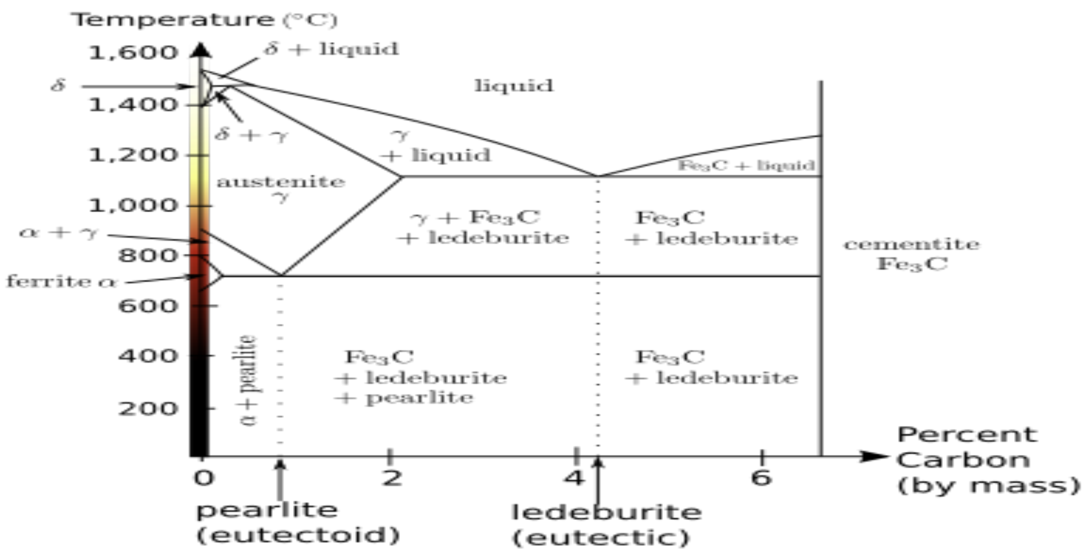

Fig. 2.1 Iron-Carbon Phase Diagram

2.7 Corrosion of Iron steel bar

Corrosion is the gradual destruction of materials usually metals by electrochemical reaction with their environment. It occurs naturally, which transforms a metal into a stable chemical form, such as its oxide or hydroxide. An iron steel bar as an alloy with different equilibrium potentials of two constituent phases, when it is exposed to an electrolyte solution is susceptible to corrosion [32]. The cathode is the phase with a positive potential while the constituent phase with a lower potential acts as an anode and this is the electrode that corrodes. Atmospheric corrosion may occur when thin films of liquid water, in the range of up to hundreds of micrometers, forms on metal surfaces in contact with humidified air. The thickness of the film depends on the relative humidity of the surrounding air, but also on factors such as surface roughness and the presence of particles, especially salt crystals. The thin film of moisture acts as electrolyte, and may cause various corrosion phenomena, such as crevice corrosion or galvanic corrosion. Steels are in general liable to uniform and localized forms of corrosion. The electrochemical nature of corrosion transpired at the interface between the metal and the electrolyte solution. The degradation of a metal is related to the rate of corrosion, which is mostly determined by the anodic and cathodic reaction. The anodic reaction involved in the corrosion of steel is shown below:

$$Fe \rightarrow Fe^{2+} + 2e \qquad 2.7.1$$

Oxygen is reduced into hydroxide ion at the cathode

$$O_2 + 2H_2O + 4e \rightarrow 4OH \qquad 2.7.2$$

The redox reaction can be written as follows

$$2Fe(OH)_2 + H_2O + \frac{1}{2}O_2 \rightarrow 2Fe(OH)_3 \qquad 2.7.3$$

2.8 Types of Corrosion

Corrosion is generally classified into two main types in metallic materials that is, localized and uniform corrosion. The sections below describe the major sub classification of the types of corrosion.

2.8.1 *Uniform Corrosion*

This type of corrosion is readily noticeable by visual assessment and mostly common. Due to the electrochemical reaction that occurs at the interface of metal, leads to production of an even loss of metal at its surface.

This reaction leads to a decrease in the thickness of the oxidized metal surface at a uniform rate, which can consequently be anticipated over time. The uniform corrosion rate is expressed as a loss of mass (thickness) per unit time. Coating or alloying of the material best provides the resistance to uniform corrosion.

2.8.*2 Localized Corrosion*

This types of corrosion normally occurs at a limited area (localized sites) with faster rate while the other part of the metal undergo low rate of corrosion

2.8.3 ***Pitting Corrosion***

Pitting corrosion occurs in small portions of metal dispersing out to produce a pit, and is one of typical example of localized corrosion. Mostly, the rest of the surface corroding metal remains undamaged while pitting will start from the small holes formed in the metal, typically as a result of de-passivation of a small area. This small holes area formed now becomes anodic area, while the other part of the remaining metal becomes cathodic, leading to producing of a localized galvanic reaction. The deterioration of this small area negatively affects the mechanical properties of the metal and can lead to failure. At the anode area, the rate of corrosion normally rapid while at the cathode area very slow until the pitting causes deep holes.

2.8.4 ***Galvanic Corrosion***

In a conductive solution or environment with different electrochemical potential two dissimilar metals easily undergo galvanic corrosion. The potential difference between the two metals is the driving force for the corrosion to occur. The galvanic corrosion is prevented by insulating one of the electrodes or choosing metals that are very close in electromotive force (emf) series so that the potential difference produced will be very small and hence low driving force for the corrosion.

2.8.5 ***Crevice Corrosion***

When the supply of oxygen is restricted in enclosed environments or cracks, crevice corrosion occurs. The oxygen in the crevice or the enclosed environment when is consumed by the reaction with the metal, and further circulation of oxygen is limited. Hence the crevice area now become more anodic as the metal dissolution in the crevice builds up. The metal surface, which is more accessible to ambient oxygen, simulates the cathodic features and as such starts corrosion [33].

2.8.6 ***Intergranular Corrosion***

This is an example of localized form of corrosion initiated by the potential difference that exists between grain boundaries and the grains caused by compositional differences. A local cell is formed due to potential difference between the grains and its boundaries; the oxidized metal loses its tensile strength and thus is vulnerable to catastrophes [34]. Lowering the contents of alloying elements level to developing of precipitates and the addition of alloying elements that help to alleviate the matrix prevent intergranular corrosion.

2.8.7 *Microbial corrosion*

Microbial corrosion is usually known as Microbiologically Influenced Corrosion (MIC), bacteria, normally chemoautotrophs, stimulate this corrosion. This type of corrosion affects both metal and nonmetal. Sulfate sinking bacteria are active without oxygen (anaerobic), they cause sulfide stress cracking by producing hydrogen sulfide. While some bacteria directly oxidize iron in the presence of oxygen (aerobic) to iron oxides, hydroxides and other bacteria also oxidize sulfur and produce sulfuric acid causing biogenic sulfide corrosion.

The destructive form of MIC is another form of corrosion known as Accelerated Low-water Corrosion (ALWC). This type of corrosion affects steel pipes in seawater near the low water tidemark. ALWC does not affect pipes that are coated and have cathodic protection installed at the time of construction. Installing sacrificial anodes to unprotected steel pipes locally to inhibit the corrosion can also control accelerated Low-water Corrosion [35].

2.8.8 *High temperature corrosion*

This is an electrochemical degradation of metal as a result of thermal effect and it is a non-galvanic type of corrosion, which occurs at a very high temperature environment containing sulfur or oxygen capable of oxidizing the metal. For instance, materials used in power generation, aerospace and in car engines have to oppose continual periods at high temperature in which they are exposed to in environment having possibly extremely corrosive products of combustion. Metals that are used at room and high temperatures in aggressive conditions, the oxides that are formed provide protective layers that prevent further atmospheric attack on the metal.

2.8.9 *Stress Corrosion Cracking (SCC)*

The presence of an eroding environment and tensile stress normally produce a stress corrosion cracking. The cracks that are developed as a result of corrosion promulgate deeper under the tensile force that applies on the metal and often difficult to detect the presence of this crack and this normally lead to failure of the structures. Also, structures failure sometimes caused by hydrogen. The hydrogen atoms produced from the cathodic reactions drift and reside interstitially in the metals' lattice due to its significantly littler size, and leads to amplification of the stress under the applied load. This type of breakage is named hydrogen embrittlement and can be prevented when the metal is well treated and baked to remove the hydrogen [36].

2.9 Test Methods of Corrosion

The corrosion test investigation forms the beginning of assessment and assortment of suitable building materials, the appropriateness of the environmental, corrosion control and an archive for research purposes. The common test methods to assess the corrosion behaviour of metallic materials are immersion test and the electrochemical impedance spectroscopy (EIS). The electrochemical test methods of corrosion provide more rapid information on the passivation and the corrosion mechanisms of the material.

2.10 Mechanical Properties of Iron Steel bar

It is the mechanical properties of a material that expose its elastic and inelastic behavior when a force is applied thereby indicating its appropriateness for mechanical purposes, and these vital properties of a material are the tensile strength, percentage elongation, elasticity, hardness and fatigue limit. The mechanical properties of iron steel bar are almost always requirements of the specification used to purchase the product. For flat rolled products the properties usually specified are tensile strength, yield stress, elongation and Brinell hardness. These properties give a guarantee that the material in question has been correctly manufactured, and are also used by engineers to calculate the working loads or pressures that the product can safely carry in service [37].

2.11 Tensile Test of Iron steel bar

The primary principle test in engineering and material science is tensile test in which a material is exposed to a controlled tensional force until failure. The ultimate tensile strength, maximum elongation, yield strength and breaking strength are the tensile properties that are measured of the structure material of concerned [38]. The tensile properties of the iron steel bars denote how they react to the tensional force being applied. The tensile strength of an iron steel bar is the maximum amount of tensile stress that it can be subjected to before failure. The failure in this content varies with the iron steel bar types and its elemental composition. Tensile tests are also used to determine toughness, elastic limit, yield point, modulus of elasticity and other mechanical properties. The tensile test does not depend on the size of the material rather the material elemental composition, the design of manufacturing methodology and the temperature of the test environment [39]. The importance of tensile testing are to select a material for a specific application and also to foresee how the chosen material will perform when unexpectedly external force applied on the material. Fig. 2.2 shows the relevant parts of a typical Stress and Strain graph of an iron steel bar. Tensile testing of iron steel bar specify the standard records for other designers and engineers means to compare several options of the best structure materials. The tensile testing can also provide legal proceedings evidence for quality assurance of the structured materials.

2.12 Mechanical Properties

This section talks more about tensile properties when external force applied on a material.

i. ***Yield point*:** begins the plastic behavior of a material under tension. It is the limit point of elastic material on stress–strain curve.
ii. ***Yield strength (YS)*:** is the point on stress–strain curve that indicates the plastic deformation of a material under applied stress. The material under the applied stress permanently deformed when the applied stress is removed.
iii. ***Ultimate tensile strength (UTS)***: this is the maximum stress that is applied on structure material for instance iron steel bar can withstand before breaking while being stretched or compressed [40].

iv. ***Breaking or Fracture strength***: this is the fail point of structure material, when the applied stress is beyond the ultimate tensile strength of the material and breaking the material into two or more pieces [41]. Similarly, it is the point of rupture on the stress-strain curve after the ultimate tensile strength point [42].

v. ***Strain hardening*****:** also known, as work hardening is the reinforcement of a structure material under plastic deformation. This reinforcement occurs because of the dislocation movements generated within the crystal structure of the material [43].

vi. ***Necking*****:** as in material science, is a form of tensile distortion where relatively huge quantities of strain limit disproportionately in a small region of the structure material [44]. When a material's cross-sectional area decreases by a greater proportion than the material strain hardens from the instability during tensile deformation lead to necking [45].

vii. ***Normal Stress* (** σ **):** is the resistance the material (iron steel bar) offered per unit cross-sectional area (A) when a force (F) is applied perpendicular to the surface.

viii. ***Normal Strain* (** ε **):** is a deformation (Δ L) per unit gauge length (L) when a force is applied perpendicular to the surface.

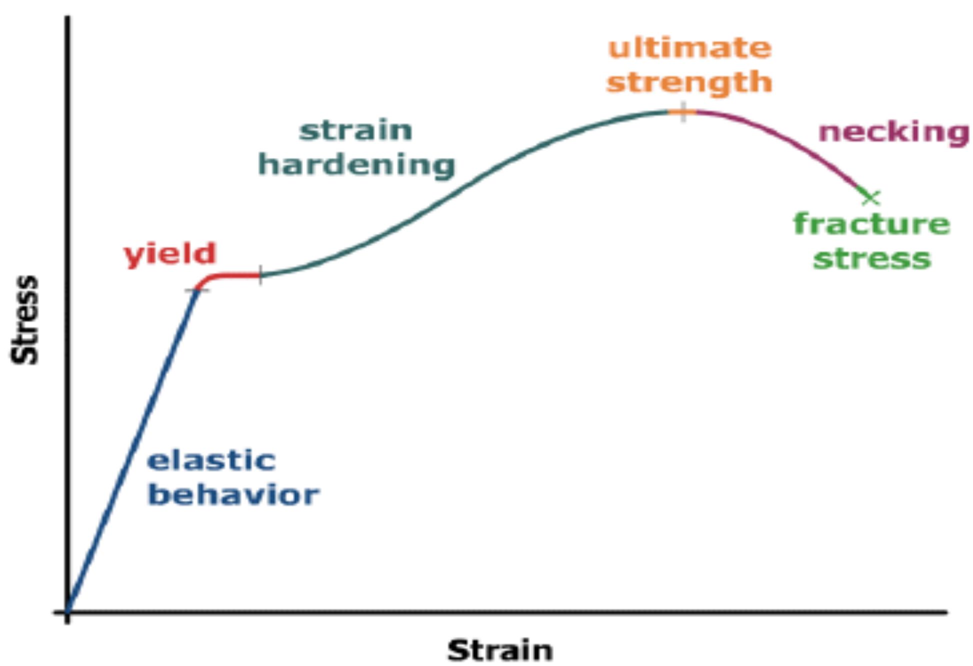

Fig. 2.2 Stress vs. Strain curve of typical structural of iron steel bar [46]

2.13 Determination of elemental composition of the iron steel bar

Fig.2.3 shows schematic diagram of Pelletron accelerator that uses ion source and accelerates the ions to higher energy. A source of negative ions by Cesium sputtering (SNICS) or Radio Frequency (RF) will generate required negative ions. These ions are then pre-accelerated within the ion source and are injected into strong electric field inside the accelerator tank, which is filled with an insulating gas. The beam is passed through an ultra-high voltage (UHV) beam line (accelerator tube). At the center of the tank is a terminal shell, which is maintained at required high voltage less than 3 MV. This terminal voltage is buildup based on the principle of Van-de Graaff accelerator. But, here a chain of metal pellets is used instead of a belt for carrying the charge to terminal. The negative ions on passing through the accelerating tubes from the column top of the tank to the positive terminal get accelerated. A stripper foil is placed at the terminal and energetic negative ions are stripped while passing through this foil. The stripper potential is set so that it can collect all stripped electrons within the needed time span. Therefore the negative ions are changed into positive ions at the terminal. These positive ions are then repulsed away from the positively charged terminal twice to accelerate the ions. On exiting from the tank, the ions are bent into horizontal plane by analyzing magnet, which also selects a particular beam of ion and charge state. The switching magnet diverts the high-energy ion beams into a pre-selected beam line of various beam lines existing in the beam hall to irradiate the sample. The characteristic x-rays produced by the photoelectrons ejected from the sample at the end station is used to analyze the elemental concentration of the samples. The presence of alloying element like manganese, iron, chromium and nickel enhances the mechanical property of iron steel. The control and operations of the accelerator is done at the control console room.

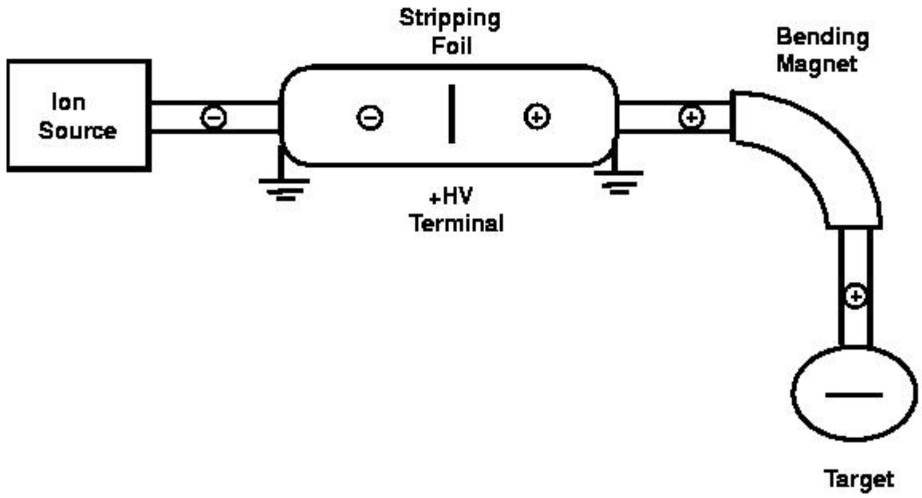

Fig. 2.3 Schematic diagram of tandem accelerator

2.14 Structure Material Quality Assurance

This is the sensitive aspect in industrial organizations ensuring that, when manufacturing products are delivered to clients, defects are prevented to avoid problems that the products might cause to the customers. Quality assurance (QA) concentrates on providing self-assurance that the quality requirements will be accomplished [47]. QA is the systematic measurement, comparing it with the standard and monitoring of the processes to prevent imperfections. The principles of Quality Assurance ensure that the products are fit for its purpose and free from mistakes [48].

2.15 Quality control

Quality control (QC) is the quality management focusing on the fulfillment of quality requirements [49]. QC splits the act of testing products to disclose defects from the conclusion to allow or reject product release, which may be determined by fiscal constraints [50].

The International Organization for Standardization's (ISO 9000) is planned to assist industrial organizations to ensuring that, the organizations meet the requests of customers and investors while meeting the statutory and supervisory requirements relating to the products [50].

2.16 Some Past Studies On Quality Of Building Materials On The Ghanaian Market

a) ***Moses Emmanuel Ako Hayford (2016)***

Moses Emmanuel Ako Hayford conducted an investigation on the Assessment of the quality of reinforcing bars on the Ghanaian market: a case study of the western region. After conducting tensile test on mild steel bars on the Ghanaian market, he concluded the mild steels on the Ghanaian market are fit for structural purpose and may not be responsible for the collapse of buildings. He further highlighted that, though there is a need for verification since the high tensile test on steel bars are inconsistent; the failure of buildings in Ghana cannot be attributed to the tensile properties of reinforcement bars in the market.

However, the nominal sizes of iron steel bar on the market are below the nominal standards and this can lead to failure. The dominance of these substandard iron steel bars on the Ghanaian market is because of its low cost and hence some designers and contractors go in for these cheap and substandard iron steel bars on the Ghanaian market to maximize profit.

He recommended that further research should be conducted on the quality of sand for construction and the quality of workmanship of building projects to establish whether it may be responsible for the recent collapse of buildings.

b). ***Danso & Boateng (2013)***

The authors recommended further studies for identification of sub-standard materials that contributed to building collapse in Ghana after they had concluded that cement produced in Ghana is not the real cause of building collapses. They repeated the call that substandard material is one of the major causes of building collapses worldwide. They further noted that the main materials mostly identified as substandard are cement, reinforcement bars, timber and aggregate. Therefore this dissertation work seeks to assess the quality of reinforcing bars in the open market as recommended by the authors.

c). ***Cephas Thywill Komla Dzogbewu (2010)***

The author researched on metallurgical studies of locally produced and imported iron rods on Ghanaian market concluded that, locally produced iron rods are very hard and brittle. This hardness property of the rod made it possible to withstand more load but fractured quickly just after the yield strength because of its brittleness. The locally produced irons steel are very stiff and high resistance to deformation and imported irons steel were tougher and more ductile. The strength and toughness of a material are two opposite variables. Thus an increase in the strength of a material leads to a decrease in the toughness. The locally produced iron rods were relatively stronger but were less tough than the imported iron rods. The hardness of iron rods does not only depend on the carbon content alone but other Ferro-alloy elements like phosphorus and sulfur which are not needed in steel as shown by the locally produce iron rods especially the Ferro Fabric samples. Varying the processing route in steel production would greatly change the microstructure and the mechanical property as shown for the locally produced samples and the imported samples.

d). *Kankam & Adom-Asamoah (2002)*

The authors carried out an experimental investigation on steel bars and reinforced concrete beams and made the observation that; the Ghanaian steel industry recycles approximately 80% steel bars from scrap metals. They recorded that physical properties such us yield strength, ultimate strength, Young's modulus; Poisson's ratio and percentage elongation determine the behavior of reinforcement in concrete. Their samples for the experiment were obtained from three local steel manufacturing companies in Ghana namely, Wahome, Tema Steel Works and Ferro Fabric. Their test results indicated that two out of the three companies did not meet the BS4449: 2005 (2009) maximum limit of 0.25% for carbon requirement for mild steel. They also concluded that the characteristic strength of locally produced mild steel bars is not consistent with specified standard values, and hence recommended that a revision of the specification assigned to locally milled steel from recycled metal.

CHAPTER THREE

METHODOLOGY

3.0 Introduction

In Fig 3.1, it outlines the three-step procedure utilized for assessing the quality of the steel bars analyzed for this study. Elemental compositions of all samples were first being determined. Elements such as Iron (Fe), Chromium (Cr), Potassium (K), Titanium (Ti), Nickel (Ni), Zinc (Zn), Copper (Cu), Vanadium (V), Calcium (Ca), Chlorine (Cl), Molybdenum (Mo), Manganese (Mn) were be measured using Proton Induced X-ray Emission, an accelerator based technique.

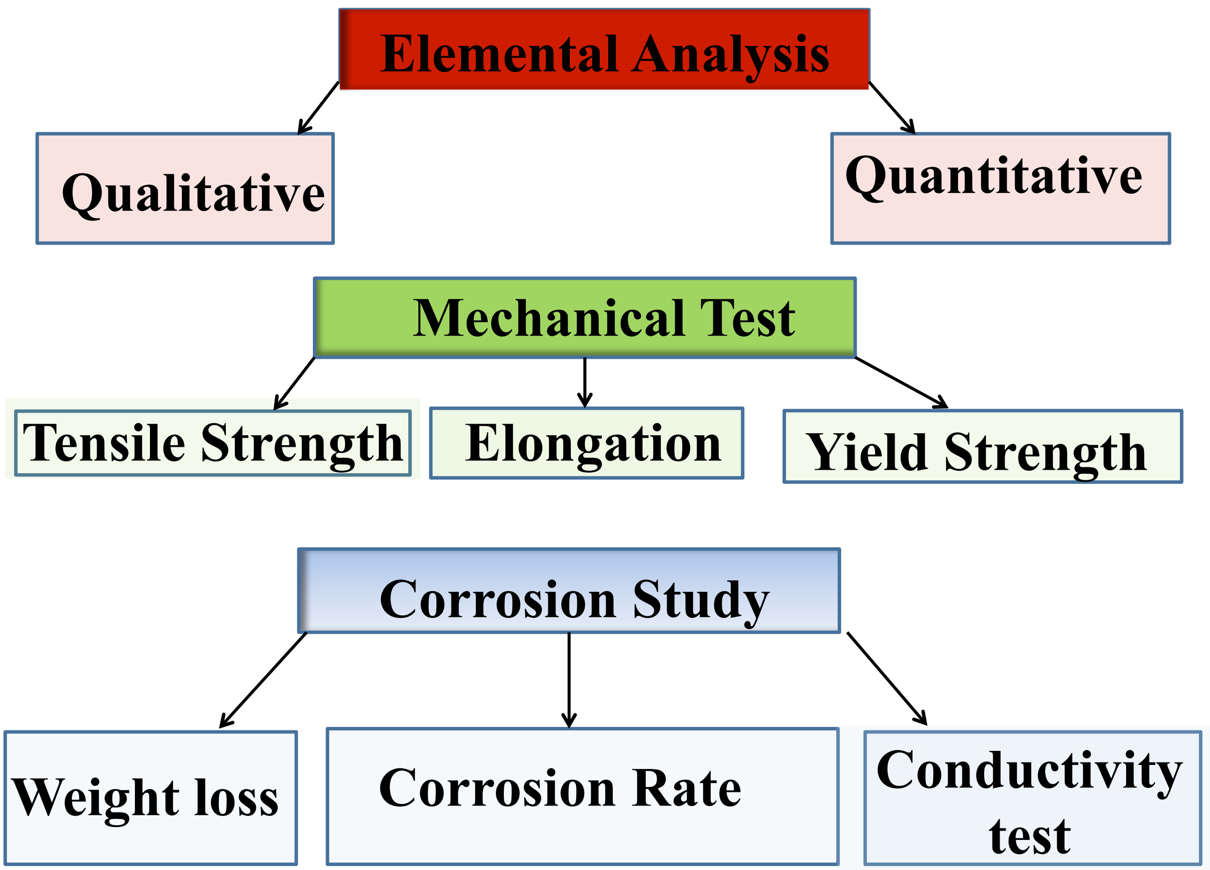

Fig. 3.1 Flowchart of elemental analysis, mechanical test, and corrosion rate of the samples

The mechanical properties of steel bars such as Tensile strength, the Yield Strength and elongation were determined for the three (3) samples using a 300 kN Hydraulic Universal

Testing Machine and the results compared to acceptable international (BS 4449) and local standards (GS 788-2).

Corrosion test was performed for all samples for a total period of 60 days. Four same brands of samples are immersed in a 5 % NaCl solution for this 60 day period to simulate an extreme coastal environment (< 3.5 % NaCl) induced corrosion. After 21 days two (2) samples were removed, washed to clean the rusts accumulated on the iron steel, dried, weighed its mass loss and then sent to the laboratory for mechanical properties testing. This procedure was repeated after 60 days of induced corrosion.

3.1 Samples Collection

After a comprehensive market survey on the most purchased and used brands of iron steel rod on the Ghanaian market, three famous brands were purchased for our studies. Since most iron steel rods are not labeled, the locally manufactured iron steel rod used in this study was purchased directly from the factory (name withheld). The other imported brands from China and Ukraine were purchased from major retail outlets in Accra. The 16 mm steel rod was chosen for this study because it is the most used steel bar for construction works in the country. In terms of pricing for the 16 mm iron steel rods, the rods from Ukraine were the most expensive. The price of Chinese rod was the same as those of locally manufactured. Fig. 3.2 shows a picture taken of the samples used for this study (imported and local).

Fig. 3.2 Samples of imported and local iron steel bars taken from major retail outlets at Accra

3.2 Samples Labeling

The sample collected from local manufacturing company was labeled Local 1, for analysis purposes and the same sample of 16 mm diameter of iron steel bar of two different imported brands were labeled Foreign 1 (from China) and Foreign 2 (Ukraine). Fig.3.3 shows prepared samples for PIXE analytical test.

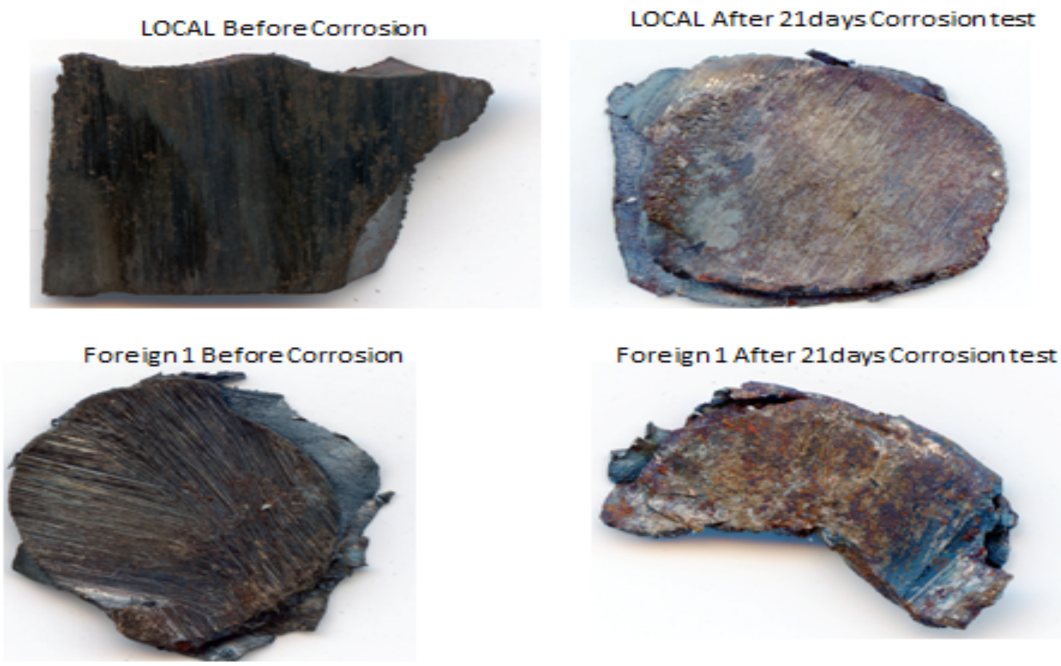

Fig. 3.3 shows prepared samples for PIXE test

3.3 Elemental Analysis using PIXE

A small part of each of the 16 mm diameter iron steel bars of Local 1, Foreign 1 and Foreign 2, were cut and well prepared for particle induced X-rays emission (PIXE) analysis to determine the elemental composition, of locally manufactured and imported iron steel bars on the Ghanaian market using a 1.7MV Pelletron accelerator Fig. 3.4.

PIXE is a technique, which utilizes high-energy charge particles interaction with target sample to release characteristic x-rays, which are detected and used for qualitative, and quantitative analysis. It operates under the principle that when high energy protons bombard a target material, it ejects an inner orbit electron, an electron from a higher orbit sensing the vacancy created will drop to fill this vacancy created, this process causes this higher shell electrons to emit its excess energy in the form of x-rays which has characteristic energy depending on the atom it resides. The Pelletron accelerator plays a vital role in providing the high-energy charged particles needed to bombard the target sample to cause the excitation for x-rays to be released and detected.

From Figure 3.4, the accelerator consists of four (4) major parts, the ion source, the main accelerator tank, the steering and focusing and the target chamber.

The ion source is where the charged particles are produced from neutral atoms, especially from gasses. Hydrogen gas is used for hydrogen ions production, whiles Helium gas is used for Alpha particles production.

He or H gas is bled into a quartz glass bottle, where radio frequency bands (100 MHz) are attached to provide the right and necessary energy to break the gas molecules into ions (H^+, He^+, He^{++} and other ions). With a potential difference of 2 kV (for H) or 6 kV (for He) applied across the quartz bottle, ion produced are moved into the charge exchanger which converts the positive ions into negative ions. This is important because the Pelletron accelerator has a positive terminal voltage at its center and thereby will only attract negative ions from the ion source. The charge exchanger contains Rubidium (Rb) vapor, which causes helium and hydrogen ions to pick up extra negative charge when allowed to pass through. Negative ions of Hydrogen (H^-) and Helium (He^-) are accelerated to the center of the accelerator tank where a 1.7 MV potential is created to provide the ions with the necessary energy to cause excitation of samples. To obtain the double acceleration of ion, as termed as tandem acceleration, negative ions at the center of the accelerator tank are stripped of excess electrons with the help of a stripper channel filled with nitrogen gas inside the high voltage terminal section. This process converts high-energy negative ions into positive ions, which are further accelerated (repel) towards the exit of the accelerator tank with a potential of 1.7 MV. Ions exiting the accelerator are always positive and have high energies to cause reactions.

The steerers and the quadruple magnets focus the high-energy ions both in the vertical and horizontal direction. The steering magnets are also the momentum filter which is the separator of charged particles that is based on their energy or momentum. The magnetic field allows charged particle to pass through it as the component of its velocity is perpendicular to the magnetic field, when this happened the charge experiences a force which moves in the direction of the applied force.

$$F_B = qv_pB = \frac{m_p v_p^2}{r} \qquad 3.3.1$$

where

- **q** is the charge state of the charge particle,
- **v** is the velocity of the charged particle,
- **m** is the mass of the particle,
- **B** is the magnetic field applied and
- **r** is the radius of curvature made by the charge particles as it travels inside the field.

Once the charges leave the magnetic field the force vanishes and they continue in a straight line toward the scattering chambers.

Inside the target chamber, the prepared samples are mounted on a sample holder and placed inside the chamber. The chamber is operated at high vacuum ~10^{-6} torr. Inside the chamber are x-ray detectors placed at 45° to the sample to pick all characteristic x-rays emitted from the sample. A silicon drift detector is utilized in the target chamber.

The X-rays emission characteristic peaks identified the elements in the iron steel samples and this emission spectrum is generated at computer control system. Also, the concentration of the characteristic X-ray emission spectrum determined the quantity of a specific element such as sulphur, calcium, vanadium, chromium, manganese, iron, cobalt nickel, copper and molybdenum in the iron steel samples.

Fig. 3.4 showing the accelerator set up at GAEC laboratory.

Gupix software is used to analyze spectra collected for both qualitative and quantitative analyses. Fig. 3.5 illustrates a typical PIXE spectrum indicating all the possible elements with the channel number where these elements were collected.

It is possible to convert the measured x-ray yield to concentrations (quantitative) for all elements identified using the equation below.

$$\mathbf{C_i = \frac{Y_i}{Yl_t\ H\ Q\epsilon\tau}} \qquad 3.3.2$$

- ✓ **H** is determined by running standards (preferably having a general similarity to the sample matrix).
- ✓ $\mathbf{Yl_t}$ is the Theoretical intensity per micro-coulomb of charge per unit concentration per steradian.

- ✓ $\mathbf{C_i}$ is the Concentration of analyte in the sample.
- ✓ $\mathbf{Q}$ is the measured beam charge.
- ✓ $\in$ is the Intrinsic detection efficiency.
- ✓ $\boldsymbol{\tau}$ is the transmission factor through any filters or absorbers between target and detector.

The Experiment Setup parameters for PIXE analysis for this study are summarized below:

- ✓ Type of Incident Ion: H+
- ✓ Incident Ion Energy: 2.3 MeV
- ✓ Incident Ion normal with sample: 90°
- ✓ Silicon Drift Detector angle to target sample: 45°
- ✓ Incident Ion beam current: 20 uA
- ✓ Total Beam Charge collected: 10 uC

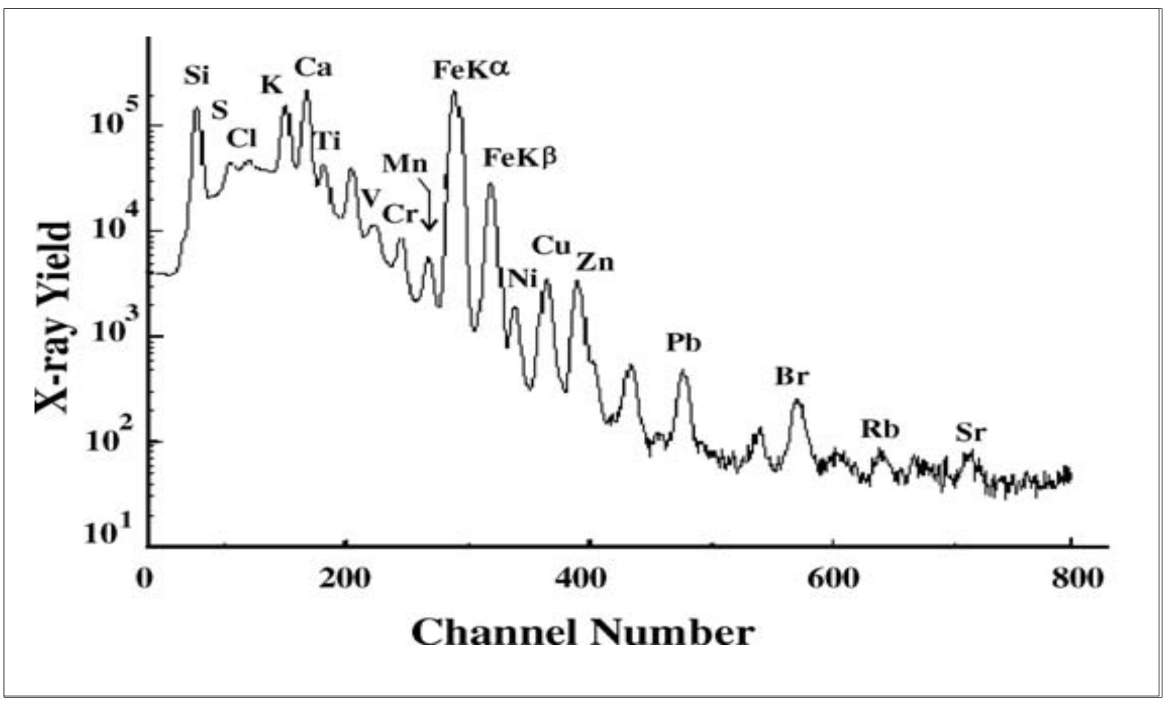

Fig. 3.5 PIXE spectrum showing all the possible elements with their X-ray yield

3.4 Mechanical Properties Tests

The samples are cut with a hacksaw blade to a length of 450 millimeters. For mechanical properties test, two each of the Local 1, Foreign 1 and Foreign 2 iron steel bars are used. Fig. 3.6 shows how each of these samples is fixed into the marker machine to a graduation of 10 mm interval on the steel bar as a requirement of the 300 kN hydraulic Universal Testing Machine. The samples are then weighed in kilogram by a weighing machine to record the mass of each sample. The software of the 300 kN hydraulic Universal Testing Machine uses the diameter and the length measured to generate the actual area of the iron steel rod. Fig.3.7 shows the iron steel bar sample fixed into the 300 kN hydraulic Universal Testing Machine for the test to begin. The sample is gripped about 150 mm in an upper level and about 150 mm in a lower level. The machine applied a force unto the sample until it is broken into two parts. Both parts are then joined together again to be able to measure with a steel rule to record the new length of the sample after the machine had stretched it. Finally the new length is keyed in the software of the testing machine to determine the ultimate tensile strength, yield strength and elongation values of the analytes. The tests are conducted at the mechanical laboratory of Ghana Standard Authority in Accra.

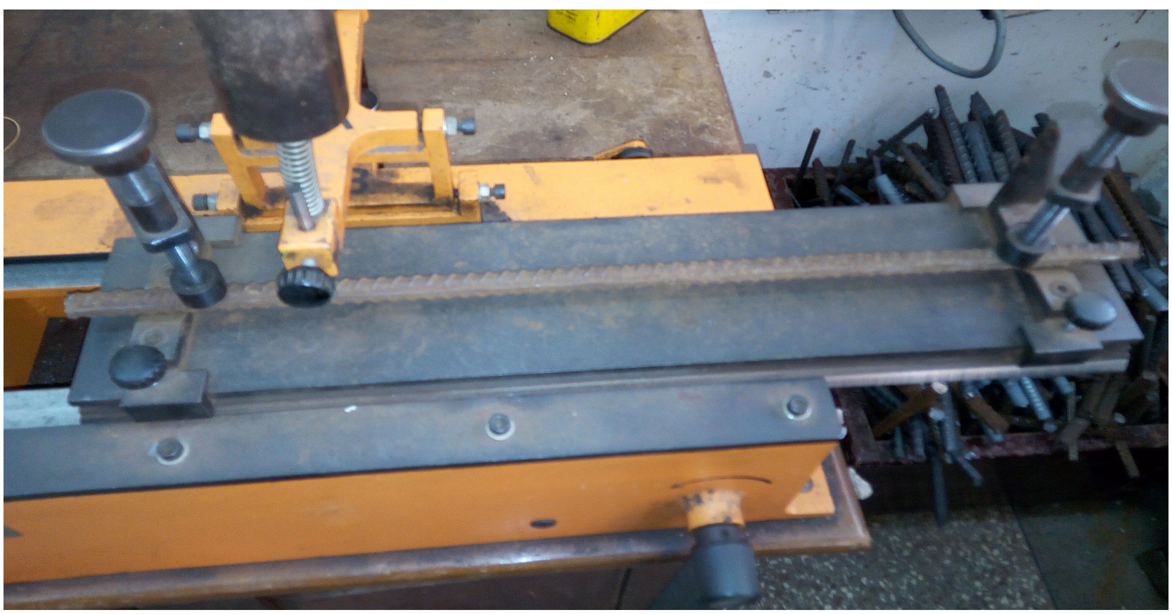

Fig. 3.6 marking of the samples after measuring their masses

Fig. 3.7 sample being held in good position to start mechanic strength test

3.5 Conductivity test

The aim is to measure the solution resistance and the resistance caused by polarization of the electrodes and the field effect interfered with the measurement. The conductivity meter applied an alternating current (I) at an optimal frequency to two active electrodes and measured the potential (V). Both the current and the potential are used to calculate the conductance (I/V). The conductivity meter then used the conductance and cell constant to display the conductivity.

During this process, the cations migrate to the negative electrode, the anions to the positive electrode and the samples solution acts as an electrical conductor. In Fig. 3.8, a 4-pole cell is shown immersed in the samples solution to measure conductivity. A current is applied to the outer rings in such a way that a constant potential difference is maintained between the inner rings. The voltage measurement takes place with a negligible current and these two electrodes are not polarized that is, the resistances of the inner rings are zero. The conductivity will be directly proportional to the applied current. The position of the conductivity cell in the samples solution has no influence on the measurement. However, the polarization, impurity, cable resistance, temperature, cable capacitance, circuit set up and frequency change influence the conductivity measurement.

Fig. 3.8 setup for conductivity measurement of the sample's solution

3.6 Calculation of Weight Loss of each Sample

Each sample was weighed thrice and the average mass recorded. After 21 days of immersing samples in 5 % NaCl solution, each sample is taken out, dried and weighed using digital electronic balance shown in Fig. 3.9. The weight loss of each sample is determined by subtracting the mass of each sample after 21 days immersion from initial mass before corrosion test and divided by the number of days (21 days) in the test solution (5 % NaCl solution). The same procedures are used to determine the final weight loss of each sample.

Fig. 3.9 weighing sample before its mechanical test

3.7 Corrosion Test

Four of the 450 mm each of local and imported iron steel bars were put in 5 % sodium chloride solution in different containers of the same pH, conductivity and temperature. However, the control container's conductivity is not the same as the other three containers with 5 % NaCl solution. Sodium chloride solution stimulate coastal environment. After 21 days, two each from the different containers are taken, dried and cleaned for mechanical strength test again while the remaining two each in the different containers continue the corrosion test for the 60 days and also dried and cleaned for the mechanical strength test. The results for sample tested for mechanical properties before, after 21 days and 60 days are tabulated.

3.8 Preparation of Samples' Solution

The sample containers are thoroughly washed well to ensure it does not contain any contaminants and are rinsed with distilled water and dried. A 50 g of NaCl is weighed using electronic balance. It is poured into a volumetric flask containing about 850 ml of distilled water. The NaCl is dissolved completely in it and the distilled water is added to bring the volume of the solution up to the final 1000 ml. This prepared 5 % NaCl solution is then poured into the dried containers except control container. The conductivity, pH and temperature of each of the solution in the containers as shown Fig. 3.10 are measured. Fig. 3.11 also shows the change colour of the samples and their respective colour changed solutions after immersing in the 5 % NaCl solution. The colour changed of solutions depicts the presence of ions forming in the solution.

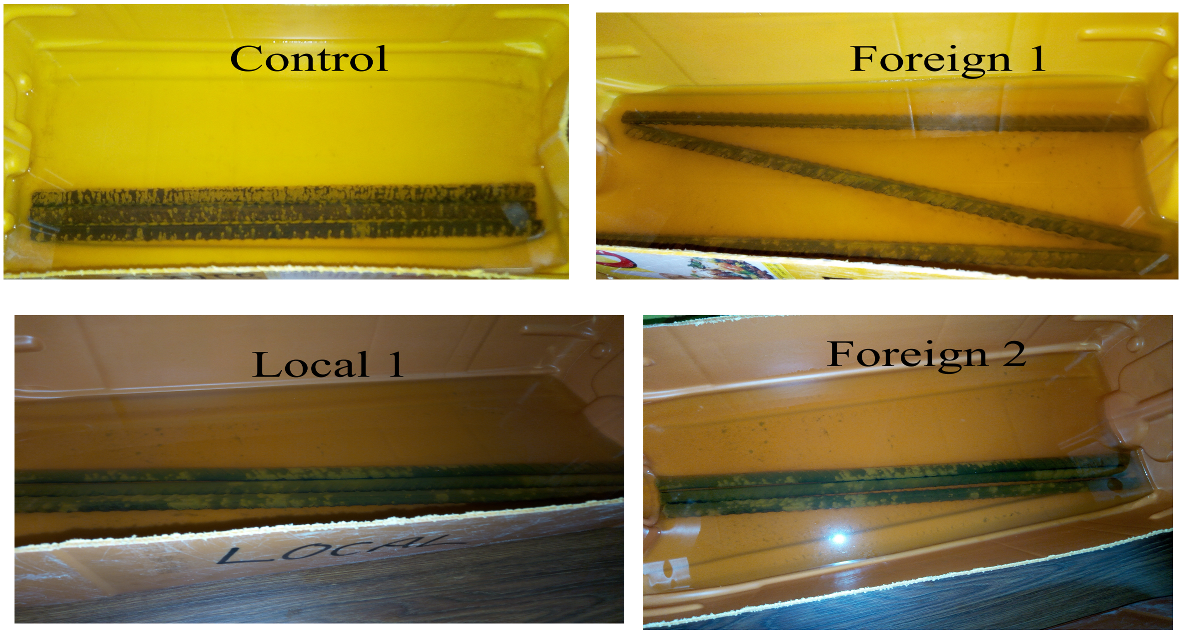

Fig. 3.10 picture of iron steel bars samples immersed in 5 % NaCl solution.

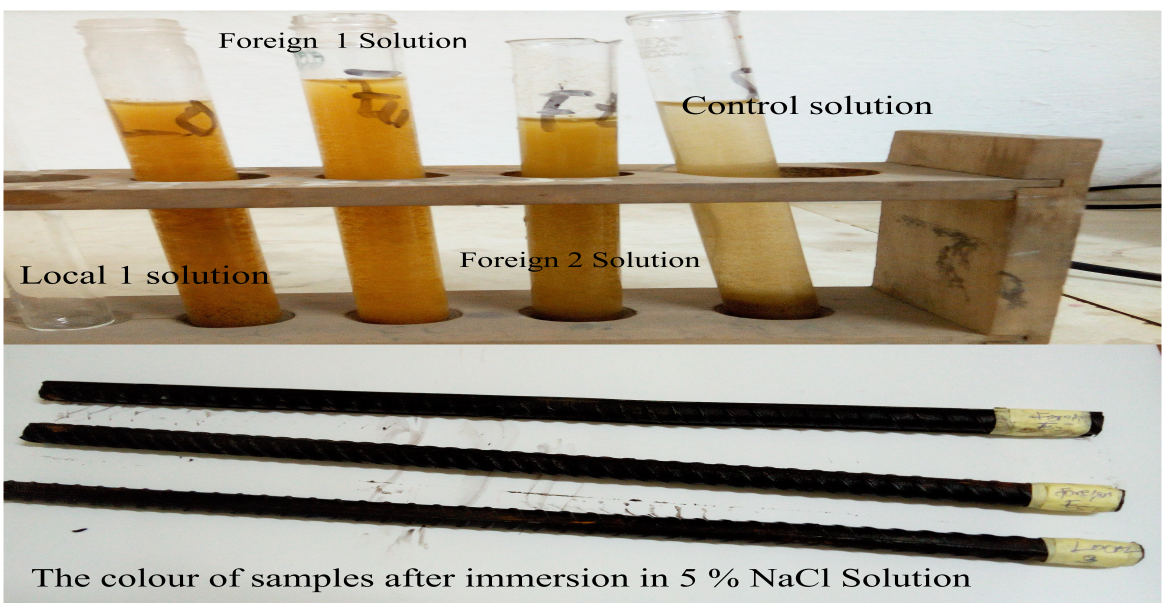

Fig. 3.11 picture of the samples and their respective colour changed after corrosion test.

3.9 Determination of Corrosion Rate

The samples are taken out of the solution, washed to clean rusts accumulated on steel, dried and weighed to estimate mass loss. The estimation of corrosion rate from mass loss is to weigh the sample before and after exposure to the 5 % NaCl solution and divide by the total exposed area and the total exposure time.

$$C_R = \frac{k \times \Delta w}{A \times T \times \rho} \qquad 3.8.1$$

Where

- $\mathbf{C_R}$ is Corrosion rate
- $\mathbf{\Delta w}$ is Weight loss in gram per day
- **A** is Exposed surface area of Iron rod
- **P** is Density of iron rod
- **T** is Time of exposure in hours
- **K** is Constant for unit conversion.

CHAPTER FOUR

RESULTS AND ANALYSIS

4.0 Introduction

Properties that are directly measured through tensile test are ultimate tensile strength; yield strength, maximum elongation and mass loss in iron steel samples. Tensile properties indicate how the material reacts to forces being applied in tension. The results of the tensile tests, corrosion test, corrosion rate and elemental composition of local and imported iron steel bar brands are presented in this chapter. The sample's mass and mechanical properties were measured before corrosion test. Besides, the conductivity, pH and temperature of each corrosion bath were recorded as well before and after corrosion test.

4.1 Elemental Composition of the Iron steel bar using PIXE technique

The presence of some alloying elements enhances the mechanical properties of the iron bar. Such elements were on the lookout as the elemental analysis for this study was performed.

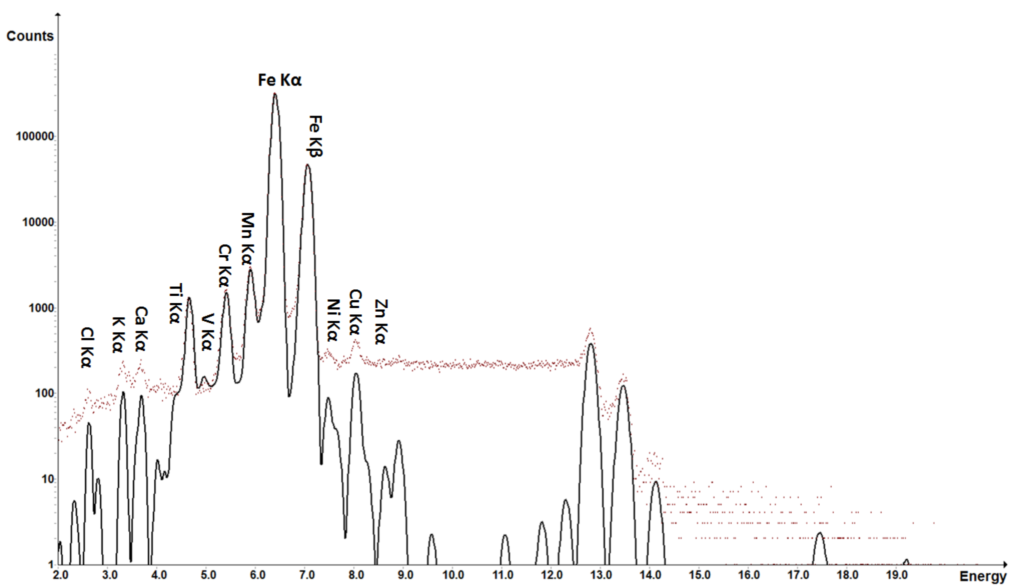

Fig. 4.1 fitted PIXE spectrum for the Local 1 iron steel bar

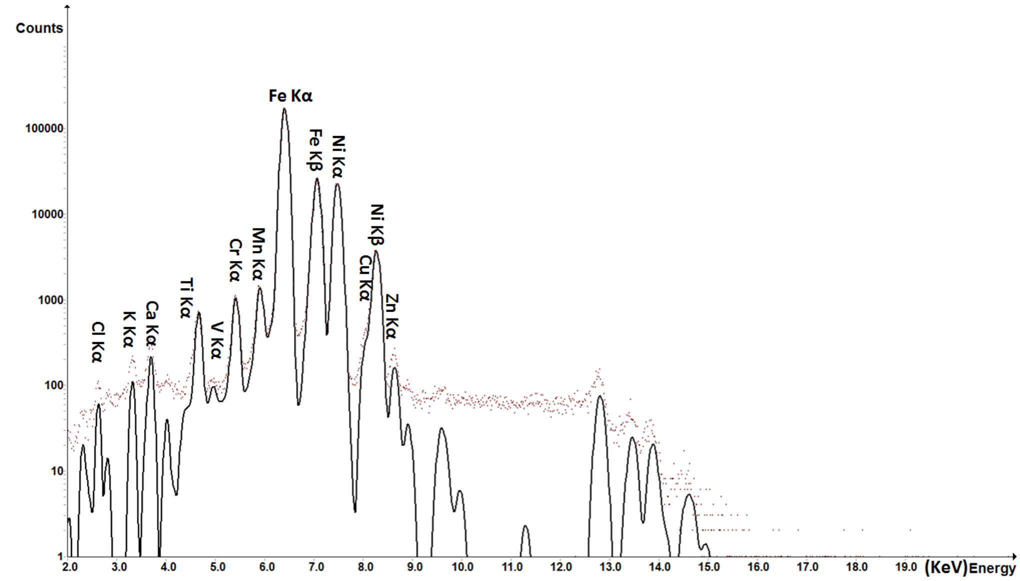

Fig. 4.2 fitted PIXE spectrum for the Foreign 1 iron steel bar

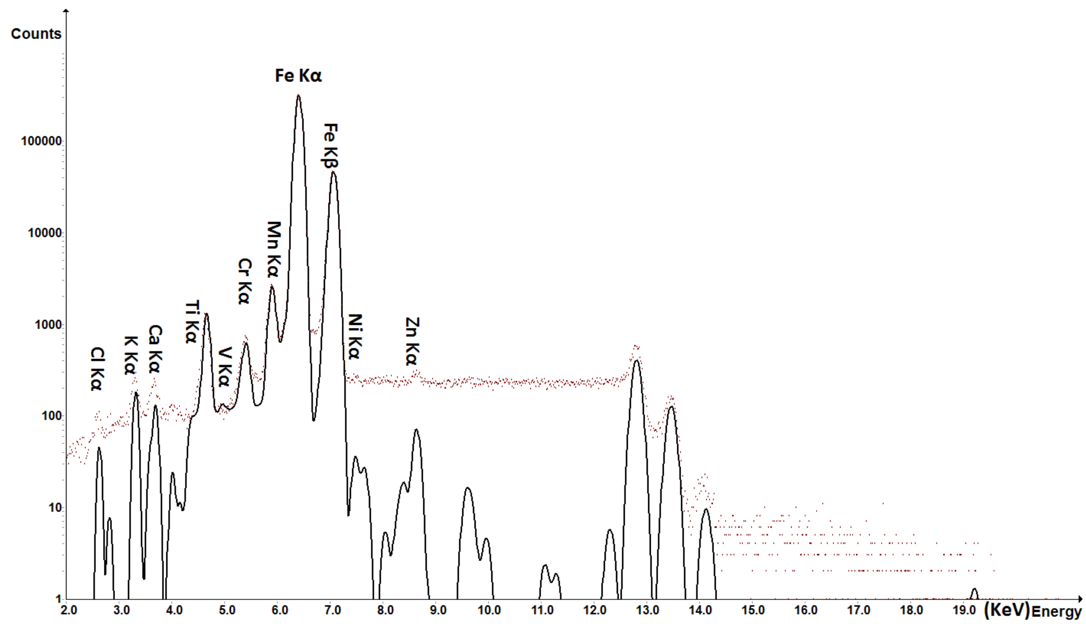

Fig. 4.3 fitted PIXE spectrum for the Foreign 2 iron steel bar

From Fig. 4.1- 4.3 illustrate the PIXE spectrum for the entire iron steel bar sample, showing x-ray counts as a function of energy. A total of eleven (11) elements were identified in the entire Steel bar samples. All the necessary elements needed in steel could be identified in all the samples, Fe, Mn, Cr, Ni, Cu.

Elements	Local (wt.%)	Foreign 1(China) (wt.%)	Foreign 2(Ukraine) (wt.%)
Cl	0.086	0.156	0.086
K	0.046	0.067	0.079
Ca	0.025	0.085	0.036
Ti	0.025	0.032	0.035
V	0.005	0.005	Nd
Cr	0.232	0.241	0.079
Mn	0.594	0.364	0.587
Fe	93.30	60.60	98.70
Ni	0.117	37.50	0.054
Cu	0.264	0.396	0.010
Zn	0.025	0.336	0.145
Mo	nd	0.197	Nd

Table 4.1 the elemental composition of Local 1, Foreign1 and Foreign 2

All the steel bars analyzed contained Fe, which is the key element in steel bars. Foreign 2 and Local 1 samples contained Fe concentrations above 90 %, which is the minimum requirement for Fe content in steel bars. The problem was with the Foreign 1 sample, which recorded a far too low Fe content (60.6 %), which is below the standard value.

Manganese (Mn) was present in all samples analyzed. Although its concentration was less than 1% in the sample, the presence of manganese in steel bars have been found from literature to increase the hardenability of the steel, and act as the deoxidizer in the steel. Manganese also prevents the creation of iron sulphate insertions, which may cause hot cracking problems of the iron steel.

Chromium, which enhances corrosion resistant in the steel, was identified in all samples, Foreign 2 steel bar recorded relatively the lowest concentration (0.079) among all samples analyzed.

Nickel also improves the corrosion resistance of the steel bar under conditions where the passive layers formed on steel are destroyed uniformly or locally. High Nickel content (37.5) recorded for Foreign 1 samples was too much. From the Table 4.6, it was observed Local 1 and Foreign 2 have their nominal elemental chemical composition of iron steel in their acceptable proportion as compare to British (BS4449) and Ghana (GS 788-2) nominal Standard chemical composition of iron steel bar (alloy steel). The sample, Foreign 1 contains too much sulphur (0.24 %) and nickel

(33.28 %), the iron which is the main principal alloying element of the steel bar also fall below the standard concentration of alloying element of iron steel bar.

The molybdenum high melting point gives strength to the iron steel. Molybdenum improves the resistance to pitting in chloride environments and to crevice corrosion in alloys steel. The iron steel, in the presence of oxygen, oxidizes freely with its natural environment, molybdenum minimizes this effect and indemnifies passivity; decrease the tendency of previously formed passive films to break down further. Molybdenum, vanadium, cobalt, and chromium are added to iron steel to provide greater strength, toughness, and corrosion resistance of iron steel bar.

4.2 Result of Mechanical Properties of Iron steel bar

The figures below show the stress and strain graph, that portray the ultimate tensile strength values, yield strength and maximum elongation of local iron steel bar of diameter 16 mm Local 1 (from Ghana) and imported iron steel bar of diameter 16 mm Foreign 1 (from China) and Foreign 2 (from Ukraine) respectively before corrosion test.

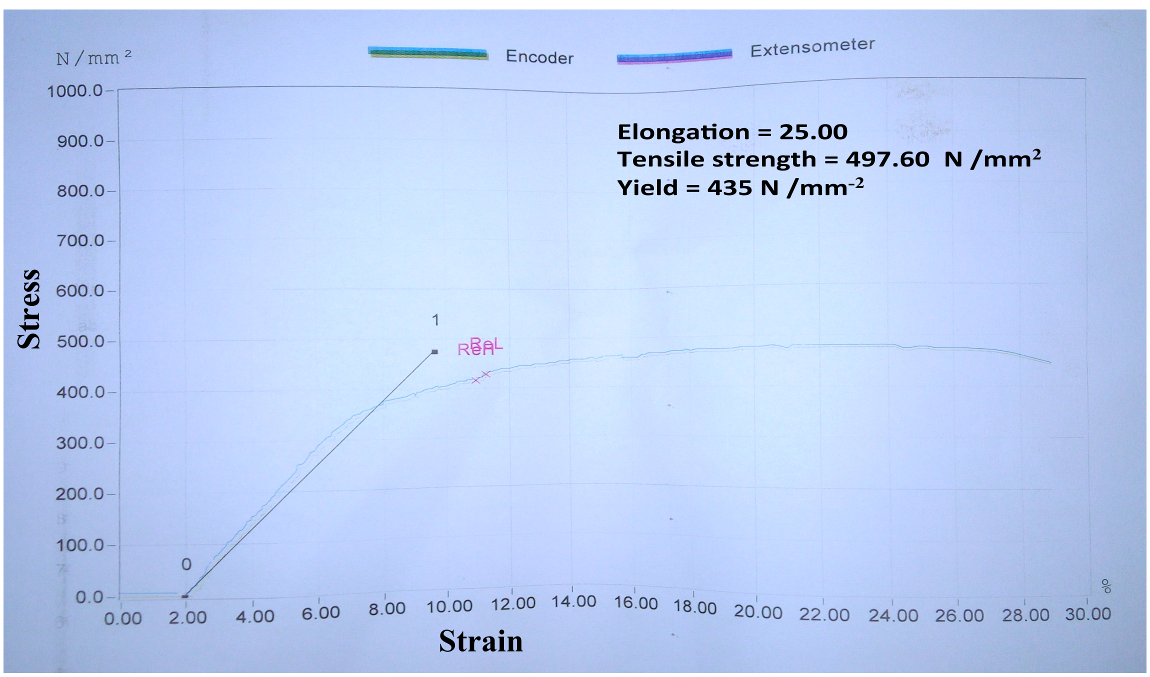

Fig. 4.4 shows the Stress and Strain graph of Local 1 iron steel bar before corrosion test

From the graph in Fig. 4.4, it shows that when a force of 80.76 kN was applied on the Local 1 steel bar, it produced high yield strength of 435 N/mm^2 and percentage elongation of 25.00 %.

These values were above the minimum required limits set for Yield strength, which is 400, Nmm^{-2} (British BS 449 standard) and 300 Nmm^{-2} (GS 788-2:2008, Ghanaian standard). Its ultimate tensile strength was 497.6 N/mm^2, there are no set standard values for ultimate tensile strength, and therefore the Yield standard was chosen as a guideline. The original gauge length of local steel bar was 450 mm, which has a mass of 637 grams and diameter 14.4 mm the area of the steel before the corrosion test was 162.3 mm^2.

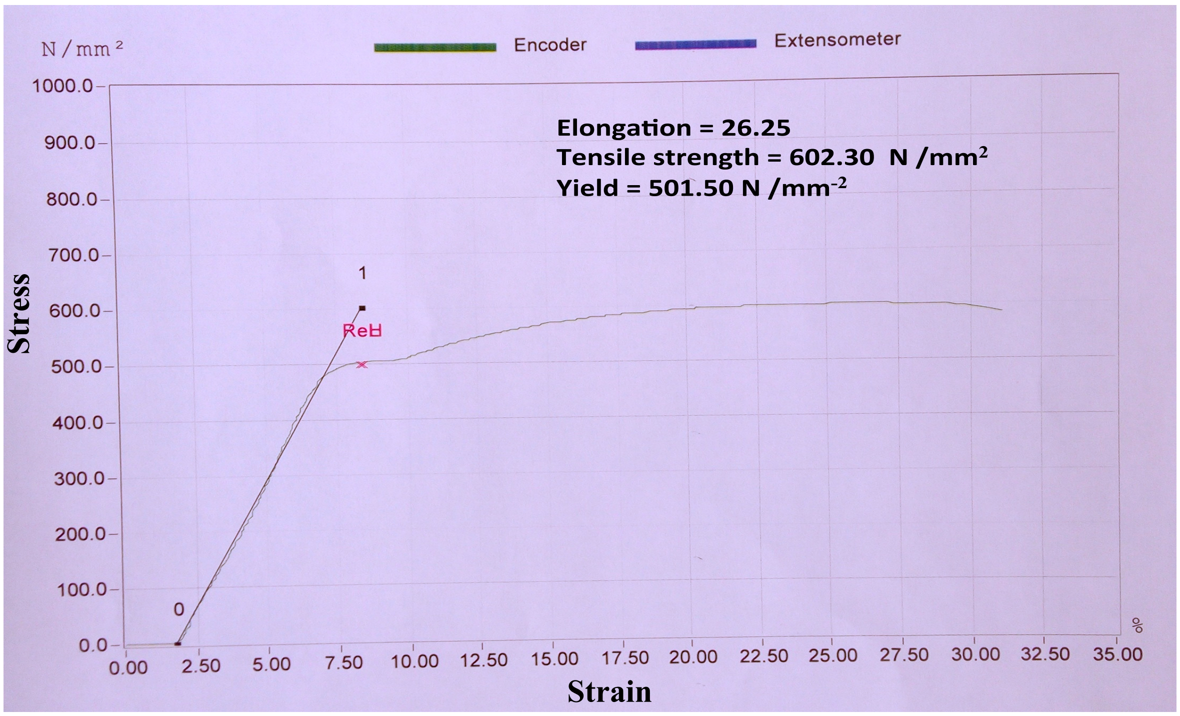

Fig. 4.5 Shows the Stress and Strain graph of Foreign 1 iron steel bar before corrosion test

From Fig. 4.5 when a force of 119.72 kN was applied on Foreign 1 it produced a yield strength of 501.50 N/mm^2; and an ultimate tensile strength of 602.30 N/mm^2 and percentage elongation of 26.25 %. The average initial mass was 788.11 g, diameter of 15.9 mm and area 198.8 mm^2.

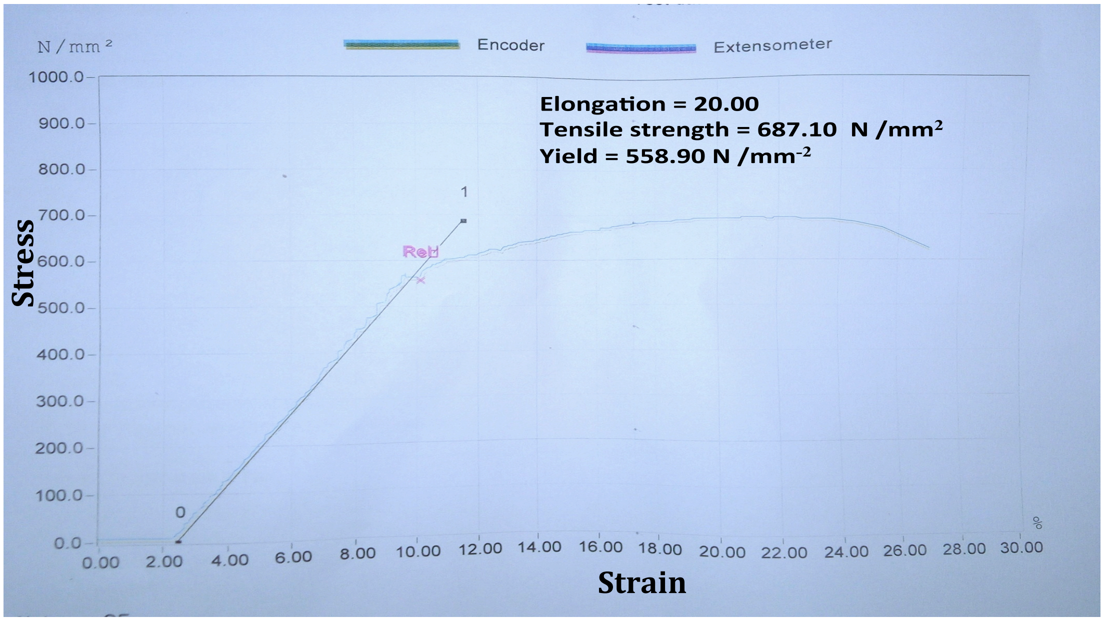

Fig. 4.6 shows the Stress and Strain graph of Foreign 2 iron steel bar before corrosion test

The initial average mass of the Foreign 2 iron steel bar was 790.22 grams, length 450 mm, diameter 15.90 mm and area of 198.10 mm^2. From the graph in Fig. 4.3, when a force of 133.43 kN applied on Foreign 2 steel bar, it produced a yield strength of 558.9 N/mm^2, percentage elongation of 20 % and has an ultimate tensile strength of 687.10 N/mm^2.

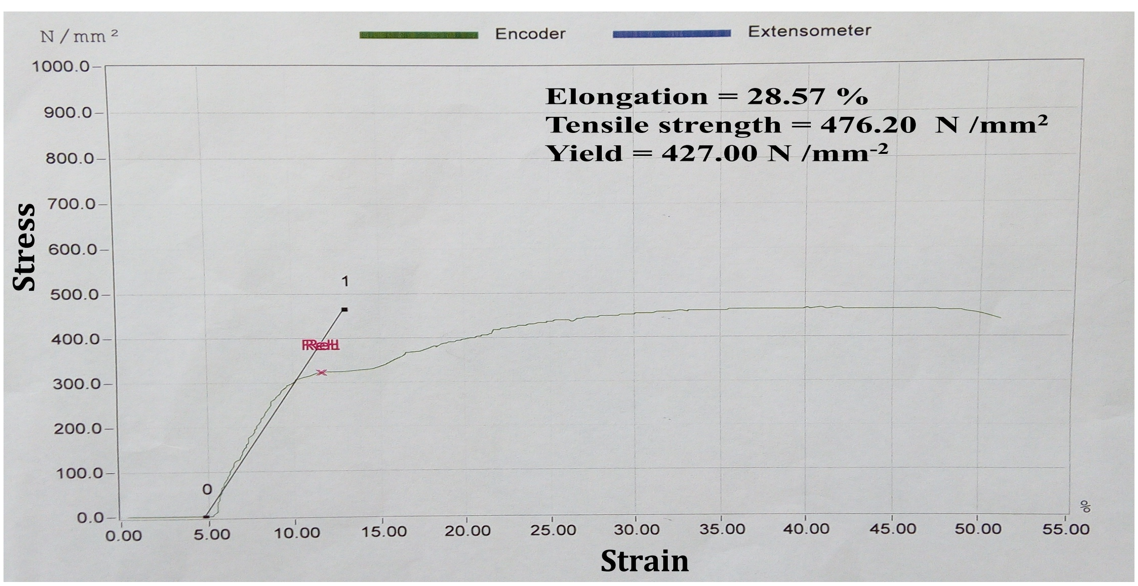

Fig. 4.7 shows the Stress and Strain graph of Local 1 iron steel bar after 21 days

From the graph in Fig. 4.7, it was observed that, after 21 days of induced corrosion of the Local 1 sample, its Yield strength and Tensile strength had dropped from 435 to 427 N/mm^2 and 497.6 to 476.20 N/mm^2 respectively. Percentage elongation had increased from 25 to 28 % indicating the gradual loss of hardness in the sample making it more ductile. Although the drop in these parameters was expected, the values recorded after the 21 days corrosion tests for local 1 sample were within standard minimum requirement.

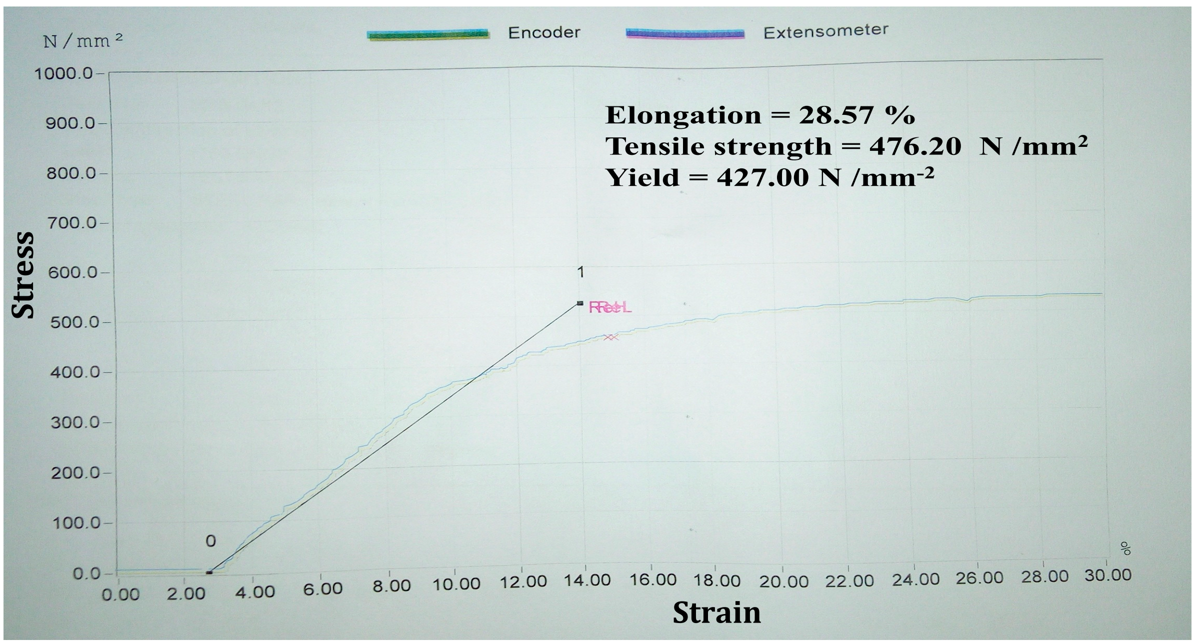

Fig. 4.8 shows the Stress and Strain graph of Foreign 1 iron steel bar after 21 days

After the 21 days immersion of Foreign 1 in 5 % NaCl solution, yield strength of 456.00 N/mm^2 was recorded which a drop from its original value of 501.50N/mm2. There was also a drop in the ultimate tensile strength was from 602.30 to 528.60 N/mm^2. Percentage elongation for this sample did not record an appreciable change (from 26.25) to 25.71 %.

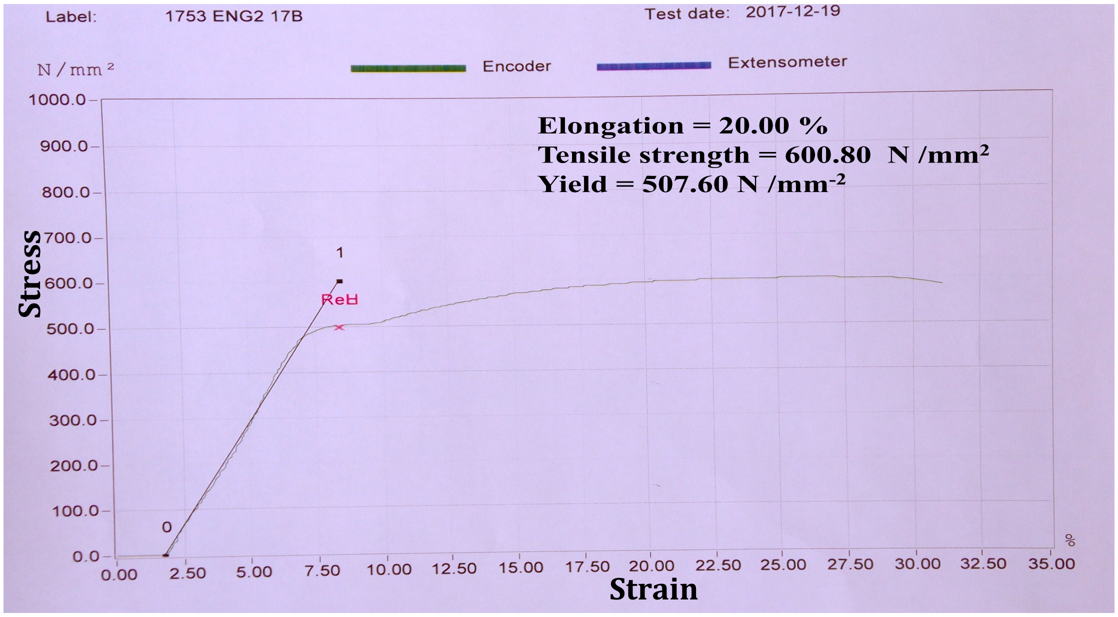

Fig. 4.9 shows the Stress and Strain graph of Foreign 2 iron steel bar after 21 days

From Fig. 4.9, after 21 days of corrosion test of Foreign 2 samples there was a reduction in the yield strength from 558.9 to 507.60 N/mm^2. The ultimate tensile strength also dropped from 687.1 to 600.8 N/mm^2. It was observed that the diameter of the steel dropped from 15.9 mm to 15.7 mm, which also has changed its area from 194.2 mm^2 to 192.6 mm^2. The drop in diameter of the iron steel bar is an indication that the iron oxidized and this has increased the conductivity and decreased the pH of the solution.

Day	Sample	Applied force/ kN	Yield/ Nmm^{-2}	Percentage elongation / %	Ultimate Tensile strength / Nmm^{-2}
Before	Local 1	80.76	435.00	25.00	497.60
After 21	Local 1	75.63	427.00	28.57	476.20
After 60	Local 1	64.87	302.10	36.25	414.10
Before	Foreign 1	119.72	501.50	26.25	602.30
After 21	Foreign 1	87.68	456.10	25.71	528.60
After 60	Foreign 1	85.86	389.70	22.50	468.60
Before	Foreign 2	133.43	558.90	20.00	687.10
After 21	Foreign 2	119.02	507.60	20.00	600.80
After 60	Foreign 2	87.68	456.00	25.71	528.60

Table 4.2 Summary of mechanical properties before, after 21 days and 60 days

From table 4.2, one can observe a reduction in the necessary force required to cause a strain in the steel bar, which clearly indicates a gradual reduction of the structural integrity of the material due to corrosion. Local 1 sample recorded the highest reduction in Yield (30%) after the corrosion test but surprisingly its tensile strength did not change much. Foreign 2 samples recorded the least reduction percentage for Yield.

Sample	Yield strength drop after 60 days corrosion (%)	Ultimate Tensile strength drop after 60 days corrosion (%)
Local1	30.6	16.7
Foreign1	22.3	22.2
Foreign2	18.4	23.1

Table 4.3 Summary of the percentage reduction in mechanical properties of samples

Table 4.3 indicates a summary of the reduction in the mechanical properties of all samples after 60 days of induced corrosion.

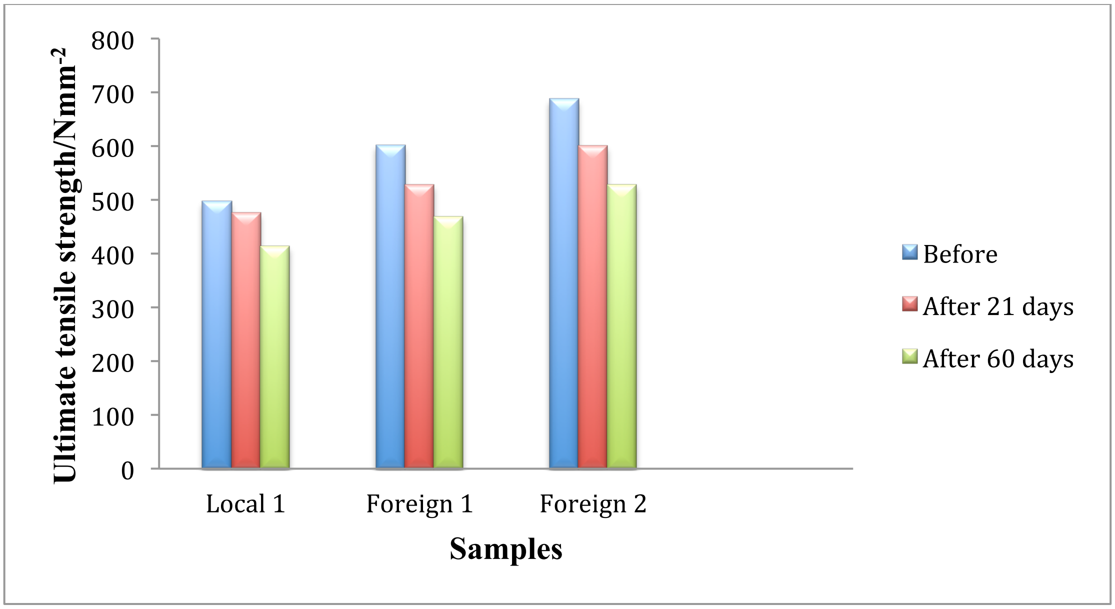

Fig. 4.10 showing the ultimate tensile strength of Local 1, Foreign 1 and Foreign 2

Fig. 4.10 shows the maximum tensile strength, which the locally manufactured iron steel bar (Local 1) and imported iron steel bar (Foreign 1 and Foreign 2) can withstand before fracture. From figure 4.10, a downward trend is observed. The percentage reduction for Local 1 sample was 16 %, which is the lowest recorded. This can infer that the Local samples are less sensitive to corrosion in respect to its ultimate tensile strength properties. A reduction of 22 and 23 % is observed for Foreign 1 and foreign 2 respectively.

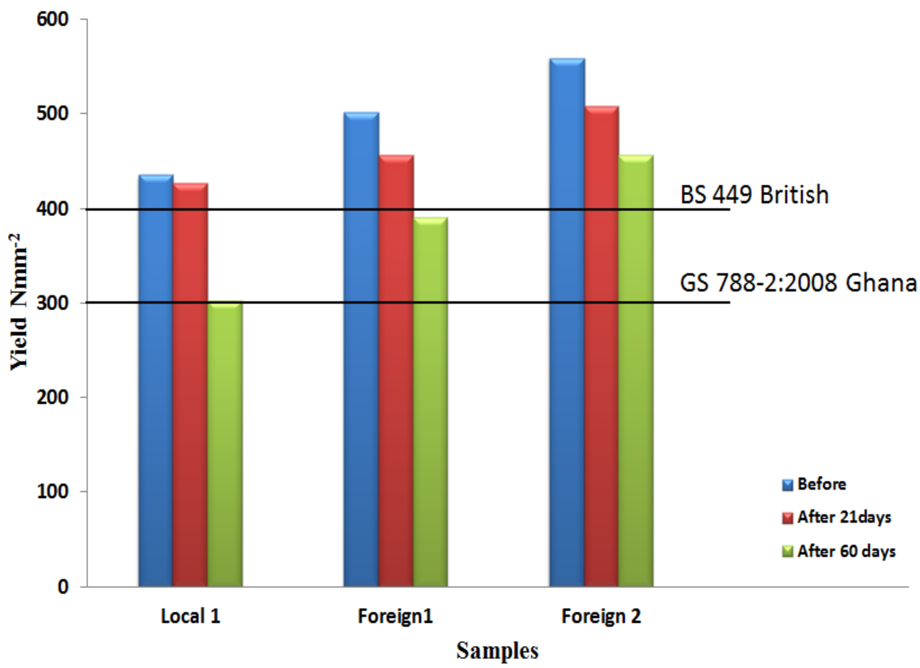

Fig. 4.11 showing the Yield strength of Local 1, Foreign 1 and Foreign 2

The yield strength of the iron steel is the point on the stress and strain graph curve where the iron steel bar starts undergoing plastic deformation and at this point when the applied force is removed the steel cannot move back to its original shape or form. This is where the nonlinearity between stress and strain begins. From Fig. 4.11 the yield strength of locally manufactured iron steel before the corrosion test was 435.0 Nmm^{-2}, and for imported iron steel bar Foreign 1 and Foreign 2 yield strength were 501.50 Nmm^{-2} and 558.90 Nmm^{-2} respectively. Also, from the Fig. 4.11 there was a decline in the yield strength of each sample as the immersion period increased. This declination in the yield strength of the iron steel bar was due to the reduction in the area of the samples and the reduction and oxidation (Redox) reaction that the iron steel bars undergone with its environment. This reaction affected the chemical structural and the bonds of the atoms in the iron steel bar and hence affecting the iron steel bar mechanical properties. After the 60 days of immersion of the locally manufactured iron steel bar yield strength dropped to 302.10 Nmm^{-2} and Foreign 1 and Foreign 2 yield strength respectively dropped to 389.70 Nmm^{-2} and 456.00 Nmm^{-2} as shown in Table 4.1 and Fig. 4.8. It also observed that, after the 60 days immersion of the iron steel bars of Local 1, Foreign 1 and Foreign 2 in 5 % NaCl solution, only Foreign 1 and Foreign 2 samples yield strength were above the minimum nominal standard of 300 Nmm^{-2} specification provided by BS 449 and GS788-2. The Local 1 sample yield strength was little below the minimum nominal standard.

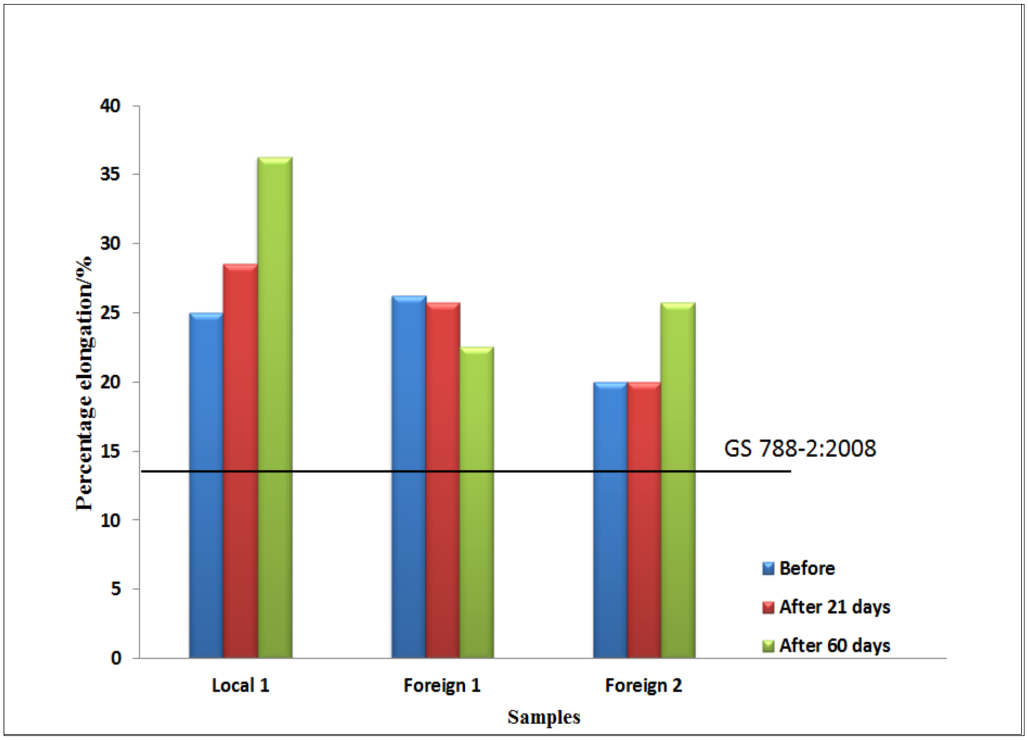

Fig. 4.12 showing the Percentage elongation of Local 1, Foreign 1 and Foreign 2

The percentage elongation is the amount of strain that the iron steel bar can experience before rupture in the tensile testing. The elongation is the increase or a change in the gauge length of the iron steel bar subjected to tensile forces divided by the original gauge length and it is expressed as a percentage. The ductility of the iron steel bar is directly proportional to its elongation. The large elongation of the iron steel bar, gives a better ductility of the iron steel bar. From Fig. 4.12 it was observed that the elongation of locally manufacture iron steel bar increased from 25 % to 36.25 % this could be due to the less percentage content of carbon since carbon contributed to the hardenability of the iron steel. This high percentage elongation range of Local 1 iron steel bars enabled it to neck for long after its ultimate tensile strength before fracture. Also, from Fig. 4.12 it was observed that the Foreign 1 percentage elongation rather decline from 26.25 % to 22.50 %, this was due to the less percentage content of iron in Foreign 1 and as can be seen in the Table 4.1, the chemical composition of Foreign 1 the content of iron was 64.90 %, nickel was 33.28 % and sulphur 0.24 %. The nickel also contributed to the hardenability and toughness of the iron steel hence making the Foreign 1 hard and brittle and reducing its ductility. For Foreign 2 sample, the elongation before the corrosion test and after 21 days remained the same. After 60 days of immersion its elongation increased from 20 % to 25.71% this was due to when the carbon started detaching from the iron steel and this made the iron surface turned very black.

4.2 Conductivity Test Result

Day	**Sample**	**Conductivity/mScm^{-1}**	**pH**	**Temperature/°C**
Before	Local 1	69.70	6.53	30.0
	Foreign 1	69.70	6.53	30.0
	Foreign 2	69.70	6.53	30.0
After 21 days	Local 1	99.80	5.86	29.4
	Foreign 1	95.20	6.20	29.4
	Foreign 2	100.40	5.46	29.4
After 60 days	Local 1	381.60	5.74	29.7
	Foreign 1	418.40	5.42	29.4
	Foreign 2	354.00	5.80	29.7

Table 4.4 shows the result of conductivity and pH before, after 21 days and 60 days

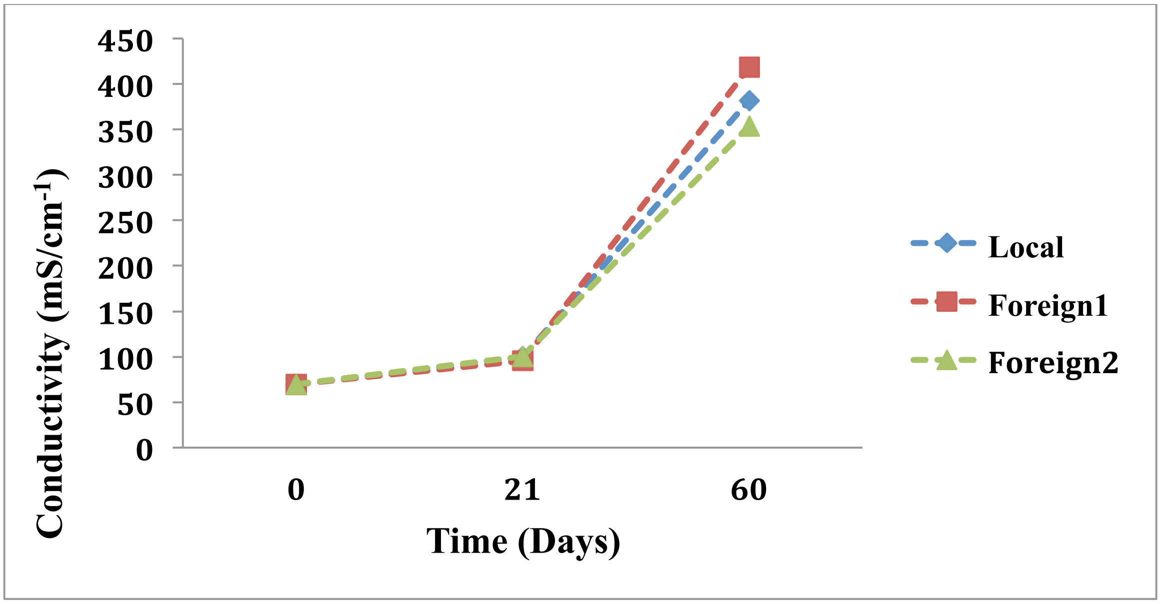

Fig. 4.13 Conductivity test graph of Local1, Foreign 1 and Foreign 2 after 21 and 60 days

From figure 4.13, conductivity increased with corrosion time, the conductance level in the corrosion solution of foreign 1 was the highest, this means that more ion are dissolved from the sample into the solution, this data was compared with the mass loss measured for samples as indicated in Fig. 4.14. Foreign 1 had the highest mass loss, which was expected.

4.3 Corrosion Test Result

After the 21 days immersion of the samples in 5 % NaCl solution, the colour of the samples solution changed and this changed in colour depicted the dissociation of the iron and the dissociation of Fe^{2+} in the samples solution. This increases the conductivity of the samples solution and hence increasing the number of ions in the solution that speeds up the galvanic corrosion due to potential difference in the solution. After 21 days of immersion of the samples, it was observed also that the local iron steel bar immersion container conductivity changed from 69.7 $mScm^{-1}$ to 99.8 $mScm^{-1}$, the pH also dropped from 6.53 to 5.86. Moreover, the decreased in pH value implies that the iron dissociated in the solution reacted with the oxygen in the solution to form iron (II) oxide, the presence of chlorine ions in the solution also contributed to an increased in ions in the solution and this led to a decreased in the pH and an increased in the conductivity of the samples solution as shown in Table 4.4.

4.4 Mass Loss

Table 4.5 shows drop in mass of each sample after the 21 days immersion in the 5 % NaCl solution. The drop in the mass of each sample was an indication of carbon detaching from the iron and this made the iron rods turned very black as shown in Fig. 3.11. Also, the drop in the mass of the samples indicated the disassociating of the Fe^{2+} in the solution hence this led to an increased in the conductivity of the samples solution.

MASS OF SAMPLE BEFORE CORROSION TEST		
SAMPLE	**Average Mass/gram**	
Local 1	637.44	
Foreign 1	784.00	
Foreign 2	790.22	
MASS OF SAMPLE AFTER 21 DAYS OF CORROSION TEST		
SAMPLE	**Mass/gram**	**Mass Loss/gday^{-1}**
Local 1	562.11	3.59
Foreign 1	587.89	9.34
Foreign 2	687.56	4.89
MASS OF SAMPLE AFTER 60 DAYS OF CORROSION TEST		
SAMPLE	**Mass/gram**	**Mass Loss/gday^{-1}**
Local 1	547.33	1.50
Foreign 1	568.11	3.67
Foreign 2	587.11	3.39

Table 4.5 shows the result of mass loss after 21 days and 60 days

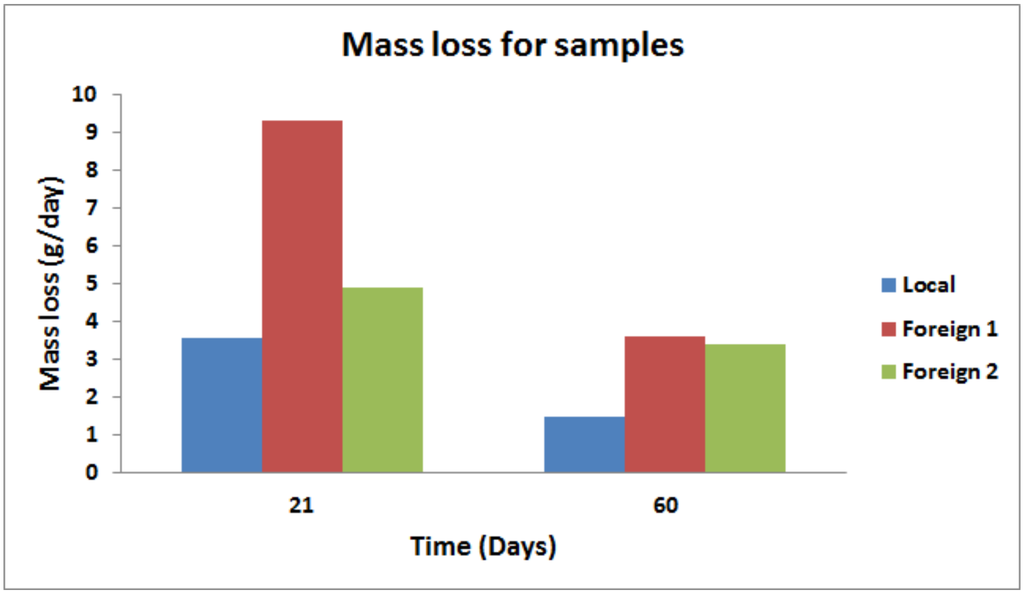

Fig. 4.14 Mass loss of each sample after 21 and 60 days

From this Fig. 4.14 Foreign 1 lost more mass than all the samples, which means it is very sensitive to corrosion.

4.5 Corrosion Rate

Table 4.6 shows the corrosion rate of each sample that was estimated from the mass loss by weighing the corroding sample before and after exposure time and divide by the total exposed area and the total exposure time. At the end of the 60 days corrosion test, the corrosion rate of Local 1 was 0.07 mm per year and Foreign 2 corrosion rate was 0.16 millimeter per year. Foreign 1 recorded the high corrosion rate 0.17 mm per year. Fig. 4.15 shows a stack plot corrosion rate chart of all the three brands iron steel bars analyzed.

CORROSION RATE AFTER 21 DAYS OF CORROSION TEST			
SAMPLE		Corrosion Rate/mmyear-1	
Local 1		0.5	
Foreign 1		1.25	
Foreign 2		0.68	

CORROSION RATE AFTER 60 DAYS OF CORROSION TEST			
SAMPLE		Corrosion Rate/mmyear-1	
Local 1		0.07	
Foreign 1		0.17	
Foreign 2		0.16	

Table 4.6 the corrosion rate of Local 1, Foreign1 and Foreign 2 after 21 and 60 days

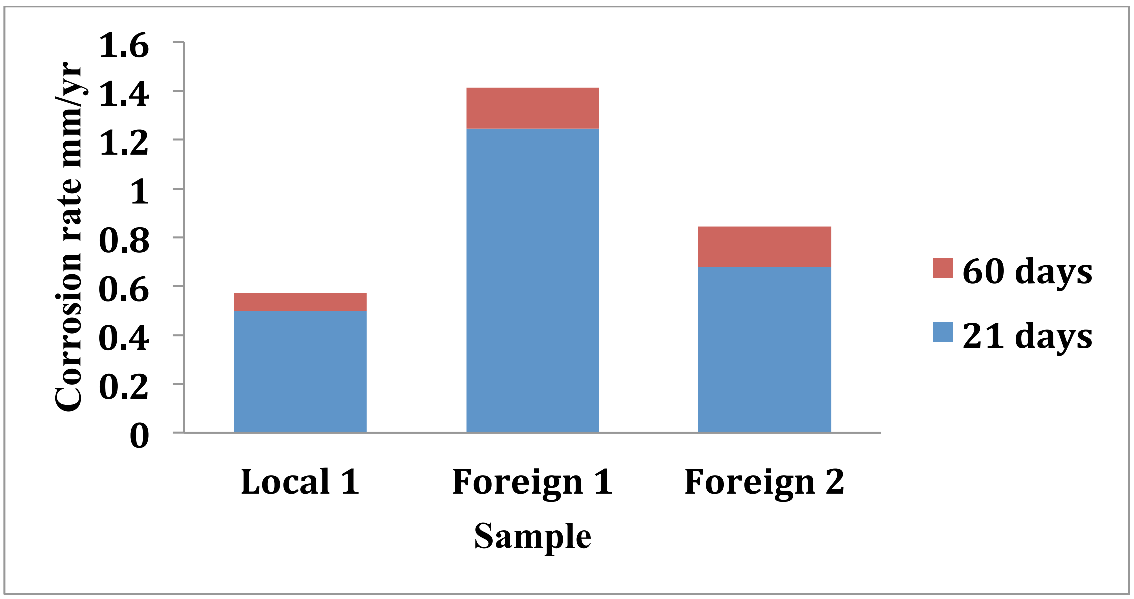

Fig. 4.15 Stack plot of corrosion rate of Local, Foreign 1 and Foreign 2 after the 21 and 60 days

From Fig. 4.15, the corrosion rate for Foreign 1 was the highest with Local 1 recording the lowest corrosion rate.

4.6 Nominal Diameter of Iron steel bar

Table 4.7 presents the nominal diameter of imported and locally manufacture iron steel bar on the Ghanaian market. It is observed that, Local 1 and Foreign 1 iron steel bar are far below the British and Ghana minimum provision standard, while Foreign 2 is just little below the minimum provision standard.

Sample	Diameter/ mm	BS (4449) &GS (788-2) Minimum Provision	Remarks
Local 1	15.40	16	Below
Foreign 1	15.80	16	Below
Foreign 2	15.90	16	Little below

Table 4.7 Nominal diameters of Local 1, Foreign1 and Foreign 2 on the Ghanaian market

4.2 Elemental Signatures

In this research, two elements Chromium and Manganese were found to be the main signatures that could relate mechanical strength to corrosion rate of the iron steel bars.

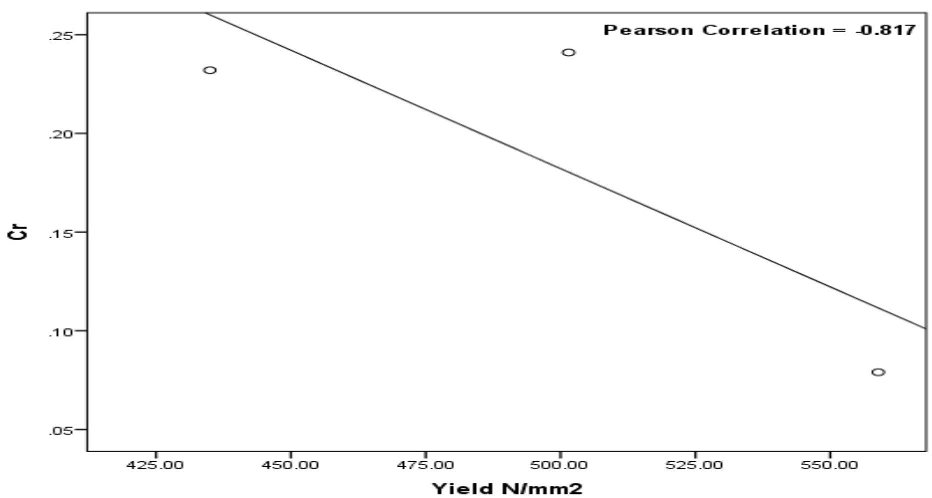

Fig. 4.16 Correlation plot of Chromium and Yield strength

From Fig. 4.16 there was a strong negative correlation between chromium and the yield, though chromium contributed to corrosion resistant of iron steel bar when chromium content increases in the iron steels it affects the yield strength by reducing it. Hence from literature the percentage concentration of chromium in iron steel bar should be less than 0.03 %. Also, from Fig. 4.4 the correlation plot between the chromium and the yield strength indicate that as chromium contents increase in the iron steel bar the corrosion rate also decreases and this is a positive correlation.

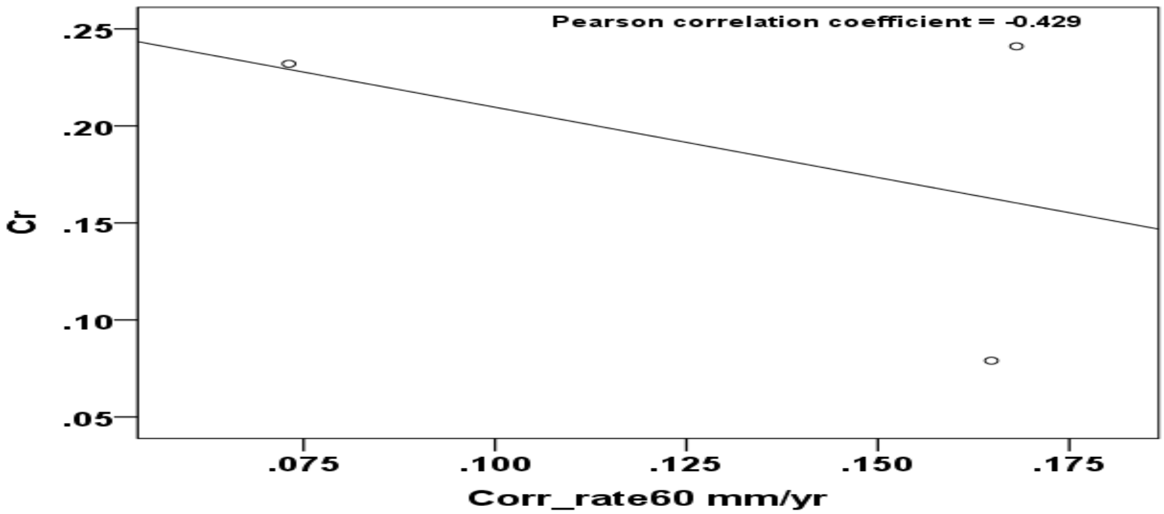

Fig. 4.17 Correlation plot between Chromium and corrosion rate

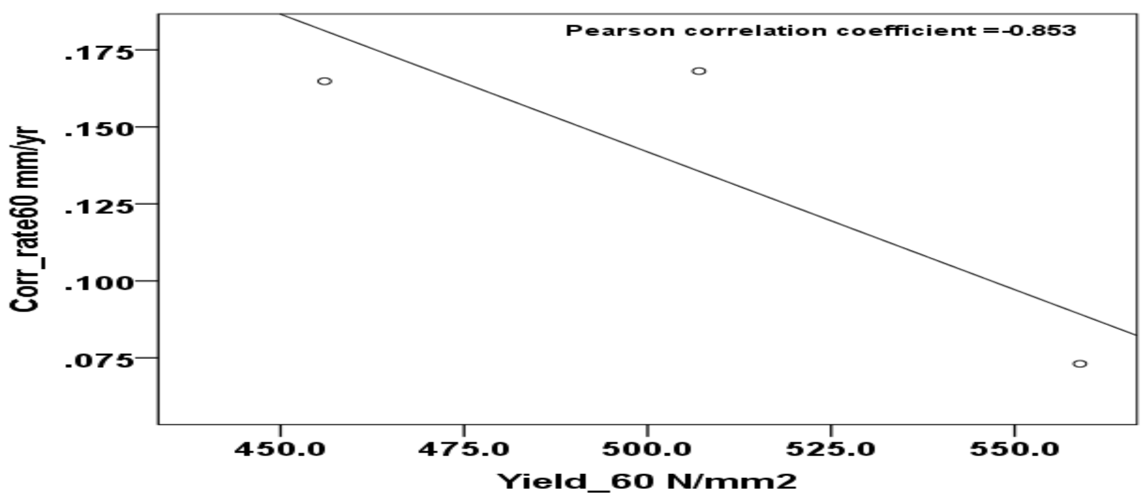

Fig. 4.8 Correlation plot of Corrosion rate and Yield strength

Fig. 4.18 shows the correlation plot between the corrosion rate after 60 days against the yield strength. A negative correlation was observed, and this means that as the corrosion rate of the analyzed sample increased the yield strength of the sample also decreased.

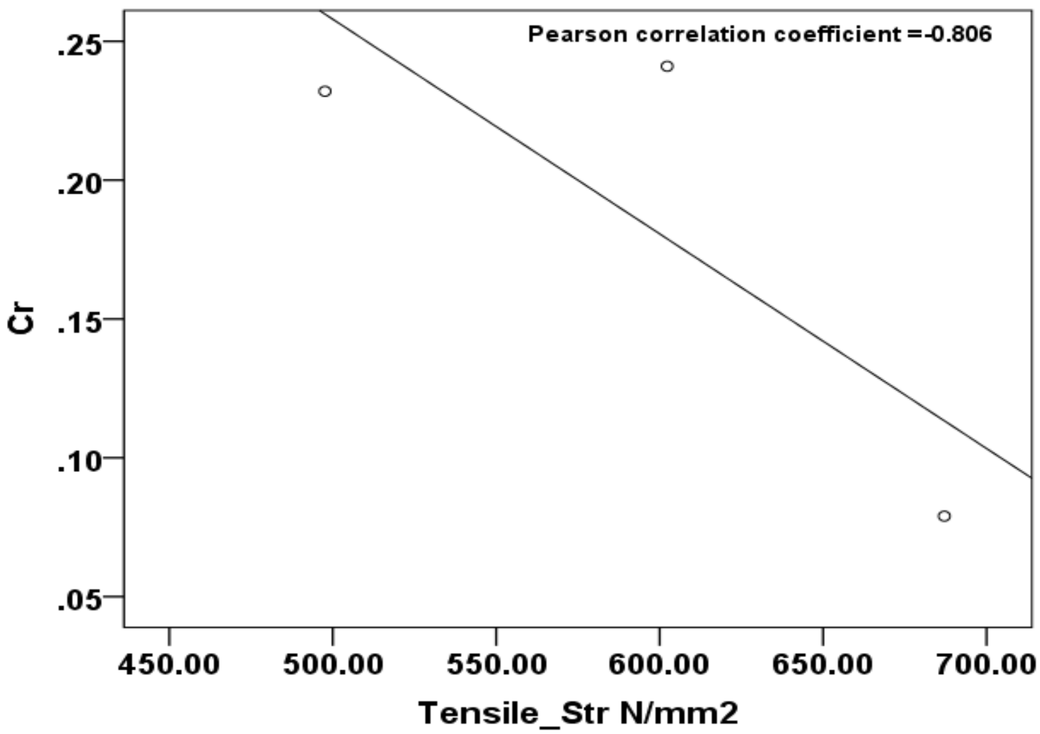

Fig. 4.19 Correlation plot between Chromium and ultimate tensile strength

The same reduction trend was observed when chromium concentration in each sample plotted against its ultimate tensile strength a negative correlation was observed and this indicated that as the chromium content in the iron steel bar increased it affects the ultimate tensile strength and percentage elongation (ductility) of the iron steel bar but improved the iron steel corrosion resistant.

Manganese as one of the elemental signatures that relate to the sensitivity to corrosion also exhibited similar trend properties as chromium. The manganese role in the iron steel bar is to react with the sulphur and oxygen to form MnS and MnO respectively and acted as deoxidizer in the iron steel bar. Though, sulphur contributed to hardenability of the iron steel bar it can also cause cracking and makes the iron steel bar brittle when subjected to elevated temperature environment. Oxygen on the other hand takes off the valence electron of the iron and cause the iron in the steel bar to oxidize and forms iron (II) oxide with oxygen. This stable form of iron weakens the iron steel bar mechanical properties and lead to mass loss as well.

Fig. 4.20 shows the correlation graph between manganese and corrosion rate and a fair correlation was observed, as Mn increased there is a tendency or possibility of a decreased in the corrosion rate of the iron steel bar.

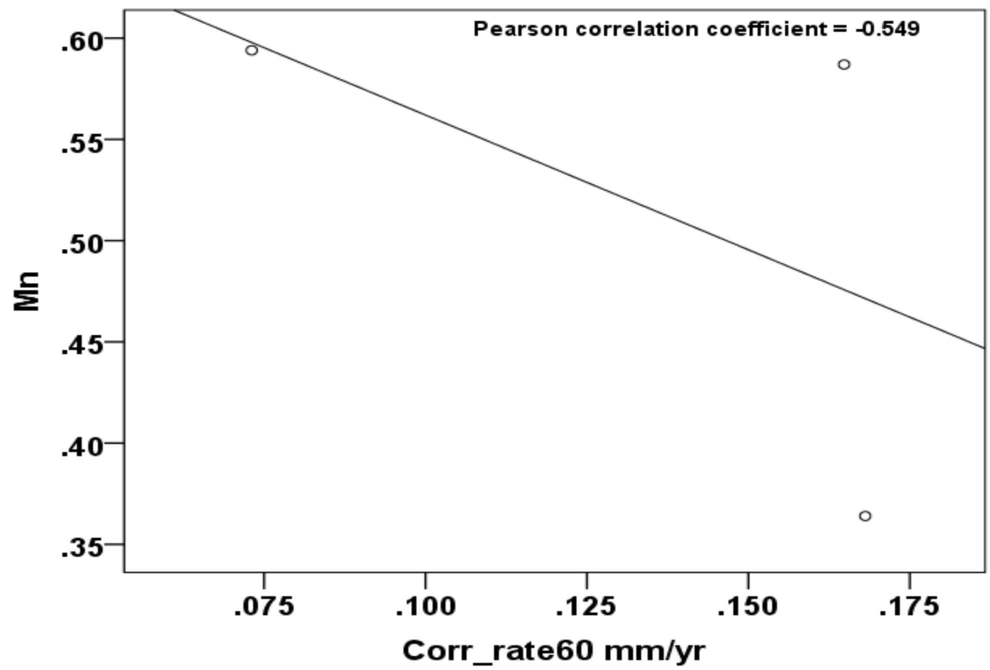

Fig. 4.20 Correlation plot between manganese and Corrosion rate

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.0 Introduction

This section consists of the summary of the research work, the conclusion and the recommendation for further research works. The outcome of the corrosion behavior of iron steel bars, its elemental composition and its mechanical perspective are listed below.

5.1 Summary

- Iron steel bar undergoes electrochemical reaction with its environment and a low pH environment increases the corrosion rate. The steel bar oxidizes to form iron (II) oxides, which is another stable form of iron.
- The corrosion rate also increased with the increasing days of immersion of samples in 5 % NaCl solution.
- The weight loss of iron steel bar is directly proportional to corrosion rate of iron steel bar in its environment.
- The elemental composition of the iron steel bar has direct impact on the corrosion rate of the iron steel bar in its environment. The presence of these elements manganese, nickel, chromium, copper, cobalt and molybdenum in iron steel bar enhanced the corrosion resistance of the iron steel bar in its environment.
- The presence of manganese in the iron steel bar composition also increases the hardenability of the iron steel bar and act as deoxidizer in the iron steel. Chromium enhances corrosion resistant in the iron steel bar.
- The high percentage content of carbon in iron steel bar affected the ductility of the steel bar and makes iron steel bar breaks easily under high tensional force. Also, small content of the carbon too makes the iron steel bar have high percentage elongation and low tensile force. This affects the yield point of the iron steel bar.
- The presence of the trace elements such as phosphorus and sulphur in the chemical composition of the iron steel bar affect the mechanical properties of the iron steel.

5.2 Conclusion

- When PIXE analytical technique method used to analyse locally manufactured 16 mm iron steel bar and the two imported 16 mm iron steel bar mostly used in all building sites the following elements, Chlorine, Potassium, Calcium, Titanium, Chromium, Manganese, Iron, Nickel, Copper, and Zinc were found present in all the three brands 16 mm iron steel bar samples analysed as shown in Table 4.6.
- At the end of this research, Chromium and Manganese were found to be the main signatures that could relate mechanical strength to corrosion rate of the iron steel bars. These two alloying elements in the 16 mm iron steel bar mitigate the rate of corrosion of iron steel bar in its environment and provided enabling environment for passivity.
- After the 60 days corrosion test, it was found that the corrosion rate of locally manufactured 16 mm iron steel bar (Local 1) was 0.07 mmpy (millimetre per year) and its percentage mass loss was 14.14 % of its initial mass 637.44 g. Also, the imported 16 mm iron steel bar from China named Foreign 1 had corrosion rate of 0.17 mmpy and 27.54 % dropped in its initial mass 784 g. The 16 mm iron steel bar imported from Ukraine, Foreign 2 had a corrosion rate of 0.16 mmpy and 25.70 % mass loss of its initial mass 790 g.
- The results obtained showed that an increased in immersion time produced a continuous decrease in weight of the iron steel bar samples.
- The results also showed that corrosion behaviour of iron steel bars depend on the chloride ion in the solution. The halide ions break the passivity of the iron.
- The 16 mm iron steel bar from China (Foreign 1) recorded the highest corrosion rate among the samples. Although, the Local 1 sample had the lowest corrosion rate, after 60 days of corrosion test its yield was far below the minimum specification requirement by Ghana Standard Authority 300 Nmm^{-2} (GS788-2, 2008).
- The mechanical properties Yield, Percentage elongation and Ultimate tensile strength of all the 16 mm steel bars were determined prior to corrosion analysis and all samples passed the nominal minimum specification for Yield 400 Nmm^{-2} (BS4449) and 300 Nmm^{-2} (GS788-2) respectively.
- Per the British Standard (BS 4449), Foreign 2 steel bars analyzed after 60 days of induced corrosion passed the required minimum specification for Yield in 16 mm iron

steel bars with the exception of the Local 1 sample which recorded a yield of (300 Nmm^{-2}) and the Foreign 1 sample from China (389 N/mm^2). And, per the Ghanaian standard (GS 788-2, 2008), all the 16 mm steel bars analysed passed the specified required minimum value for Yield in iron steel.

- Besides, it was observed that the high conductivity of the sample solution after some days (low pH) increases corrosion rate by providing more ions in the samples solution. The reduction of the valence electrons by oxygen in the iron that led to destruction of passive layers formed at the surface of the iron steel caused the iron in the steel to oxidize and hence forming iron (II) oxide. This process affected the molecular energy bond between the elements at lattice levels in the iron steel bar and this dislocation of the elements at lattice levels of the iron steel bar has direct negative impact on mechanical properties of the iron steel bar samples and hence weaken the iron steel bar to with stand any external tensional force that exert on it.
- Finally, after 60 days of induced corrosion of the samples, a negative correlation was found between corrosion rate and the mechanical properties of the steel.

5.3 Recommendation

The appropriate authority should conduct regular assessment of all the iron steel bar brands to eliminate all substandard iron steel bars on the Ghanaian market.

Moreover, it is recommended that Ghana Standard Authority should add corrosion test to their mechanical property test of the iron steel bar since corrosion rate depends on mass loss and the elemental composition of the iron steel bar.

It is also recommended that Ghana Standard Authority should add Proton-Induced X-ray Emission (PIXE) analytical techniques to their existing Atomic Absorption Spectrometry (AAS). Since PIXE is faster and more efficient than AAS in determining the elemental composition of the iron steel bar.

It is recommended that further research should also be conducted on the quality of cement and water used at the construction site. The chloride content of the cement and water could also affect the corrosion rate and mechanical properties of the iron steel bar, hence there is a need for that, to establish whether it may be the main cause of the recent collapsing of buildings in our country, Ghana.

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APPENDICES

APPENDIX A

1. Calculation of 5 % NaCl solution.

$$5\ \%\ \text{NaCl solution} = \frac{50 \text{ grams of NaCl}}{\text{Disolved in 1000 ml distilled water}} \times 100$$

2.The mass of each samples were measured thrice and the average value was chosen.

MASS OF SAMPLE BEFORE CORROSION TEST		
SAMPLE	**Average Mass/gram**	
Local 1	(637.33+638.33+636.67)/3 =	**637.444**
Foreign 1	(788.33+786.33+777.33)/3 =	**784.000**
Foreign 2	(790.00+791.33+789.33)/3 =	**790.222**

Table 1 average masses of the samples

3. The corrosion test was performed for three batches of each 16 mm iron steel bar samples and mechanical test was performed on one of each of the three brands sample.

	MASS OF SAMPLE BEFORE CORROSION TEST								
	LOCAL1			**FOREIGN 1**			**FOREIGN 2**		
	A	B	C	A	B	C	A	B	C
	637	638	636	788	787	787	790	792	789
	637	639	637	789	786	788	790	791	790
	638	638	637	788	786	788	790	791	789
AVERAGE=	**637.33**	**638.33**	**636.67**	**788.33**	**786.33**	**787.70**	**790.00**	**791.33**	**789.33**
MASS OF SAMPLE AFTER 21 DAYS OF CORROSION TEST									
	561	562	562	586	587	589	686	689	688
	562	562	563	587	588	590	686	688	688
	561	563	563	587	588	589	687	689	687
AVERAGE=	**561.33**	**562.33**	**562.67**	**586.67**	**587.67**	**589.33**	**686.3**	**688.67**	**687.67**
MASS OF SAMPLE AFTER 60 DAYS OF CORROSION TEST									
	546	548	547	568	569	567	586	588	588
	547	549	547	569	569	566	585	589	587
	546	548	548	568	570	567	586	588	587
AVERAGE=	**546.33**	**548.33**	**547.33**	**568.33**	**569.33**	**566.67**	**585.67**	**588.33**	**587.33**

Table 2 average masses before, after 21 and 60 of the samples

3. The density of the samples is calculated by multiplying the density of the element in each sample by the concentration of the elements in each sample and a total sum of the respective density of each element is found.

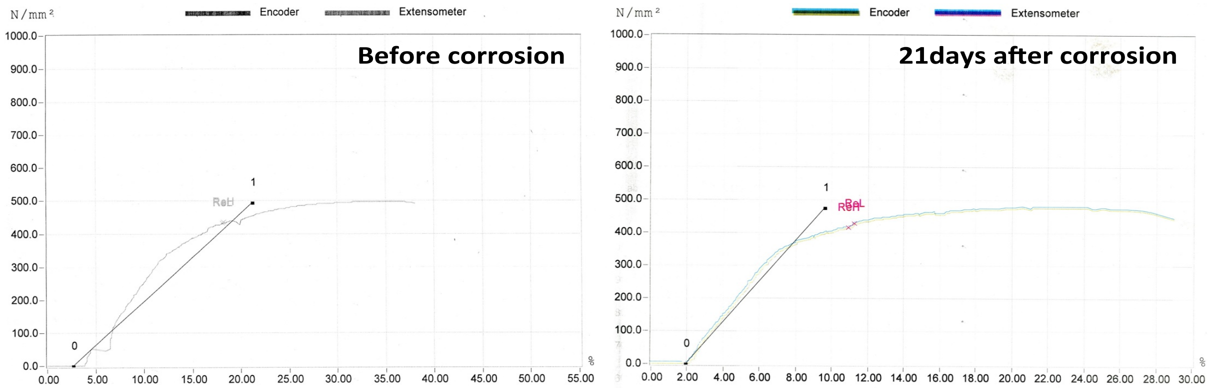
		Samples' Element Concentration / %			Samples' Density/gcm-1		
Element	Density of Element	Local 1	Foreign 1	Foreign 2	Local 1	Foreign 1	Foreign 2
Cl	0.003	0.086	0.086	0.09	0.00	0.00	0.00
K	0.856	0.046	0.067	0.08	0.04	0.06	0.07
Ca	1.55	0.025	0.085	0.04	0.04	0.13	0.06
Ti	4.507	0.025	0.032	0.04	0.11	0.14	0.16
V	6.11	0.005	0.005	0.00	0.03	0.03	0.00
Cr	7.14	0.232	0.241	0.08	1.66	1.72	0.56
Mn	7.47	0.594	0.364	0.59	4.44	2.72	4.38
Fe	7.874	93.300	60.600	98.70	734.64	477.16	777.16
Ni	8.908	0.117	27.500	0.05	1.04	244.97	0.48
Cu	8.92	0.264	0.396	0.01	2.35	3.53	0.09
Zn	7.14	0.025	0.336	0.15	0.18	2.40	1.04
Mo	10.28	0.000	0.197	0.00	0.00	2.03	0.00
	Total=	**94.719**	**89.909**	**99.81**	**7.86**	**8.17**	**7.85**

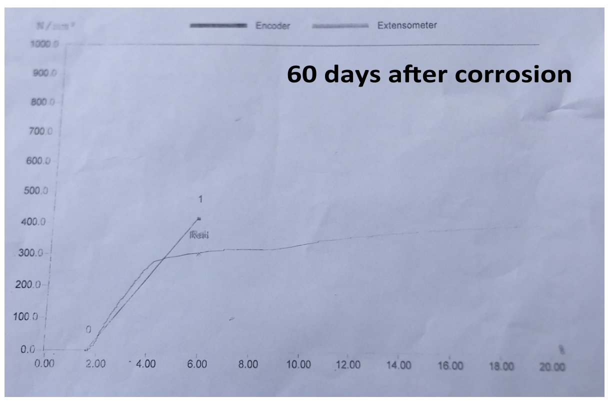
The Density of Local 1 sample =	**7.86 gcm^{-3}**
The Density of Foreign 1 sample =	**8.17 gcm^{-3}**
The Density of Foreign 2 sample =	**7.85 gcm^{-3}**

Table 4 average densities of the samples

APPENDIX B

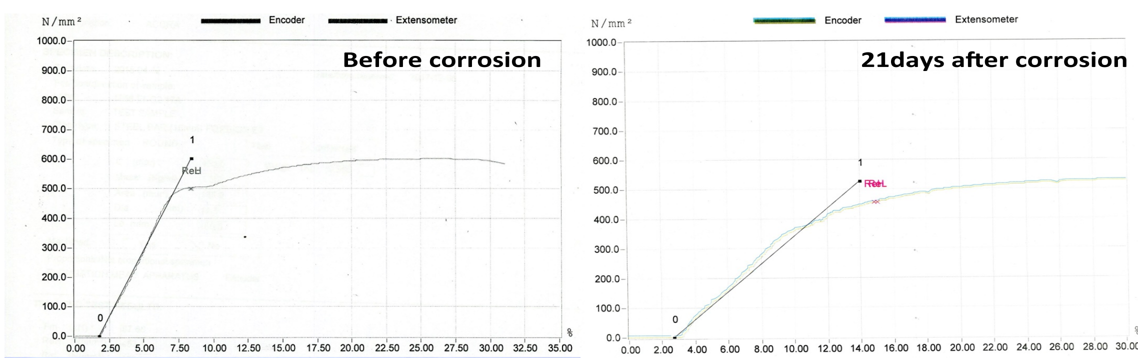
1. A graph of Stress and strain comparing before, after 21 and 60 days corrosion test of Local 1.

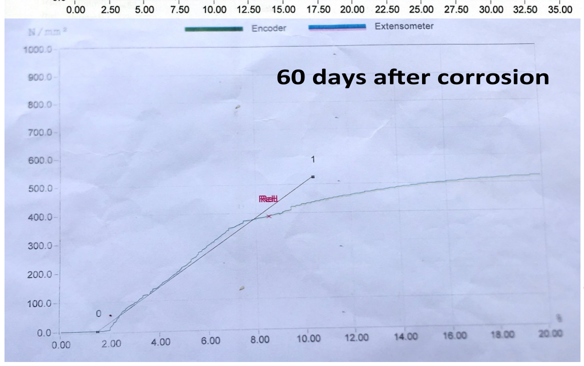




Comparison of Local 1 steel rods

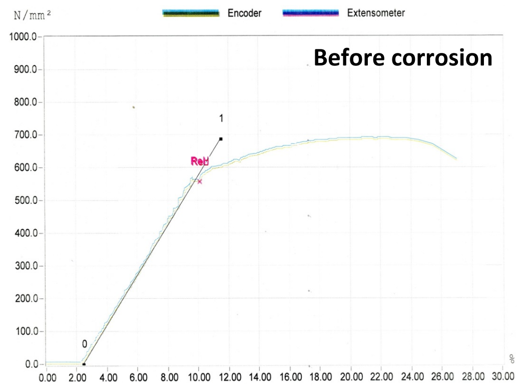
2. Stress vrs strain graph comparing before, after 21 and 60 days corrosion test of Foreign 1.

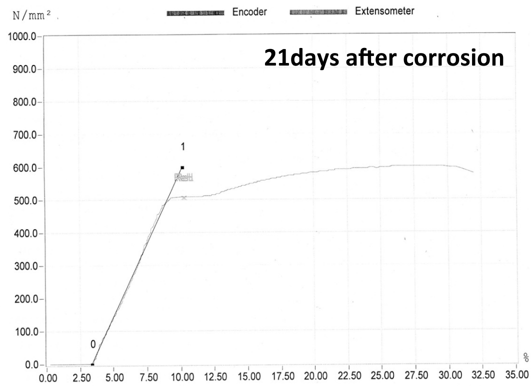


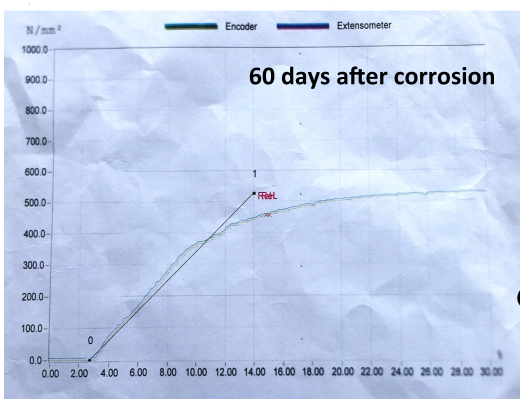


Comparison of Foreign 1 steel rods

2. Stress vrs strain graph comparing before, after 21 and 60 days corrosion test of Foreign 2.







Comparison of Foreign 2 steel rods