EFFECT OF INTAKE WORKS CORROSION ON SURFACE WATER QUALITY AND USE OF CATHODIC PROTECTION AS A REMEDIAL MEASURE

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CERTIFICATION

This is to certify that this work "**Effect of Intake Works Corrosion on Surface Water Quality and Use of Cathodic Protection as a Remedial Measure**" was carried out by **Udoh, Sunday Emmanson (Reg. No: 20154944548)** in partial fulfillment of the requirements for the award of Master of Engineering (M.Eng) degree in Civil Engineering (Water Resources Engineering) of the Federal University of Technology, Owerri.

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DEDICATION

This research thesis is dedicated to the Almighty God who has been so merciful and faithful to me.

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LIST OF ABBREVIATIONS

ipy	inches of penetration per year
ipm	inches of penetration per month
gm^{-2}perday	gram per square meter per day
$mgdm^{-3}$perday	milligrams per decimeter cube per day
mg/l.	milligrams per litre
ppm	part per million
mm/yr.	millimeter per Year
g/cm^3	grams per Cubic Centimeter
cm^2	Square Centimeter
µg	micro grams
µs/cm	micro seconds per Centimeter
NTU	Nephelometric Turbidity Unit
TCU	True Colour Unit
^0C	Degree Celsius
EDTA	Ethylenedianemtetracetic Acid
DO	Dissolved Oxygen
TDS	Total Dissolved Solid
WHO	World Health Organization
EIC	Environmental Induced Cracking
SCC	Stress Corrosion Cracking

HIC	Hydrogen Induced Cracking
NSDWQ	Nigerian Standard for Drinking Water Quality

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ABSTRACT

This research thesis on “Effect of Intake Water Corrosion on Surface Water Quality and Use of Cathodic Protection as a Remedial Measure” was aimed at studying the effect of intake works corrosion on surface water quality and how cathodic protection can be used to fix the problem while leaving the quality of the water at the intake point better. Primary and secondary data were collected for studies. Analysis of water sample collected at the intake point was carried out in the laboratory. Water quality parameters such as total dissolved solid (TDS) pH value, Temperature, dissolved oxygen (DO), Iron, Zinc, Aluminum, Flouride concentrations in mg/l, total hardness and calcium hardness were determined in the laboratory analysis. A corrosion rate of iron bars immersed in water for 7days, 14days to 49th day were determined. A simple mathematical linear relationship connecting the corrosion rate and total dissolved solids was established. It showed a simple linear regression equation that can be used to predict total dissolved solid whenever the iron concentration of the water sample is known. The result of the research showed that when the intake work members are made the cathode with the intake water serving as an electrolyte while a sacrificial anode is used to close the circuit, a simple electrolytic cell will be set-up, this will have the intake works members gain weight in the process thereby becoming cathodically protected and the water finally at the intake point becoming purer and clearer.

Key words: Corrosion, Water quality, Mathematical relationship, Cathodic protection, Iron Bars.

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND INFORMATION

The first practical use of cathodic protection is generally credited to Sir Humphrey Davy in the 1820s. Davy's advice was sought by the Royal Navy in investigating the corrosion of copper sheeting used for cladding the hulls of naval vessels. Davy found that he could preserve copper in sea water by the attachment of small quantities of iron or zinc; the copper became, as Davy put it, "cathodically protected".

The most rapid development of cathodic-protection systems was made in the United States of America to meet the requirements of the rapidly expanding oil and natural gas industry which wanted to benefit from the advantages of using thin-walled steel pipes for underground transmission. For that purpose the method was well established in the United States in 1945.

In the United Kingdom, where low-pressure thicker-walled cast-iron pipes were extensively used, very little cathodic protection was applied until the early 1950s. The increasing use of cathodic protection has arisen from the success of the method used from 1952 onwards to protect about 1000 miles of wartime fuel-line network that had been laid between 1940 and 1944. The method is now well established.

Cathodic protection can, in principle, be applied to any metallic structure in contact with a bulk electrolyte. In practice its main use is to protect

steel structures buried in soil or immersed in water. It cannot be used to prevent atmospheric corrosion.

Structures commonly protected are the exterior surfaces of pipelines, ships' hulls, jetties, foundation piling, and steel sheet-piling, and offshore platforms. Cathodic protection is also used on the interior surfaces of water-storage tanks and water-circulating systems. However, because an external anode will seldom spread the protection for a distance of more than two or three pipe-diameters, the method is not suitable for the protection of small-bore pipe work. Cathodic protection has also been applied to steel embedded in concrete, to copper-based alloys in water systems, and, exceptionally, to lead-sheathed cables and to aluminium alloys, where cathodic potentials have to be carefully controlled.

Corrosion in aqueous solutions proceeds by an electrochemical process, and anodic and cathodic electrochemical reactions must occur simultaneously. No net overall charge builds up on the metal as a result of corrosion because the rate of the anodic and cathodic reactions are equal.

Excessive negative potentials can cause accelerated corrosion of lead and aluminium because of the alkaline environments created at the cathode. These alkaline conditions may also be detrimental to certain paint systems, and may cause loss of the paint film. Hydrogen evolution at the cathode surface may, on high-strength steels, result in hydrogen embrittlement of the steel, with subsequent loss of strength. It may also cause disbanding of any insulating coating: the coating would then act as an insulating shield to the cathodic protection currents.

The principles of corrosion study in relation to water resources engineering is to determine the influence of corrosion rate of galvanized steel and copper pipe used as water work intake members on water quality of potable water system. The effects of corrosion on surface water quality and use of cathodic protection as a remedial measure is a research that proffers solution to this environmental problem.

1.2 PROBLEM STATEMENT

Corrosion of water work structures most particularly at the intake has brought significant pollution of the water body; namely pollution of water quality at the intake resulting from the presence of filtrates from corroded members of intake work structure, increase cost of water treatment as a result of corrosion, limited use of water as a result of poor quality of water caused by corrosion, and depreciation of intake works members and final breakdown of the affected members.

Effect of Intake Works Corrosion on Surface Water Quality can be controlled in order to protect the quality of water in our intake point while prolonging the life span of such fabulous structural members.

The increasing cost of water treatment arising from corrosion of water intake work members at the intake not only affects the water quality for consumers but also limits the use of water.

1.3 OBJECTIVES OF THE STUDY

The main objective of this research is the effect of intake works corrosion on surface water quality and the use of cathodic protection as a remedial measure.

However, the specific objectives are to:

i. Analyze some key water quality parameters as a result of the corrosion effect.
ii. Determine corrosion rate of members in the water intake.
iii. Establish relationship between corrosion effect and water quality parameters (TDS).
iv. Ascertain the effect of cathodic protection on the water quality.

1.4 JUSTIFICATION OF THE STUDY

The damage occurring in metals and alloys which enter into electrochemical and chemical reactions with their surroundings consisting of mostly aqueous and gas medium is usually as a result of corrosion. Most of the metals widely used in the industry lose their stabilities in various mechanisms, including atmosphere and ground. All the metals, excluding gold and platinum, are found in oxidized form in nature. It is a challenging process to isolate metals from their oxides and this requires the use of large amount of raw materials, energy and manpower. Corrosion is a slow progressing phenomenon. Therefore, it takes a long time to see its detrimental outcomes. This phenomenon is the main reason for undervalue of corrosion in the design of metallic structures.

Corrosion is the major factor in determining the investment and production costs in the industry. Among the major problems in today's world is the ongoing lack of knowledge at an alarming level on corrosion and its possible outcomes.

Finding the remedy to this is the most important aspect of this research work.

1.5 SCOPE OF THE STUDY

The scope of this research work focuses on various ways through which corrosion of water intake works can be controlled for increased lifespan of structural members. It takes a look at the Effect of corrosion on surface water quality and how cathodic protection can be used as a remedial measure. The various ways and activities carried out in order to control corrosion are examined. Cathodic protection of water work structure is extensively analysed and other options and activities carried out for corrosion to be averted are dealt with.

Cathodic protection, coatings of the service members, use of inhibitors are among the various methods covered by the scope of this research.

1.6 LIMITATIONS OF THE STUDY

Firstly, this research was conducted within a limited time frame. Data for studies were generated under experimental conditions. Aqueous solution through which data were generated was varied in order to obtain data for studies. And also, the change in chemical conditions of working

environment may also pose a threat to the result of this research as different chemical behaviour of environment are likely to influence reactions of various intake works members.

CHAPTER TWO

LITERATURE REVIEW

2.1 TYPES OF METALLIC CORROSION

Corrosion of mild steel has the same principles as the corrosion of other metals (Moore, 2013). However, failures of metals can result from any of corrosion types described in the next sub-sections.

i. Uniform corrosion.

ii. Local attack.

2.1.1 Uniform corrosion

Uniform corrosion is characterized by a literally constant corrosion; for example, in the atmospheric corrosion of galvanized steel, the speed of corrosion depends on the thickness of the steel such that the thicker the steel coating, the longer the service life of the metal. Moore (2013) stated that uniform attack is the most common form of corrosion and causes the greatest destruction of metals on a weight basis.

Uniform corrosion is often expressed in terms of depth of penetration of corrosion or as weight loss (Moore, 2013; Dean, 2003). The units often quoted in literature are ipy (inches of penetration per year), ipm (inches of penetration per month), gm^{-2} per day and $mgdm^{-3}$ per day.

2.1.2 Local attack

Corrosion damage due to local attack cannot be easily predicted Moore (2013). However, it causes premature failure implying that it is of much

greater technical importance than uniform corrosion. The different types of corrosion that may result from local attacks are discussed as follows:

i. Pitting corrosion;
ii. Crevice corrosion;
iii. Galvanic corrosion;
iv. Inter-granular corrosion;
v. Erosion corrosion;
vi. Cavitation corrosion;
vii. Inter-film corrosion;
viii. Fretting corrosion;
ix. Environmentally induced cracking; and
x. De-alloying and de-zincification:

2.1.2.1 Pitting corrosion

Pitting corrosion results from galvanic action where the metal surface appears to have pinholes. The pit is the anode with the surrounding surface as the cathode (Jones, 2009; Moniz, 2006; Cusherman et al., 2012). Pitting may occur as a result of one of the following:

i. A change in the acidity of the pit area. In most cases, the lower the pH the higher the corrosion of the metal surface. (Moore, 2013).
ii. Differential aeration may also be a contributing factor to the increase in pits because most solutions are in contact with air and because of convection/diffusion, transportation of oxygen through the solution leads to areas of high or low oxygen concentration.

Therefore, where the metal surface contains the solutions, the variation may cause the area with the higher oxygen concentration to become a cathode while an area of lower oxygen concentration becomes the anode resulting in localized attack. (Moore, 2013).

iii. Depletion of an inhibitor will also cause pits to form. In most cases, naturally formed oxides on the metal surface act as inhibitors and protect the substrate from pits. When this oxide film is removed, it leaves the surface exposed and prone to corrosion. (Moore, 2013).

Pitting corrosion is a common occurrence with aluminium and stainless steel in aqueous environments containing metallic chloride salts whereas copper and brass are less prone to pitting corrosion (Roberge, 2012).

Real pitting initiates as localized breakdown of protective films on the metals. This breakdown is followed by rapid film repair but if the damaging condition persists long enough, the film may not be able to repair itself and a pit is initiated. The active corrosion pit is surrounded by a passive metal establishing a small electrochemical cell with a large potential gradient. After initiation, the mechanism of propagation is just the same as that for crevice corrosion. In essence, the pitted metals have created its crevice. The cathode reactant becomes depleted in the pit while the anode reaction continues. Migration of chloride and other aggressive ions into the pit permits metal salts to be formed and hydrolyzed, making the solution in the pit very acidic. However, crevice corrosion nucleates more easily than pitting because pitting first has to make a crevice. Therefore, metals that pit are also susceptible to crevice

corrosion (Jones, 2007; Moniz, 2006; Roberge, 2009). As the acidity and concentration of chloride inside the pit increase with time, the maximum pit depth (D) often obeys Equation (2.1):

$$D = kt^n \qquad (2.1)$$

Where

k and n are constant and t is the time.

Pitting corrosion can be prevented by the following methods:

i. Reduction in environmental corrosivity by reducing chloride concentration, lowering temperature, reducing acidity and oxidizer concentration.

ii. Prevention of stagnant conditions by increasing flow rate and draining all equipment during shutdown.

iii. Addition of inhibitor in sufficient amount to protect the entire surface.

iv. The use of cathodic or anodic protection.

v. Shot penning the surface to increase the potential of steel to about 100mV and therefore reduces pitting.

vi. The more resistant materials should be selected for example type 316 or 317 stainless steel for materials expected to be exposed to chloride.

vii. The use of protective coating: organic coatings, zinc-rich paint and metallic zinc are commonly used.

viii. The thickness of the metal should be increased in order to increase the time required for pitting.

ix. Passivation of the metal.

2.1.2.2 Crevice corrosion

Crevices are present in all equipment. They occur naturally around bolts, rivets, etc. they are also created by scratches on the metal surface. Crevice corrosion may also occur in areas where gaskets are used because the gasket materials absorb and draw solution toward the reactive area (Roberge and Sastri, 2012). Crevice corrosion is influenced by the same factor affecting pitting corrosion and is indeed a specific form of pitting corrosion

2.1.2.3 Galvanic corrosion

Galvanic corrosion often occurs when two different metals are in contact in the presence of a conducive solution. According to Oldfield (2008), the result of galvanic corrosion is similar to the reaction of a car battery with an anode and a cathode. In most cases, a potential difference may develop between an area on the metal surface if a foreign metal such as copper or iron (Cu or Fe) precipitates. Consequently, the more active metal oxidized, more quickly it will be in the galvanic arrangement while an inert or noble metal will essentially be unaffected (Kruger, 2001; Jones, 2009). Fontana (2010) stated that, the extent of galvanic corrosion increases with the potential difference of the metal. The relative size of the anode (active metal) or cathode significantly affects the

relationship between the active and inert metals. Therefore, a small anode in the presence of a large cathode will corrode more quickly than the reverse. Galvanic corrosion can be avoided by keeping dissimilar metals in order to interrupt current flow Günter (2009).

2.1.2.4 Inter-granular corrosion

Inter-granular corrosion occurs by localized attack at grain boundaries which behave as anode to the larger surrounding cathode grains (Moore, 2013; Hackerman and Snaveley, 2016; NACE, 1999). Metals usually are not homogeneous. Impurities or alloying elements may segregate into grain boundaries. Heat treatment or localized heating by welding may provoke changes in composition localized in or near grain boundaries (Noore, 2009; NACE, 1999; Philip et al., 2010).

2.1.2.5 Erosion corrosion

Almost all corrosive media can bring erosion corrosion and nearly all metals and alloys are susceptible to this except those metals or alloys that are capable of forming hard, dense, adherent and continuous surface film (Moore, 2013; Migahed et al., 2003). The extent of erosion corrosion increases as the velocity of the corroding medium increase. In some cases, the high velocity increases the supply of oxygen or other gases at the metal surface, which may depolarize the cathodic reaction and consequently increase the corrosion rate (Van and Orden, 2008; Atkins, 2002; Szklarska, 2017).

2.1.2.6 Cavitation corrosion

Formation and collapse of tiny gas bubbles in a liquid stream called cavitations may mechanically destroy any protective layer, causing localized corrosion called cavitation corrosion (Thomas, 2004; Moore, 2013). Similarly, when an object such as a propeller rotates in water, the pressure on the trailing surface of the blade fluctuates continually. At some points, very low pressures are produced which create tensile forces high enough to exceed the inter-atomic binding forces of the liquid (Breakell et al., 2005). The result is that at these points, atoms are distorted to create voids and subsequently collapse in few seconds (ASTM G96-90, 2001). When the void walls collide, a tremendous shock wave is generated. The generated shock wave can deform the metals and lead to cavitations corrosion according to Denny (2004) and Achebe et al., (2012).

2.1.2.7 Inter-film corrosion

Coating, such as paints conversion coating or metallic coating may lose their adhesion with substrate due to diffusion through the actual coating or to reaction starting from defects like pinholes or scratches (Morgan, 2011; SPE, 2008; Rajendran, 2000). When this happens, residues of soluble salts, acids or bases will attract water through a paint film because of osmotic effect. The blister filled with water will be formed. Fill-form corrosion is a wormlike de-lamination of a paint film driven by salt residue and high humidity about 80-90 percent (Yurt et al., 2006).

2.1.2.8 Fretting corrosion

Fretting corrosion is a combination of mechanical wear and atmospheric oxidation which frequently occurs between close fitting metal components (Cabot et al., 2014; Moore, 2013). For fretting corrosion to occur, the surface is usually under load and subject to slight relative movement resulting in damage to the contact surfaces and formation of oxide debris such as Fe_3O_4 for iron (Zucchi and Oma, 2011).

2.1.2.9 Environmentally induced cracking

Environmentally induced cracking (EIC) is a brittle fracture of a normally ductile alloy in an environment that causes minimal uniform corrosion (Zhou et al., 2010). There are three types of EIC. These include, Stress Corrosion Cracking (SCC), Corrosion Fatigue Cracking (CFC) and Hydrogen Induced Cracking (HIC).

SCC occurs in an alloy with a static tensile stress in the presence of specific environment conditions. According to Zhang et al., (2004), pure metals are comparatively resistant to SCC. Quraishi (2004), also opinioned that for SCC to occur, a passive surface film under oxidizing conditions must be formed. Also required is a specific dissolved species for example, stainless steel corrodes easily in the presence of hot chloride, brass in ammonia solutions and carbon steel in nitrate solutions (Moore, 2013; Deb and Evans, 2014).

CFC occurs under cycle stress in a corrosive environment (Moore, 2013) and susceptibility to fatigue cracking without corrosion is usually increased in the presence of corrosive environment.

HIC results when atomic hydrogen diffuses into a metal causing the metal to be brittle (Tavassoli-Salardini, 2004; Tamashov, 2012). This embrittlement occurs when hydrogen atom diffuses ahead of a crack tip and accumulates in a region of high triaxial stress particular in grain boundaries between metal atoms resulting in lowering of their cohesive forces, production of micro cracks ahead of the main crack and allowing the crack to extend under tensile stresses below the yield strength.

2.1.2.10 De-alloying and de-zincification

An alloying element that is active (negative electrochemically) to the major solvent element is likely to be preferentially corroded by de-alloying (Zhang et al., 2004). The de-alloying of brass known as dezincification is a common and frequently cited example. Brass is an alloy of zinc and copper but zinc is strongly active to copper and readily leached out of brass, leaving behind relatively pure porous copper with poor mechanical properties. Another example of this type of corrosion is graphite corrosion which is the selective leaching of iron from gray cast iron, leaving behind a weak porous network of inert graphite that can be scratched with pen knife. Graphite corrosion is common in buried cast iron pipes and becomes evident only after decades.

2.2 CORROSION OF IRON

The most familiar and costly examples of corrosion is the formation of rust on iron. Iron and steel structures are highly susceptible to corrosion, and their protection costs billions of dollars annually (Moore, 2013). The chemistry of corrosion under atmospheric conditions is extremely complex and is catalyzed by H^+ (aq), showing why increased acid precipitation causes increased rates of corrosion. Oxygen gas and water must also be present for iron to rust.

Rusting is a redox reaction, involving the loss and gain of electrons between reactants (Pourbaix, 2007; Oldfield, 2008). An electrochemical cell is created with sites of impurity in the iron acting as cathodes for the reduction of O_2 gas and a region of the metal surface serving as the anode, where the oxidation of iron occurs (Equation 2.2):

$$2Fe_{(s)} = 2Fe^{2+}\ (aq) + 4e^- \qquad (2.2)$$

The electrons given off by the iron reduce atmospheric oxygen to water at the cathode (Equation 2.3):

$$O_{2(g)} + 4H^+(aq) + 4e^- = 2H_2O_{(l)} \qquad (2.3)$$

This reduction (half – reaction) occurs in an acidic medium, The H^+(aq) ions are provided, together with the water required, by acid rain. Therefore as acid precipitation increases, the rate of corrosion also increases. Oxygen and water are obviously abundant therefore the rusting of iron is limited to the availability of H^+ (aq) from acid precipitation.

The Fe_2^+ (aq) formed at the anode are further oxidized by oxygen and the overall redox Equation is as expressed by Equation (2.4):

$$4\ Fe^{2+}_{(aq)} + 3O_{2\ (g)} + 6H_2O_{\ (1)} = 2Fe_2O_3.6H_2O_{(s)} \qquad (2.4)$$

2.3 ENVIRONMENTAL FACTORS AFFECTING CORROSION OF IRON

Exposure of iron to aerated water at room temperature may make the corrosion rate to be pH dependent (Okafor and Ebenso, 2007; Deb and Evans, 2014). In the range of pH of 4 to 10, the corrosion rate of iron is relatively independent of the pH of the environment. In this pH range, the corrosion rate is governed largely by the rate at which oxygen reacts with absorbed atomic hydrogen, thereby depolarizing the surface and allowing the reduction reaction to continue. For pH values below 4.0, ferrous oxide (FeO) is soluble. Therefore, the oxide dissolves as it is formed rather than depositing on the metal surface to form a film. In the absence of the protective oxide film, the metal surface is in direct contact with the acid solution and the corrosion reaction proceeds at a higher rate than that at higher pH values.

Hydrogen is produced in acid solutions below a pH of 4, suggesting that the corrosion rate no longer depends entirely on depolarization by oxygen, but on a combination of the two factors (hydrogen evolution and depolarization). For pH values above 10, the corrosion rate is observed to fall as pH is increased. This is believed to be due to an increase in the rate of the reaction of oxygen with $Fe(OH)_3$ (hydrated FeO) in the oxide

layer to form the more protective Fe_2CO_3. However, this effect is not observed in de-aerated water at high temperatures.

Like most other chemical reactions, corrosion rates increase as temperature increases (Moore, 2013). Temperature and pressure of the medium govern the solubility of the corrosive species in the fluid such as oxygen (O_2), carbon dioxide ($CO_{2)}$, chlorides, and hydroxide. A rule of thumb is that the reaction rate doubles for a temperature increase of 20^{o}F to 50^{o}F. This linear increase with temperature does not continue indefinitely due, in part, to a change in the oxide film.

When iron or steel is exposed to high temperature water, the rate of corrosion of the metal is observed to decrease with exposure time during the early period of exposure (Popova et al., 2003). After a few thousand hours, the corrosion rate becomes relatively constant during the early period of exposure. While the corrosion rate is decreasing, the oxide film on the surface of the metal grows in thickness. However, the rate at which the film grows decrease with time. The thickness of the oxide film is soon constant after which expected, relatively constant corrosion rate and oxide film thickness are attained at about the same time.

The condition and composition of the metal surfaces may also affect the corrosion rate. Scale deposits or irregular surfaces create areas on the metal where local corrosion can initiate and proceed at a faster rate than normal. Certain metal alloys have higher corrosion resistance than others. The velocity of the surrounding fluid (example water) may also affect the rate of corrosion (Odoemelam et al., 2009).

When water velocity is extremely high, the impact of the water tends to remove the protective oxide layer and some of the metal under it (erosion), thus, exposing more metal to corrosion. Water velocities of 30 to 40ft. per second are usually said to cause erosion.

An increase in the concentration of oxygen in water to which iron is exposed increases the corrosion rate. Oxygen promotes corrosion in two ways. First, it is a powerful cathode depolarizer. When an acid gas such as hydrogen sulphide or sulphur (IV) oxide or carbon (IV) oxide is present, hydrogen gas tends to be formed at the cathode according to Equation (2.5):

$$2H^{+} + 2e^{-} = 2H^{0} = H_2 \qquad (2.5)$$

Accumulation of gaseous hydrogen tends to form a film and polarize the cathode.

$$2H^{0} + {}^{1}/_{2}O_2 = H_2O \qquad (2.6)$$

Therefore, cathodic reaction resulting in the attendant corrosion is promoted because polarization by hydrogen is minimized in the presence of oxygen. Secondly, the oxygen removes iron by precipitation of iron oxides at the anode and thus prevents anodic polarization by Fe^{2+} ion.

The presence of carbon (IV) oxide in the surrounding water can also catalyse the corrosion of mild steel (Oguzie and Ebenso, 2005). According to Kruger (2001), it is evident that the rate of corrosion can be affected by partial pressure of CO_2. Increase in CO_2 partial pressure has been observed to increase the concentration of carbonic acid which is known to

accelerate the cathodic reaction. Okafor and Ebenso (2007) stated that the CO_2 partial pressure affects the pH of the solution which in turn affect the speciation of species involved in the proves and that in a film forming condition, increase in CO_2 partial pressure will lead to increase in CO_3^{2-} concentration.

CO_2 is a stronger acid than H_2S. It combines with water to form trioxocarbonate (IV) acid according Equation (2.7):

$$CO_2 + H_2O = H_2CO_3 \quad (2.7)$$

The acid formed (Equation 2.7) ionizes to hydrogen and trioxocarbonate ions (Equation 2.8)

$$H_2CO_3 = H^+ + HCO_3^- \quad (2.8)$$

The ionization constant for the above reaction is $K_1 = 4.31 \times 10^{-7}$ (Atkins, 2002). However, the major contribution of CO_2 to corrosion of mild steel is the increase in acidity by H^+ formed in the above reaction and the corrosion product $FeCO_3$ (siderite).

The presence of hydrogen sulphide in the surrounding water may also catalyze the corrosion of mild steel. Hydrogen sulphide is a weak acid but is abundant in oil producing areas. The acidity or ability of hydrogen sulphide to generate H+ ions is depicted by its first ionization constant (Equation 2.9):

$$K_1 = \frac{[H^+][SH^-]}{[H_2S]} = 5.7 \times 10^{-8} \quad (2.9)$$

Under standard conditions, each mode of hydrogen sulphide in solution produces only 5.7×10^{-8} moles of H^+ ion. However, as the H^+ ion is

removed by cathodic reaction, more is formed and hydrogen gas readily appears on steel exposed to air free water containing H_2S. The anion, SH^- dissociates further to S^{2}- and H^+. The sulphide anion reacts with iron to form the black FeS corrosion product.

Some micro-organism has been found to aid the corrosion of mild steel. According to SPE (2008), accumulation of bacterial slimes, fungi and moulds contributes to corrosion of mild steel equipment. In an oil producing environment, sulphide that is generated by metabolic processes of certain organisms. The most commonly found sulphide producers are desulfovibrio species such as desulfovibrio, dsesulfuricanes. They are referred to as sulphate reducers because they utilize SO_4^{2-} ions from salty waters and from H_2S. to a limited extent, sulphide corrosion results from the hydrogen sulphide generated by species of clostridia from organic sulphur compounds.

2.4 THERMODYNAMICS AND KINETICS OF CORROSION

The anodic reaction involved in the dissolution of iron (oxidation) during the corrosion of mild steel is given by (Equation 2.10)

$$Fe = Fe^{2+} + 2e^- \quad (2.10)$$

The cathodic reaction involves the reduction of water by electrons released by the oxidant species. This reaction may involve oxygen reduction in basic and neutral solution or hydrogen evolution in acidic medium as shown by Equations (2.8) and (2.9) respectively.

$$O_2 + 2H_2O + 4e^- = 4HO^- \quad (2.11)$$

The driving force for metallic corrosion is the thermodynamic instability of metal in its surrounding environment. The electrode potential of a metal is a measure of its tendency to corrode. According to Tavassoli-Salardini (2004), all metals with negative dissolution potentials are prone to corrosion. The more negative the dissolution potentials, the more readily the metal will corrode. Tavassoli-Salardini (2004) also pointed out that Equation 2.10 is a simplified form of the mild steel corrosion process and noted that in reality, the reactions involved are often very complicated. Fontana (2010) also stated that the chemisorptions of species, present in solution, influences the dissolution of a metal and will result in the formation of iron oxide or other insoluble compounds on the metals surface.

In the absence of any surface-active compound, the oxidation of iron is the main anodic reaction and the possibility of the oxidation of iron in aqueous solution based on thermodynamics can be demonstrated by the reactions shown by Equation (2.12) to (2.17) (Tavassoli-Salardini, 2004). The calculated potentials of oxide formation at pH of 7 are also indicated in the respective equations.

$$Fe + 2OH = FeO + H_2O\ 2e^-;\ E^0 = -0.422V \quad (2.12)$$

$$3Fe + 8OH = Fe_3O_4 + 4H_2O\ 8e^-;\ E^0 = -0.437V \quad (2.13)$$

$$2Fe + 6OH^+ = Fe_2O_3 + 3H_2O\ 6e^-;\ E^0 = -0.431V \quad (2.14)$$

$$Fe + H_2O = FeO + 2H^+\ 2e^-;\ E^0 = -0.450V \quad (2.15)$$

$$3Fe + 4H_2O = Fe_3O_4 + 8H^+\ 8e^-;\ E^0 = -0.421V \quad (2.16)$$

$$2Fe + 3H_2O = Fe_2O_3 + 6H^+ 6e^-;\ E^0 = -0.463V \quad (2.17)$$

The feasibility of the above reactions depends on the potentials established on the electrode surface. The relationship between pH and electrode potentials given by the Nernst equation is depicted by Equation (2.27) and (2.31):

$$E = E^0 + \frac{0.059}{n} Log_{10}\left(\frac{a^2 H+)}{pH_2}\right) \quad (2.18)$$

$$E_H = -059pH - 0.030Log_{10}P_H \quad (2.19)$$

Where pH_2 is the partial pressure of the hydrogen gas. Similarly for oxygen evolution, Equation 2.19 becomes Equation 2.20:

$$EO_2 = +1.23 + 0.015Log_{10}\, Po_2 - 0.059pH \quad (2.20)$$

Best demonstrated by Pourbaix (potential- pH) diagram (Moore, 2013). Although Pourbaix diagram cannot supply information on the kinetics of corrosion, it gives an idea of the region in which the corrosion of mild steel can occur, region in which passivity can be observed or region in which immunity can be observed (Moore, 2013).

Corrosion rate is measured by the rate of anodic dissolution of a metal in solution and the relationship between the anodic cathodic partial reaction rate and potential is given by Tafel equation (Equation 2.21 and 2.22, Monika and Dubey, 2005).

$$i_a = i\acute{o}\exp(\alpha z\eta F/RT) \quad (2.21)$$

$$i_c = i\acute{o}\exp(\alpha z\eta F/RT) \quad (2.22)$$

Where i_c and i_a are cathodic and anodic current density, α is the transfer coefficient and ŋ is the overvoltage while z is the number of electrons in Kelvin and F.

$$\eta = a + b\text{Log}i_a \quad (2.23)$$

Where b = αzŋF/RT) and a plot potential versus Logi gives a straight line with slope equal to b, a typical Tafel plot for the corrosion of iron consists of six major regions. These are the active region, transition region, the pre-passive region, passive layer formation region, passive layer region and trans-passive region (Moore, 2013).

2.5 INHIBITION OF CORROSION

According to Hosseini et al., (2009) corrosion can be controlled by the addition of chemical substances called inhibitors into acid media. By definition, an inhibitor is a chemical compound which when added in a small amount to the corrosive environment alters the cathodic and or anodic reaction and consequently, reduces the corrosion rate. This implies that inhibitors can be classified as anodic or cathodic depending on the inhibition process (Quraishi, 2004). Inhibitors can also be classified as organic or inorganic depending on their chemical nature, oxidizing or non-oxidizing depending on their characteristics. However, one of the most widely applied classification systems for inhibitors is that proposed by Oguzie and Ebenso (2005), Mercer (2004) and Ebenso et al. (2008) which classified inhibitors into the following groups:

i. Absorption inhibitors: These are inhibitors which are absorbed on the metal surface and form protective barrier films. Absorption inhibitors function by limiting the diffusion of oxygen to the corrosion surface, trapping the metal ion on the surface, stabilizing the double layer and reducing the rate of dissolution.

ii. Passivating inhibitors: Passivating inhibitors function by inducing and maintaining a passive film (consisting of metal oxide) on the surface.

iii. Surface reaction product inhibitors: These are inhibitors that form sparingly soluble compounds other than an oxide layer. Surface reaction product inhibitors cannot form a protective oxide layer because they are not oxidizing agents but interact with metal on the surface to form insoluble compounds which plug in pores and inhibit corrosion.

Denny (2004) also classified inhibitors according to the medium of their function. The inhibitors are classified into interface, electrolyte layer, membrane and passivation. However, Popova et al. (2003) modified Denny's classification and proposed interface and inter-phase inhibitors as the main types of inhibitors based on the inhibition or retardation mechanism. Hosseini et al. (2009) also classified corrosion inhibitors into three classes namely, oxidizing, precipitation and absorption inhibitors.

2.5.1 Inter-phase inhibitors

Inter-phase inhibitors function by facilitating the formation of a 3-D layer which acts as a barrier between the corroding substrate and the electrolyte. The protective film could be a solid film on the surface of the metal or a liquid film adjacent to it. The solid film may be an oxide layer, corrosion product, metallic or non-metallic coating or inhibitor forming a porous layer or non-porous film (Mercer, 2004; Monika and Aiddique, 2005). However, the liquid film is the electrolyte in the inter-phase which differs from the bulk of the solution in its chemical or physical properties. Based on this model, the inhibition of metal corrosion is governed by the properties of the layer such as its porosity and stability.

2.5.2 Passivating/oxidizing inhibitors

Pourbaix (2007) stated that iron polarizes anodically in the presence of oxidizing inhibitors and passivates as the open circuit potential shift to more positive potential. It is also possible that the inhibitors are reduced and the reduction product is deposited on the weal points of the films to improve its protective effect.

An oxidizing inhibitor functions by inducing and maintaining a passive surface layer on the metal surface. These inhibitors are effective at certain concentrations (critical concentration, C_{crit}). At concentrations below the critical concentration, corrosion is enhanced but at very high concentrations of the inhibitor, increase in the anodic current density is observed.

According to Rezenfield (2009), passivation accomplished by oxidizing inhibitor is a consequence of either an increased effectiveness of the cathodic process or a reduced rate of the anodic process.

2.5.3 Non oxidizing inhibitors

Non oxidizing inhibitors are also capable of passivating metals. They include compounds such as NaOH and the salt of weak acids and strong bases such as Na_3PO_4, Na_2HPO_4, Na_2CO_3, $NaBO_3$ and $Na_2B_4O_7$ (Tavassoli-Salardini, 2004). These substances are also capable of passivating steel electrochemically by hydroxyl ions.

2.5.4 Interface inhibitors

According to Tavassoli-Salardini (2004), interface occurs due to a strong interaction between the corroding metal and the inhibitor. The adoption of the inhibitor depends on the potential of the electrode as well as the charge on the adsorbate molecule. The protective film is a 2-D adsorbate, which can affect the corrosion reaction by one of the following mechanisms:

i. Geometric blocking: in this case an inert inhibitor blocks the surface of the metal at a high degree of coverage and forms a diffusion barrier which restricts the access of reactants to the metal surface for example, inhibition provided by proteins, polysaccharides or compounds with hydrocarbon chains.

ii. Deactivation coverage: In this process, instead of the complete coverage of the metallic surface, only the active sites are covered

by an inert adsorbate and the rates of the reactions (cathodic and anodic) are reduced in proportion to the extent of coverage of the reactive sites.

iii. Reactive coverage: In this case, the absorbate undergoes electrochemical reaction and primary or secondary inhibition occurs either by the absorbate or its reaction product respectively.

Adsorption inhibition is observed when a bare metal is in contact with the adsorbate (inhibitor) and this is usually the case in acidic solutions where the condition is not favorable to oxide formation (Rozenfield, 2009). According to Tavassoli-Salardini (2004), majority of the very effective interface inhibitors are organic compounds containing nitrogen, sulphur and oxygen.

It has been found that some interface inhibitors after initial absorption onto the metal surface, can be reduced and the reduction product may also possess some inhibitive properties.

2.6 FACTORS AFFECTING THE EFFICIENCY OF INHIBITION

Most known inhibitors are organic compounds containing N, O, and or S atoms. Generally, it is assumed that the first step in the mechanism of inhibition is the absorption of the inhibitor on the metal surface. The absorption process depends on the nature and surface charge of the metal, the chemical structure of the inhibitor, distribution of the charge on the molecule and the nature of the aggressive medium (Emregul et al., 2003).

The efficiency of an inhibitor is influenced by a number of factors which include, concentration of the inhibitor, pH, level of aggressive ions, concentration of dissolved oxygen, solution temperature, solution mobility and immersion time (Odoemelam et al., 2009; Muralidharan et al., 2000).

The efficiency of an inhibitor changes with pH as does the dissolution of ion. In the absence of inhibitors, the mechanism of iron dissolution in neutral solution (pH = 6.9) is similar to that encountered in alkaline media. However, in acidic solution, the mechanism is different and is not as complicated as it is in neutral and alkaline solutions, due to the presence of 3-dimensional acidic and corrosion products on the surface (Oguzie and Ebenso, 2005).

The concentration of halide ion(s) is often taken as an index of the corrosion potential of most metals in aqueous or acidic medium. In the presence of chloride ion for example, the corrosion attack is usually localized (crevice or pitting) provided the metal surface is covered by an oxide layer. Rajendran et al. (2000) stated that the much higher concentration of chloride ions in the pits compared to that in the bulk solution indicates that the chloride ion is directly involved in pit initiation and propagation.

Tavassoli-salardini (2004) also observed the importance of immersion time as one of the important parameters in corrosion inhibition and derived an equation which correlates the corrosion rate and the immersion time Equation (2.24):

$$CR = \frac{(CI)^{0.509}(SO4)^{0.025}(Alk)^{0.423}(DO)^{0.194}}{(Ca(^{0.030}(\beta)^{0.030}(10^{SI})^{0.107}(Days)^{0.387}} \quad (2.24)$$

Where (CI), (SO4), (Ca) are the concentrations of chloride, sulphate and calcium ions in water respectively. CR is corrosion rate, (Alk.), (DO) and (β) are the alkalinity, dissolved oxygen concentration and the buffer capacity of the water. SI is the saturation index and days are time of immersion. From Equation 2.24, it can be seen that the corrosion rate of a metal increases with increase in concentration of chloride ion, sulphate ion, alkalinity and dissolved ion but decreases as the concentration of calcium ion increases.

2.7 METHODS OF MONITORING CORROSION OF MILD STEEL

Some of the techniques used in monitoring the corrosion of metals and its inhibition are discussed in this section. They are as follows:

2.7.1 Weight loss method

The weight loss approach is the most widely used method for monitoring the corrosion of metals and their inhibition (Szklarska, 2017). The method is cheap and can be easily applied and is therefore a preferred method in corrosion monitoring. It has been found that due to the absence of surface perturbation, weight loss simulates the real situation better than the electrochemical methods (Tavasssoli-Salardini, 2004). Mercer (2004) also stated that the method is usually used as the first step in corrosion studies but does not provide sufficient information about local corrosion attack such as pitting corrosion (Tavassoli-Salardini, 2004).

2.8 EFFECT OF CORROSION ON HOUSEHOLD PLUMBING SYSTEM

Corrosion which is highly associated with behaviour of metals in its environment, research referred the behaviour of metals used in intake water work and in plumbing system in surface water as suitable for household use.

Water itself can present many different environments. Surface water is quite different from groundwater. Both vary geographically and surface water also varies seasonally. Many communities take their water supply from multiple sources and certain communities even supply mixed surface and groundwater, and so much for the variable water environment.

Household plumbing constitutes a second variable environment. The fact that a number of metals, alloys, and even nonmetals may commonly be used in a single household plumbing system or water using appliance adds further variation and complexity.

Unfortunately, therefore, domestic water supplies vary in quality and in their tendency to corrode and the materials used to construct plumbing systems differ in their tendency to be corroded (Bond, 2012).

Up to this point we have viewed corrosion in water as a chemical phenomenon, subject to variations in chemical impurities (gases and minerals) present in the water and variations in the chemical composition of plumbing materials. We have not yet considered the physical factors of water temperature and water flow velocity both of which can strongly influence corrosion rates.

Lastly, it is generally accepted that corrosion of metals is electrochemical, resulting from the flow of electric current between electrodes, which may be between different metals, or between anodic and cathodic areas on the surface of a single metal. Disintegration of the metal occurs at the anode areas. This brings our discussion of corrosion to a third variable or complexity: the fact that metal surfaces themselves are not homogenous in their composition and therefore a number of anodic and cathodic areas may be present on the surface of metal. Metallic impurities, accumulations of sediment or corrosion products, even adherent biological deposits may be directly or indirectly related to the development of electrical corrosion circuits or galvanic cells (Bond, 2012).

An excellent method for corrosion control in water heaters is cathodic protected which involves the use of a sacrificial anode, usually composed of magnesium or aluminum. Chemical control of corrosion attempts to retard electrode reactions. Ever since the problems connected with corrosion of municipal distribution systems and household plumbing systems in the United State began to be recognized early in this century, achievement of a cure has continued to remain elusive, as has the determination of exact causes of corrosion and the ability to predict or anticipate rates of corrosion using life expectancy of distribution and plumbing systems.

While great strides have been made, chiefly in the use of corrosion resistant materials of construction through the use of cathodic protection for water heaters, each solution has encountered a few problems in

universal country wide application. In fact, use of each material or system has uncovered new types of corrosion problems which were largely unpredicted.

Corrosion of plumbing systems in water supplies depends on so many interdependent variables that no applicable simple equation or corrosion index is available for appropriate corrective treatment (Bond, 2012).

2.9 CORROSION EFFECT ON DRINKING WATER STANDARD

The chemical parameters normally found in our drinking water are seriously affected by corrosion. The limits of the percentage content of these minerals beyond which our water can become unpleasant or even dangerous are being altered by corrosion effect, sometimes affecting piping in the distribution system or from the water intake structures. Modern water works carefully monitor this regularly and take a sample for simple mineral analysis for necessary action to maintain acceptable level (Bond, 2012).

Table 2.1 gives the acceptable level of mineral content in potable water and likely water problems posed when they are present in concentration above the permissible limits. However each of these minerals listed on the Table 2.1 is in one way or the other affected by corrosion (Carl, 2015).

Table 2.1: Acceptable levels of chemicals in drinking water

Indication	Acceptable Level	Effect Above Level
pH	6.0-8.0	Above is Alkaline, Below is Acidic
Aluminum	0.15ppm	Deposits
Ammonia	0.02ppm	Pollution
Calcium	200.00ppm	Hardness
Carbon dioxide	10.00ppm	Corrosion
Chlorides	250.00ppm	Salt taste
Chlorine	0.20ppm	Taste
Copper	1mg/l	Stain, bitter taste.
Colour	20 Hazen units	Visual
Detergent	1.00ppm	Pollution
Fluoride	1.00ppm	Molten teeth
Iron(Ferrous)	0.20ppm	Taste
Lead	0.10mg/l	Poison
Magnesium	125.00mg/l	Hardness
Manganese	0.20mg/l	Deposits
Nitrites	0.00mg/l	Pollution
Nitrates	10.00mg/l	Toxic
Oxygen	1.00mg/l	Pollution
Phenol	0.00mg/l	Taste
Phosphates	1.00mg/l	Pollution
Silica	20.00mg/l	Scale
Sulphite	250.00mg/l	Taste, Diarrhoea

Source: WHO

2.9.1 Effect of pH on corrosion

Although pH usually has no direct impact on consumers, it is one of the most important operational water quality parameters. Careful attention to pH control is necessary at all stages of water treatment to ensure satisfactory water clarification and disinfection. For effective disinfection with chlorine, the pH should preferably be less than 8; however, lower pH

water is more likely to be corrosive. The pH of the water entering the distribution system must be controlled to minimize the corrosion of water mains and pipes in household water system. Alkalinity and calcium management also contribute to the stability of water and control its aggressiveness to pipes and appliances. Failure to minimize corrosion can result in the contamination of potable water and has adverse effects on taste and appearance. The optimum pH required will vary in different supplies according to the composition of the water and the nature of construction materials used in the distribution system, but it is usually 6.5-8.5 extreme values of pH can result from accidental spills, treatments breakdown and insufficiently cured cement mortar pipe linings or cement mortar linings applied when the alkalinity of water is low. No health based guideline values have been proposed for pH (Carl, 2015).

2.9.2 Aluminium effect on corrosion and water quality

Naturally occurring aluminium as well as aluminium salts used as coagulants during water treatment are the primary sources of aluminium in drinking water. Aluminium like any other metal is likely to be attacked by very corrosive water thus increasing the aluminium level above the permissible level of acceptability. This will always lead to formation of deposits on water supply mains in the distribution system. Water works structure with aluminium members are likely to be corroded in a very corrosive water and also depending on the pH of the water. pH of water less than 6.0 promotes corrosion of water work members. The presence of aluminium at concentrations in excess of 0.1-0.2 mg/l often leads to

consumer complaints as a result of deposition of aluminium hydroxide floc and the exacerbation of discoloration of water by iron. It is therefore important to optimize treatment processes in order to minimize any residual aluminium entering the distribution system. Under good operation conditions, aluminium concentrations of less than 0.1mg/l are achievable in many circumstances. Available evidence does not support the derivation of a health based guideline value for aluminium in drinking water (Carl, 2015).

2.9.3 Ammonia effect on corrosion and water quality.

Ammonia corrosion is a corrosive attack on a material that is caused by the interactions between it and ammonia. Ammonia corrosion occurs when liquid containing ammonia is brought in contact with mild steel. Ammonia is also corrosive to other materials even when ammonia does not contain impurities. Ammonia corrosion can cause stress corrosion cracking in steels. This occurs when the contaminant in the ammonia is brought in contact with the steel, a situation that commonly occurs with pressure vessels. Care must be taken to ensure that pressure vessels are not subjected to this type of corrosion. Ammonia that is mixed with water is less corrosive to iron or steel. It is however corrosive to many other metals like zinc, copper and brass. These metals should not be brought into contact with water containing ammonia because ammonia corrosion can occur. Thus, the tendency for water work structures that are made of zinc, copper and brass to distort surface water quality at the intake is

enormous as they have strong affinity to corrosion when in contact with ammonia water (Carl, 2015).

2.9.4 Chloride effect on water quality

High concentrations of chloride give a salty taste to the water and beverages. Taste thresholds for the chloride anion depend on the associated cation and are in the range of 200-300 mg/l which are increasingly likely to be detected by taste, but some consumers may become accustomed to low levels of chlorine-induced taste. No health-based guideline value is proposed for chloride-drinking water (Carl, 2015).

2.9.5 Chloramines effect on water quality

Chloramines, such as monochloramine, dichloramine and trichloramine (nitrogentrichloride) are generated from the reaction of chlorine with ammonia. Ammonium-chloramines, monochloramine only useful chlorine disinfectant and chlorination systems are operated to minimize the formation of dichloramine and trichloramine. Higher chloramines, particularly trichloramine, are likely to give rise to taste and odour complaints, except at very low concentrations. Formonochloramine, no odour or taste detected at concentrations between 0.5 and 1.5 mg/l. however, slight organoleptic effects within this range and thresholds of 0.65and 0.48 mg/l have been reported to have odour and taste. For dichloramine, the organoleptic effects between 0.1 and 0.5 mg/l were found to be “slight” and “acceptable”. Odour and taste thresholds of 0.15 and 0.13 mg/l were reported respectively. An odour threshold of 0.02

mg/l has been reported for trichloramine, and it has been described as “geranium” (Carl, 2015).

2.9.6 Chlorine on water quality.

Most individuals are able to smell or taste chlorine in drinking water at concentrations well below 5 mg/l, and some at levels as low as 0.3 mg/l. the taste threshold for chlorine is below the health-based guideline value of 5 mg/l. Until recently, concerns about drinking water focused on elimination pathogens. The chlorine used to reduce the risk of infectious disease may account for a substantial portion of the cancer risk associated with drinking water. Chlorination of drinking water was a factor in reduction of the mortality rates associated with water borne pathogen. The use of chlorine was believed to be safe. With the use of chlorine, any municipal water supply can be made as pure as mountain spring water. Chlorination destroys all animals and microbial life, leaving no trace of itself afterwards. Chlorine is used to combat microbial contamination, but it can react with organic matter in the water and form dangerous carcinogenic trihamethanes.

Contaminants may enter water supply at many points before reaching the tap. The carcinogens in drinking water at the point of use may result from contamination of source water arise from the treatment processes or enter as the water is transported to the consumer. Varied, carcinogens

may contaminate the source water, but it usually exists in drinking water at low concentrations (Carl, 2015).

Chlorine dissolves in water forming a diluted hydrogen chloride acid and this acid as corrosion facilitator or catalyst to water work members. The presence of chlorine in water promotes corrosion of cast iron even within water distribution network. This leads to serious leakages and loss due to leakages in water distribution system. Corrosion of sewers in water distribution that leads to leakages in the system not only cause losses but also affect water quality in terms of mineral concentration per milligram per liter of water. When the water work members were basically cast iron, it leads to colorization of water in the mains. The colour of the water will appear pale yellow due to high concentration of iron as a result of corrosion caused by dissolution of chlorine in water.

Today, so many cancers are traced to traces of chlorine presence in water. It also introduces bitter taste to water when present in the concentration above the acceptable that is 0.20mg/l. (Carl, 2015).

2.9.7 Corrosion effect on taste, odour and appearance.

Drinking water should ideally have no visible colour. Colour in drinking water is usually due to the presence of coloured organic matter (primarily humic and fulvic acids) associated with humus fraction of soil. Colour is also strongly influenced by the presence of iron and other metals, either as natural impurities or as corrosion products. It may also result from contamination of the water source with industrial effluents and may be

the first indication of a hazardous situation. The source of colour in a drinking water supply should be investigated, particularly if a substantial change has taken place. Most people can detect colour above 15 True Colour Unit (TCU) in a glass of water. Levels of colour below 15 TCU are often acceptable to consumers. High colour from natural organic carbon (e.g humic) could also indicate a high propensity to produce by-products from disinfection processes. No health-related guideline value is proposed in drinking water.

The provision of drinking-water that is not only safe but also acceptable in appearance, taste and odour is of high priority. Water that is aesthetically unacceptable will determine the confidence of consumers. It will lead to complaints and more importantly, could lead to the use of water from sources that are less safe. To a large extent, consumers have no means of judging the safety of drinking water themselves, but their attitude towards their drinking water supply and their drinking water suppliers will be affected to a considerable extent by the aspects of water quality that they are able to perceive with their own senses. It is natural for consumers to regard with suspicion water that appear dirty or discolored or that has an unpleasant taste or smell, even though these characteristics may not in themselves be of direct consequence to health (Chenoweth and Crawford, 2013).

The appearance, taste and odour of drinking water should be acceptable to consumer. Water that is aesthetically unacceptable can lead to the use of water from sources that are aesthetically more acceptable, but

potentially less safe. Some substances of health concern have effect on the taste, odour or appearance of drinking water that would normally lead to rejection of the water at concentrations significantly lower than those of concern for health. The concentration at which constituents are objectionable to consumers is varied and dependent on individual and local factors, including the quality of water to which the community is accustomed and a variety of social, environmental and cultural considerations. Guideline values have not been established for constituents influencing water quality that have no direct link to adverse health impacts. However, guideline values have been established for some substances that may cause taste or odour in drinking-water at much lower concentrations than the guideline value because there is such a wide range in the ability of consumers to detect them by taste or odour.

It is important to consider whether existing or proposed water treatment and distribution practices can affect the acceptability of drinking-water and to manage change and operations to minimize the risk of problems for acceptability as well as health. For example, chloramination that is not properly managed can lead to the formation of trichloramines, which can cause unacceptable taste and odour. Other problems may indirectly cause the disturbance of internal pipe deposits and bio-films when the flow is disturbed or changed in distribution systems (Chenoweth and Crawford, 2013).

It is not normally appropriate to directly regulate or monitor substances of health concern whose effects on the acceptability of water which will

normally lead to rejection of the water at concentrations significantly lower than that concern health. Rather, these substances may be addressed through a general requirement so that the water would be acceptable to the majority of consumers. For such substances, a formal guideline value is not usually derived, but a health-based value is derived. This is to assist in judging the response that is needed when problems are encountered, in some cases to provide reassurance to health authorities and consumers with regard to possible health.

Taste and odour in drinking water may be an indicator of some form of pollution. These malfunctions are taken care of during water treatment. It may also be an indication that appropriate health authorities should be consulted. Especially when there is a sudden or substantial change in Colour, cloudiness, particulate matter and visible organisms. It may also be noticed by consumers and may create concerns about the quality and acceptability of a drinking water (Chenoweth and Crawford, 2013).

2.9.8 Effects of dissolved oxygen on water quality.

The dissolved oxygen content of water is influenced by the source, raw water temperature, treatment, and chemical or biological processes taking place in the distribution system. Depletion of dissolved oxygen in water supplies can also cause an increase in the concentration of ferrous iron in solution, with subsequent discoloration at the tap when the water is aerated. No health-based guideline value is recommended. However, very high levels of dissolved oxygen may exacerbate corrosion of metal pipes.

The dissolved oxygen (DO) is usually the amount of oxygen dissolved in a specified sample of water. It is always expressed in mg/l. The saturated amount of dissolved oxygen in natural waters at 20^{o}c is about 9.2mg/l. The value of dissolved oxygen in water decreases with increase in temperature. The stronger the amount of waste discharged in the stream the greater the amount of dissolved oxygen (DO) required by microorganisms to completely degrade the waste. Hence the amount of waste discharged must be controlled so that the dissolved oxygen (DO) available for aquatic organisms will not be depleted. Excess of dissolved oxygen in water promotes corrosion of water work members and hence facilitates water pollution (Chenoweth and Crawford, 2013).

2.9.9 Effect of hardness on water quality.

Hardness caused by calcium and magnesium is usually indicated by precipitation of soap scum and the need for excess use of soap to achieve cleaning. Consumers are likely to notice changes in hardness. Public acceptability of the degree of hardness of water may vary considerably from one community to another. The taste threshold for calcium ions is in the range of 100-300 mg/l, depending on the associated anion, and the taste threshold for magnesium is probably lower than that for calcium. In some instances, consumers tolerate water hardness in excess of 500 mg/l.

Depending on the interaction of other factors, such as pH and alkalinity, water with hardness above approximately 200 mg/l may cause scale

deposition in the treatment works, distribution system and pipe work and tank within buildings. It will also result in high soap consumption and subsequent “scum” formation. On heating, hard waters form deposits of calcium carbonate scale. Soft water, but not necessarily cat ion exchange softened water, with a hardness of less than 100 mg/l may, in contrast, have a low buffering capacity and so be more corrosive for water pipes. No health-based guideline value is proposed for hardness in drinking water (Chenoweth and Crawford, 2013).

2.9.10 Effect of total dissolved solids on water quality

The palatability of water with a total dissolved solids (TDS) level of less than about 600 mg/l is generally considered to be good; drinking water becomes significantly and increasingly unpalatable at TDS levels greater than about 1000 mg/l. The presence of high levels of TDS may also be objectionable to consumers, owing to excessive scaling in water pipes, heaters, boilers and household appliances. No health related guideline TDS has been proposed (Chenoweth and Crawford, 2013).

2.9.11 Effect of turbidity on water quality

Turbidity in water is caused by suspended particles or colloidal matter that obstructs light transmission through the water. It may be caused by inorganic or organic matters or a combination of the two. Microorganisms (bacteria, virus and protozoa) are typically attached to particulates, and removal of turbidity by filtration will significantly reduce microbial contamination in treated water. Turbidity in some groundwater sources is

a consequence of inert clay or chalk particles or the precipitation of non-soluble reduced iron and other oxides when water is pumped from anaerobic waters, whereas turbidity in surface water may be the result of particulate matter of many types and is more likely to include attached microorganism that are a threat to health (Chenoweth and Crawford, 2013).

Turbidity in distribution system can occur as a result of disturbance of sediment and bio-films but is also from the ingress of dirty water from outside the system. In addition, turbidity can seriously interfere with the efficiency of disinfection by providing protection for organism, and much of water treatment is directed at removal of particulate matter before disinfection. This not only will increase the efficacy of disinfection by chemical disinfectants such as chlorine and ozone, but is an essential step in ensuring the effectiveness of physical disinfection processes such as ultraviolet irradiation, because light transmission through water is impaired by particulates.

Turbidity is measured by nephelometric turbidity units (NTU) and can be initially noticed by the naked eyes above approximately 4.0 NTU. However, to ensure effectiveness of disinfection, turbidity should be no more than 1 NTU and preferably much lower. Large, well-run municipal supplies should be able to average 0.2 NTU or less. Surface water and groundwater under influence of surface water treatment systems that achieve less than 0.3 NTU prior to disinfection will have demonstrated that the significant barriers against pathogens that absorb to particulate

matter. Of particular importance is the fact that this will be a good indicator that they are moving chlorine –resistant pathogens such as Cryptosporidium.

Small water supplies where resources are very limited and where there is limited or no treatment may not be able to achieve such low levels of turbidity. In these cases, the aim should be to produce water that has turbidity of at least less than 5 NTU and, if at all possible, below 1 NTU. For many of these small and usually rural supplies, measuring turbidity below 5 NTU may present a significant cost challenge, and thus providing low-cost measuring systems that can measure lower turbidities is an important requirement.

Occasionally, turbidity can be caused by minute air bubbles released when water has high dissolved air content. Such turbidity clears rapidly upwards through the surface but can cause concern for consumers, and efforts should be made to manage distribution systems to ensure that this does not happen (Chenoweth and Crawford, 2013).

2.9.12 Temperature effect on corrosion and water quality

Cool water is generally more palatable than warm water, and temperature will have an impact on the acceptability of a number of other inorganic constituents and chemical contaminants that may affect taste. High water temperature enhances the growth of microorganisms and may increase problems related to taste, odour, colour and corrosion (Chenoweth and Crawford, 2013).

2.9.13 Corrosion Rate

The rate of corrosion is the speed at which any given metal deteriorates in a specific environment. The rate or speed is dependent upon environmental conditions as well as the type and condition of the metal.

Corrosion rates are normally calculated using mils per year (mpy). I other words, corrosion rate is based on the number of millimeters (thousands of inch) it penetrates each year.

In order to calculate the rate of corrosion, the following information must be known:

i. Weight loss (the decrease in metal weight during the reference time period).
ii. Density of the metal
iii. Area (total initial surface area of the metal piece)
iv. Time (the length of the reference time period).

2.9.14 Corrosion Rate Conversion

To convert corrosion rate between the mils per year (mpy) and the metric equivalent millimeter per year (mm/y), the following equation can be used;

1mpy = 0.0254mm/y = 25.4 microm/y (2.25)

To calculate the corrosion rate from metal loss;

Corrosion rate (mm/y) = 87.6 x (W/DAT) (2.26)

Where:

W = weight loss in milligrams

D = Density of the metal in g/cm^3

A = Area of the metal sample in cm^2

T = Time of exposure of the metal sample in hours.

Moreover, corrosion rates calculation is very important because it helps to determine the lifespan of the metal-based structures. This reality dictates the choice of metals used for different purposes, and in different environments. It also helps to determine the maintenance requirements for the structures; a metal structure in a wet environment may require more frequent maintenance than a similar structure in a drier location. Maintenance schedules are developed based on the corrosion rate calculations and conversions.

Table 2.2: Density of metals

Metals	Density (g/cm^3)
Aluminium	2.70
Zinc	7.13
Iron	7.87
Copper	8.96
Silver	10.49
Lead	11.35
Mercury	13.55
Gold	19.32

Source: www.coolmagnetman.com/magconda.htm (August26, 2018 8:00pm)

Table 2.3: Comparative figures of limits for substances affecting the acceptability of water for domestic purposes [concentration (mg/l)]

Substance	WHO	Highest Desirable	International Limits Maximum Permissible	European Limits	USSR Limits	USA Limits Guide Level	Proposed EEC Limits Maximum Admissible Concentration
Phenolic compound (as phenol)	0.001	0.001	0.001	0.001		-	0.001
Fluoride (as F)	1.0-1.7	-	0.2-1.7	0.7-1.5[b]	1.4-2.4[a]	-	0.7-1.5[a]
Nitrate (as NO_3)	50-100	-	-	10(as N)	10(as N)		0.7-1.5[a]
pH	-	7.0-8.2	6.5-9.2	6.5-8.2		6.5-8.5	9.5
Copper (Cu^{2+})	0.5	0.5	1.5	1	-	-	0.5
Iron (as Fe^{2+})	0.1	0.1	1	0.5	-	0.1	0.05
Manganese(as Mn^{2+})	0.5	0.05	0.5	0.1	-	0.02	0.5
Zinc (as Zn^{2+})	5	5	1.5	5	-	-	0.1
Magnesium(as Mg^{2+})	50-125	50-150	150	-	-	50	50
Sulphate (as SO_4^{2+})	150	200	400	500	-	5	50
Hydrogen sulphate (as H_2S)	0.05	-	-	sulphide	-	-	Nil
Choride (as Cl)	200-600	200	600	350	-	5	200
Chlorine (free)	-	-	-	Nil	-	-	-
Amonic detergent	0.2	0.2	1	Individual limits	-	-	0.1
Ammonia(as NH_3)	0.5	-	-	2.0 (as N)	-	0.05	0.5
Carbon dioxide	-	-	-	-	-	-	-
Calcium (as Ca^{2+})	-	Nil	200	-	-	100	-
Mineral oil with high sulphur content	-	75	0.5	0.5	0.1	-	0.01
Turbidity (units)	-	5	25	1.5	1	5	10
Organics	0.2-0.5	-	-	-	0.7	-	-

Note: (a) Depending on temperature

(b) Varies according to climatic conditions

(c) Under certain circumstances higher levels

(d) Depending on sulphate concentration

(e) Calcium Chloroform Extract

WHO limits are being adopted as FEPA Guidelines

Source: FEPA (1991).

Table 2.4: Corrosion effect of some metals found in drinking water and health impact.

Metal/Limits	Causes	Human health Effects	Range in Natural water
Lead (< 30 µg per 100 ml	Long-range transport, atmospheric deposition and acidification of water (Norderg, 1990); lead-containing piping systems (plumbo solvency), industrial discharges	Gastrointestinal absorption of lead affects (a) hematopoietic system and result in reticulocytosis: (b) central nervous system (brain damage, convulsion, and ataxia). For example Scotland (1980-1981), there were cases of increased blood lead levels due to lead-containing piping.	Low, to 2 mg/l
Cadmium (10-15 µg/d)	Accumulation in forage of game (Wilkener et al, 1988), acidic water in pipes made of Cadmium.	Painful bone disease (Itai Itai), renal damage. May affect the reproductive system. In Sweden, symptoms of nausea, vomiting and diarrhea were observed in school children due to up to 1600 µg/l present in soft drinks.	0.1 µg/l
Aluminium (200 µg/l)	Aluminium-based coagulants	Renal failure, dementia, convulsion, speech disorders, bone diseases, death may occur after much accumulation.	100 µg/l
Copper (3000 µg/l)	Copper pipes, contaminated beverages, use of brass utensils	Acute gastrointestinal disturbances with vomiting, epigastric burns and diarrhoeal cirrhosis was reported in india due to the use of brass utensils (Bhave et al, 1987).	100 µg/l

Source: Water Engineering System

CHAPTER THREE

MATERIALS AND METHODS

3.1 MATERIALS

This research work used both secondary and primary data. The following materials were used to obtain the primary data; water sample from Cross River State Water Board Calabar, 32mm diameter iron bar of 30cm length, water testing kit (water analyzer), spectrometer, Electric oven, Ammeter, 2.5Ω resistor, wires, pure iron bar, water sample after 7 days interval of iron bar immersions, thermometer, conical flasks, 100ml burette, buffer solution (Ammonium Chloride), diluted tetraoxosulphate (vi) acid solution, diluted hydrochloric acid solution, sodium hydroxide solution, distilled water, Ethylenedianemetetracetic acid (EDTA), Eriochrome black T indicator and methyl orange indicator. The tests were carried out in the water analysis laboratory of Civil Engineering Department of Akwa Ibom State Polytechnic, Ikot Osurua, Ikot Ekpene, Akwa Ibom State.

3.2 METHODS

3.2.1 Analyses of Water Parameters with Increase in Corrosion Effect.

i. Determination of pH values.

The electrical sensor of the water analyzer was rinsed with the water sample and submerged into the sample conical flask. The device was calibrated to pH standard values using distilled water and pH value control knob and the instrument was allowed to stay in the water sample for about 5 minutes. Thereafter, the meter of the instrument was allowed to be steady before recording the results displayed.

ii. Determination of electrical conductivity, total dissolved solid and salinity.

The electrical sensors of the water analyzer for conductivity, total dissolved solid and salinity meter were rinsed with the water sample and submerged into the water sample contained in a conical flask, the device was switched on and the knob was tuned to conductivity mode, the sensor was allowed into the water sample for 5 minutes and the displayed results for conductivity were recorded, after that, the knob was turned to the total dissolved solid mode and the results obtained were recorded after 5 minutes. Thereafter, the salinity mode was also tuned and the results were recorded for each of the water samples.

iii. Determination of dissolved oxygen.

The electrical sensor of the water analyzer for dissolved oxygen was rinsed with the distilled water and submerged into the water sample (A) in a conical flask, the device was switched on and the calibration was returned to zero. The button for dissolved oxygen knob was tuned to read the value of the dissolved oxygen directly from the screen. These procedures were repeated for the corrosive water samples (Sample Bs) and the results obtained were recorded.

iv. Determination of temperature.

The immersed iron bars were put into an electric oven together with the water sample to regulate the temperature, these set-up were allowed for 7, 14, 21, 28, 35, 42, and 49 days respectively. Thereafter each of the 7days, the water samples was removed, the temperature of the control sample was taken at room temperature of the laboratory and it was observed the temperature affected the corrosion.

v. Determination of phosphate, suspended solid/ total silica.

The meter was switched on and stored programmed number for phosphate (501P) was entered, the wave length (810nm) was also entered and the calibrated meter returned to zero reading, the AccuVac Ampul of the spectrophotometer was filled with each of the

samples. Each sample was placed into cell holder and lid was used to close the mouth of the plastic container, the button for phosphate was pressed and the readings were allowed to be steady and the sample results were recorded as 12.4mg/l and 14.8mg/l for sample A and B respectively. The procedures were repeated for suspended solid and total silica using their respective stored programmed numbers (630Ss and 645Si) and wave lengths (830nm and 820nm). Their respective results were recorded appropriately.

vi. Determination of chloride, fluoride, aluminium and selenium.

The meter was switched on and the stored programmed number (70Cl) for Chloride was entered, the sample was rotating at wave length 455nm and the meter calibrated was returned to zero reading. The spectrophotometer was filled with each sample. Each sample was placed into the cell holder and the lid was closed, the chloride button was pressed and the meter reading was allowed to be steady. Concentration of the minerals in the samples was recorded. The same procedures were followed to get the results for fluoride, aluminium and selenium using programmed numbers (195F, 10Al and 640Se) and wavelengths (575nm, 525nm and 560nm) and their results were recorded accordingly.

vii. Determination of copper, zinc, barium and iron.

The meter was powered on and the stored programmed number for the properties (145Cu, 780Zn, 20Ba and 261Fe) were entered, the wave length of each element starting from copper (550nm, 610nm, 450nm and 500nm) was selected and the calibrated meter was returned to zero reading. The AccuVac Ampul of the spectrometer was filled with each sample, the samples were placed into the cell holders, the lid was closed and the button for each of the elements were pressed, the meter was allowed to steady and the concentrations for the samples were recorded.

viii. Turbidity

Two turbidity flasks were rinsed with distilled water and filled with distilled water and the water sample (Sample A), and the distilled water was used to calibrate the turbid meter using the knob to tuned it to zero. Thereafter, the flask was inserted into the turbid meter and the compartment closed. The displayed result was recorded. The procedures were repeated for the other water samples.

ix. Total alkalinity (Titration)

The burette was rinsed with sulphuric acid (H_2SO_4) solution and 50ml of the water was measured into the conical flask, sulphuric acid was poured into the burette. 3 drops of phenolphthalein and 3 drops of methyl orange were used in the test. The solution was titrated against sulphuric acid solution until the colour changes from pink to colourless and from colourless to light pink. The initial and final readings of the burette were recorded and used for total alkalinity calculations using the Equation (3.1);

$$Total\ Alkalinity = \frac{Titre \times 0.1 \times 1000}{Volume\ of\ sample} \quad (3.1)$$

Where;

Titre = Difference between initial and final readings of the burette.

0.1 = Alkalinity normality factor.

The procedures were repeated for other samples of the water.

x. Acidity (Titration)

The burette was rinsed with sodium hydroxide (NaOH) solution, and the burette was filled with the solution, the initial burette reading was taken. The 50ml of the sample was measured into the conical flask, 3 drops of methyl orange was added to the sample and titrated against sodium hydroxide and the final reading of the burette was recorded at the colour change, from purple to pink. Thus, the acidity of the samples were calculated using the Equation (3.2);

$$Acidity = \frac{Titre \times 0.2 \times 1000}{Volume\ of\ sample} \quad (3.2)$$

Where;

Titre = Difference between initial and final readings of the burette.

0.2 = Acidity normality factor.

3.2.2 Determination of Total Hardness, Calcium Hardness and Magnesium Hardness of Water as Corrosion Effect Increase.

i. Total hardness (Titration)

The burette was rinsed with EDTA (Ethylenedianemetetracetic acid) solution and filled with 50ml of EDTA, 50ml of the samples were measured into a conical flask, 1.0ml of buffer solution (Ammonium Chloride) was added after 3 drops of eriochrome black T indicator was added to the sample, the initial reading of burette was taken and the solution was titrated against EDTA and shaken vigorously until a permanent pink colour was observed. The final reading of the burette was also taken. The difference of the initial and the final burette readings was used to calculate the total hardness of the water sample using the Equation;

$$Total\ Hardness = \frac{Titre \times 1000}{Volume\ of\ sample} \quad (3.3)$$

Where;

Titre = Difference between initial and final readings of the burette.

These procedures were repeated for other water samples.

ii. Calcium Hardness (Titration)

The burette was rinsed with EDTA solution and the burette was filled with 50ml of the sample measured in the conical flask. 1ml of sodium hydroxide buffer solution was added to the sample and 3 drops of eriochrome black T indicator were added. The initial reading of the burette was taken and the solution was titrated against EDTA and shaken vigorously until the colour changes from wine red, through purple, to a pure rich blue, the final reading was taken and the difference was used to

calculate the Calcium hardness of the water sample using the Equation (3.4);

$$Calcium\ Hardness = \frac{Titre \times 1000}{Volume\ of\ sample} \quad (3.4)$$

Where;

Titre = Difference between initial and final readings of the burette.

These procedures were repeated for each of the water sample at the end of 7days of each immersion of the iron bar sample.

iii. Magnesium Hardness Calculation

The magnesium was calculated from the EDTA total hardness and calcium hardness (See Equation (3.5)).

$$Magnesium = Total\ hardness - Calcium\ hardness \quad (3.5)$$

3.2.3 Determination of Corrosion Rate of the Iron Bars in the Water Samples.

A sample of Iron bar of diameter 32mm and length of 30cm weighed, the Iron bar was inserted into corrosive water but before that 0.1ml of diluted hydrochloric acid solution was added to the water to induced corrosion on the Iron, and the metal was allowed to stay in the corrosive water for 7 days (one week). After the 7 days, the Iron sample was removed from the corrosive water and was air-dried, it was then reweighed to obtain its weight after corrosion, and this weight was subtracted from the initial weight to get the weight loss. Thereafter, corrosion rate was calculated for the 7 days using Equation (2.26). These procedures continued for 49 days at 7days interval. The results obtained after each 7 days were calculated and recorded.

Corrosion rate (mm/yr.) = 87.6 x (W/D*A*T) (3.6)

Where:

W = weight loss in milligrams

D = Density of the metal in g/cm^3

A = Area of the metal sample in cm^2

T = Time of exposure of the metal sample in hours.

87.6 = Conversion factor.

Corrosion rate expressed in millimeter per year (mm/yr.).

3.2.4 Determination of the Relationship between Corrosion Effect (Iron Concentration) and Water Quality (TDS).

The water quality in terms of total dissolved solids (TDS) in mg/l. was modeled against the iron concentration in mg/l in order to obtain a mathematical relationship between iron concentration and water quality. The resulting Equation is a simple linear regression model. At any known TDS concentration in mg/l then the iron concentration can be predicted and the water quality can be properly assessed. However, the chief parameter used to determine water quality is the total dissolved solid (TDS). Table 4.10 shows the parameters used in forming the mathematical modeling of TDS in mg/l and iron concentration in mg/l.

The mathematical modeling was done plotting the total dissolved solids TDS in mg/l. against iron concentration in mg/l using Microsoft Excel (Ms Excel) package and the model Equation was generated from there. Thereafter, the modeled Equation was verified using secondary data of another water sample.

3.2.5 Effect of Cathodic Protection (Coating) on the Water Works members and Water Quality

After the 49days of the iron bar immersion, the water sample and the iron bar were taken for electrochemical analysis and cathodic protection of the iron bar. The water sample was used as electrolyte, the corroded iron bar was used as cathode and another iron bar (non-corroded) was used as anode. The corroded water sample was chemically decomposed by passing direct current through it but before that, the electrodes (iron bars) weights were obtained by directly weighing them on a scale. 2.5Ω resistor was used in the electrolytic cell set up to stabilized the direct

current in order to control any damage the direct current may cause in the cell. Ammeter was connected to the cell for the reading of the current that was passing through the cell. The direct current was allowed to enter the electrolyte through the anode and leaved through cathode, the direct current was made to be steady and it was allowed to flow for 3 hours. Thereafter, the iron bars were allowed to cool and before re-weighing to obtain their new weights. The current read by the ammeter was recorded. This was used to check the new weight of the corroded iron bar (cathode) using Faraday's second law of electrolysis. During the process, it was observed that the water sample (electrolyte) was becoming clearer than it was before the electrolysis.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 RESULTS PRESENTATION

Table 4.1 shows the results of analysis of the control water sample that was obtained from the intake water works.

The results of the tested parameters were presented in Table 4.1;

Table 4.1: Chemical Analysis Results of Control Water Sample.

S/NO.	PARAMETERS	RESULT	NSDWQ	REMARKS
1	Appearance	Clear	Clear	Acceptable
2	Temperature, (^oC)	26.1	Ambient	-
3	pH	5.42	6.5-8.5	Unacceptable
4	Turbidity, (NTU)	16.7	5	Unacceptable
5	Iron (Fe^{3+}), mg/l	4.8	0.3	Unacceptable
6	Salinity, (%)	0.1	0.50	Acceptable
7	Electricity conductivity, µs/cm	119.6	1000	Acceptable
8	Total dissolved solid, mg/l	54.4	500	Acceptable
9	Phosphate (PO_4^3), mg/l	12.4	3.50	Unacceptable
10	Suspended solid, mg/l	17.1	10	Unacceptable
11	Total silica (SIO_2), mg/l	7.7	17	Acceptable
12	Sulphate (SO_4^2), mg/l	3.1	1000	Acceptable
13	Total Hardness, mg/l	58	500	Acceptable
14	Calcium Hardness (Ca^{2+}), mg/l	56	75.0	Acceptable
15	Magnesium Hardness, mg/l	2	0.2	Unacceptable
16	Acidity, mg/l	0.12	4.5-8.2	Acceptable
17	Total alkalinity, mg/l	10.8	100-200	Acceptable
18	Chloride (Cl), mg/l	5.5	250	Acceptable
19	Aluminum ($A1^{3+}$),	5.9	0.02	Unacceptable

	mg/l			
20	Selenium (Se), mg/l	1.7	-	-
21	Copper (Cu^{3+}), mg/l	5.9	1	Unacceptable
22	Zinc (Zn), mg/l	15.7	3	Unacceptable
23	Barium, mg/l	3.2	0.7	Unacceptable
24	Fluoride (F), mg/l	16.2	1.5	Unacceptable
25	Dissolved Oxygen (O_2), mg/l	0.9	1.0-5.0	Acceptable

The pH value of control sample in Table 4.1 was varied to precisely 5.40 by adding 5ml of 0.1ml of diluted hydrochloric acid solution to induced corrosion. This was to enable data generation within a reasonable length of time (7days). The iron bar was totally immersed into the water for seven days. The parameters were tested again after the 7 days and the results obtained are presented in Table 4.2.

Table 4.2: Chemical Analysis Results Of Corrosive Water Sample after 7days of Iron Immersion.

S/NO.	PARAMETERS	RESULT	NSDWQ	REMARKS
1	Appearance	Clear	Clear	Acceptable
2	Temperature, (^oC)	27.6	Ambient	-
3	pH	5.40	6.5-8.5	Unacceptable
4	Turbidity, (NTU)	98.2	5	Unacceptable
5	Iron (Fe^{3+}), mg/l	7.0	0.3	Unacceptable
6	Salinity, (%)	0.15	0.50	Acceptable
7	Electricity conductivity, µs/cm	256.0	1000	Acceptable
8	Total dissolved solid, mg/l	123.3	500	Acceptable
9	Phosphate (PO_4^3), mg/l	14.8	3.50	Unacceptable
10	Suspended solid, mg/l	20.6	10	Unacceptable
11	Total silica (SIO_2), mg/l	20.4	17	Unacceptable
12	Sulphate (SO_4^2), mg/l	4.3	1000	Acceptable

13	Total Hardness, mg/l	256	500	Acceptable
14	Calcium Hardness (Ca^{2+}), mg/l	136	75.0	Unacceptable
15	Magnesium Hardness, mg/l	120	0.2	Unacceptable
16	Acidity, mg/l	0.2	4.5-8.2	Acceptable
17	Total alkalinity, mg/l	10.2	100-200	Acceptable
18	Chloride (Cl), mg/l	6.9	250	Acceptable
19	Aluminium ($A1^{3+}$), mg/l	7.6	0.02	Unacceptable
20	Selenium (Se), mg/l	2.2	-	-
21	Copper (Cu^{3+}), mg/l	7.1	1	Unacceptable
22	Zinc (Zn), mg/l	18.7	3	Unacceptable
23	Barium, mg/l	4.6	0.7	Unacceptable
24	Fluoride (F), mg/l	16.0	1.5	Unacceptable
25	Dissolved Oxygen (O_2), mg/l	1.0	1.0-5.0	Acceptable

After determining the parameters of the water sample and calculation of the corrosion rate of the iron bar for 7days immersion, the iron bar again was totally immersed for another 7days and 14days from the start of the immersion. At the end of this 14days, the iron bar was removed and the water quality parameters were tested and the results obtained are presented in Table 4.3.

Table 4.3: Chemical Analysis Results of Corrosive Water Sample after 14days of Iron Immersion.

S/NO.	PARAMETERS	RESULT	NSDWQ	REMARKS
1	Appearance	Clear	Clear	Acceptable
2	Temperature, (^oC)	28.2	Ambient	-
3	pH	5.36	6.5-8.5	Unacceptable
4	Turbidity, (NTU)	102.6	5	Unacceptable
5	Iron (Fe^{3+}), mg/l	9.2	0.3	Unacceptable

6	Salinity, (%)	0.2	0.50	Acceptable
7	Electricity conductivity, µs/cm	278.0	1000	Acceptable
8	Total dissolved solid, mg/l	138.6	500	Acceptable
9	Phosphate (PO_4^{3-}), mg/l	16.75	3.50	Unacceptable
10	Suspended solid, mg/l	24.55	10	Unacceptable
11	Total silica (SIO_2), mg/l	24.65	17	Unacceptable
12	Sulphate (SO_4^{2-}), mg/l	5.85	1000	Acceptable
13	Total Hardness, mg/l	288	500	Acceptable
14	Calcium Hardness (Ca^{2+}), mg/l	145	75.0	Unacceptable
15	Magnesium Hardness, mg/l	143	0.2	Unacceptable
16	Acidity, mg/l	0.40	4.5-8.2	Acceptable
17	Total alkalinity, mg/l	9.6	100-200	Acceptable
18	Chloride (Cl), mg/l	8.7	250	Acceptable
19	Aluminium ($A1^{3+}$), mg/l	9.8	0.02	Unacceptable
20	Selenium (Se), mg/l	3.4	-	-
21	Copper (Cu^{3+}), mg/l	8.05	1	Unacceptable
22	Zinc (Zn), mg/l	20.30	3	Unacceptable
23	Barium, mg/l	6.20	0.7	Unacceptable
24	Fluoride (F), mg/l	15.7	1.5	Unacceptable
25	Dissolved Oxygen (O_2), mg/l	1.30	1.0-5.0	Acceptable

The process of total immersion of the iron bar into the water sample continued for anther 7days, that is, 21days from the first day of the iron bar immersion, after this 21days, the iron bar was removed and the water sample was tested to determine the water quality parameters. The weight loss and corrosion rate of the iron bar was calculated. Thus, results of the water quality parameters for 21days are presented in Table 4.4.

Table 4.4: Chemical Analysis Results of Corrosive Water Sample after 21days of Iron Immersion

S/NO.	PARAMETERS	RESULT	NSDWQ	REMARKS
1	Appearance	Clear	Clear	Acceptable
2	Temperature, (^{o}C)	29.80	Ambient	-
3	pH	5.30	6.5-8.5	Unacceptable
4	Turbidity, (NTU)	105.1	5	Unacceptable
5	Iron (Fe^{3+}), mg/l	12.5	0.3	Unacceptable
6	Salinity, (%)	0.35	0.50	Acceptable
7	Electricity conductivity, µs/cm	296.0	1000	Acceptable
8	Total dissolved solid, mg/l	142.4	500	Acceptable
9	Phosphate (PO_4^{3-}), mg/l	18.15	3.50	Unacceptable
10	Suspended solid, mg/l	27.10	10	Unacceptable
11	Total silica (SIO_2), mg/l	26.95	17	Unacceptable
12	Sulphate (SO_4^{2-}), mg/l	7.95	1000	Acceptable
13	Total Hardness, mg/l	318	500	Acceptable
14	Calcium Hardness, (Ca^{2+}), mg/l	162	75.0	Unacceptable
15	Magnesium Hardness, mg/l	156	0.2	Unacceptable
16	Acidity, mg/l	0.62	4.5-8.2	Acceptable
17	Total alkalinity, mg/l	9.0	100-200	Acceptable
18	Chloride (Cl), mg/l	10.35	250	Acceptable
19	Aluminium ($A1^{3+}$), mg/l	11.20	0.02	Unacceptable
20	Selenium (Se), mg/l	4.6	-	-
21	Copper (Cu^{3+}), mg/l	9.85	1	Unacceptable
22	Zinc (Zn), mg/l	22.40	3	Unacceptable
23	Barium, mg/l	7.90	0.7	Unacceptable
24	Fluoride (F), mg/l	15.45	1.5	Unacceptable
25	Dissolved Oxygen (O_2), mg/l	1.55	1.0-5.0	Acceptable

Table 4.5 shows the test results of the water quality parameters obtained after 28days of total immersion of the iron bar.

Table 4.5: Chemical Analysis Results Of Corrosive Water Sample after 28days of Iron Immersion.

S/NO.	PARAMETERS	RESULT	NSDWQ	REMARKS
1	Appearance	Fairly Clear	Clear	Unacceptable
2	Temperature, (^{o}C)	31.20	Ambient	-
3	pH	5.25	6.5-8.5	Unacceptable
4	Turbidity, (NTU)	107.40	5	Unacceptable
5	Iron (Fe^{3+}), mg/l	14.8	0.3	Unacceptable.
6	Salinity, (%)	0.40	0.50	Acceptable
7	Electricity conductivity, µs/cm	308	1000	Acceptable
8	Total dissolved solid, mg/l	158.40	500	Acceptable
9	Phosphate (PO_4^{3-}), mg/l	20.05	3.50	Unacceptable
10	Suspended solid, mg/l	29.90	10	Unacceptable
11	Total silica (SIO_2), mg/l	27.10	17	Unacceptable
12	Sulphate (SO_4^{2-}), mg/l	9.15	1000	Acceptable
13	Total Hardness, mg/l	342	500	Acceptable
14	Calcium Hardness, (Ca^{2+}), mg/l	176	75.0	Unacceptable
15	Magnesium Hardness, mg/l	166	0.2	Unacceptable
16	Acidity, mg/l	0.86	4.5-8.2	Acceptable
17	Total alkalinity, mg/l	7.80	100-200	Acceptable
18	Chloride (Cl), mg/l	12.85	250	Acceptable
19	Aluminium ($A1^{3+}$), mg/l	13.10	0.02	Unacceptable
20	Selenium (Se), mg/l	6.4	-	-
21	Copper (Cu^{3+}), mg/l	11.65	1	Unacceptable

22	Zinc (Zn), mg/l	24.20	3	Unacceptable
23	Barium, mg/l	9.70	0.7	Unacceptable
24	Fluoride (F), mg/l	15.25	1.5	Unacceptable
25	Dissolved Oxygen (O_2), mg/l	1.80	1.0-5.0	Acceptable

Table 4.6 presents the results of the water/corrosion relationship parameters obtained at the end of 35days of immersing the iron bar totally in the corrosive water sample.

Table 4.6: Chemical Analysis Results Of Corrosive Water Sample after 35days of Iron Immersion.

S/NO.	PARAMETERS	RESULT	NSDWQ	REMARKS
1	Appearance	Fairly Clear	Clear	Unacceptable
2	Temperature, (^oC)	34.10	Ambient	-
3	pH	5.05	6.5-8.5	Acceptable
4	Turbidity, (NTU)	109.60	5	Unacceptable
5	Iron (Fe^{3+}), mg/l	17.2	0.3	Unacceptable
6	Salinity, (%)	0.45	0.50	Acceptable
7	Electricity conductivity, µs/cm	338	1000	Acceptable
8	Total dissolved solid, mg/l	169.80	500	Acceptable
9	Phosphate (PO_4^{3-}), mg/l	22.85	3.50	unacceptable
10	Suspended solid, mg/l	31.80	10	unacceptable
11	Total silica (SIO_2), mg/l	29.60	17	Unacceptable
12	Sulphate (SO_4^{2-}), mg/l	11.10	1000	Acceptable
13	Total Hardness, mg/l	386	500	Acceptable
14	Calcium Hardness, (Ca^{2+}), mg/l	208	75.0	Unacceptable
15	Magnesium Hardness, mg/l	178	0.2	Unacceptable
16	Acidity, mg/l	1.02	4.5-8.2	Acceptable

17	Total alkalinity, mg/l	7.0	100-200	Acceptable
18	Chloride (Cl), mg/l	14.55	250	Acceptable
19	Aluminium ($A1^{3+}$), mg/l	15.65	0.02	unacceptable
20	Selenium (Se), mg/l	8.10	-	-
21	Copper (Cu^{3+}), mg/l	13.85	1	unacceptable
22	Zinc (Zn), mg/l	26.60	3	unacceptable
23	Barium, mg/l	11.90	0.7	unacceptable
24	Fluoride (F), mg/l	14.95	1.5	unacceptable
25	Dissolved Oxygen (O_2), mg/l	2.10	1.0-5.0	Acceptable

Moreover, the total immersion of the iron bar continued for another 7days and 42days from the start of the process, the results of the parameters obtained are presented in Table 4.7.

Table 4.7: Laboratory Chemical Analysis Results Of Corrosive Water Sample after 42days of Iron Immersion.

S/NO.	PARAMETERS	RESULT	NSDWQ	REMARKS
1	Appearance	Not Clear	Clear	Unacceptable
2	Temperature, (^oC)	36.80	Ambient	-
3	pH	4.90	6.5-8.5	Unacceptable
4	Turbidity, (NTU)	126.80	5	Unacceptable
5	Iron (Fe^{3+}), mg/l	21.4	0.3	Unacceptable
6	Salinity, (%)	0.55	0.50	Unacceptable
7	Electricity conductivity, µs/cm	362	1000	Acceptable
8	Total dissolved solid, mg/l	185.60	500	Acceptable
9	Phosphate (PO_4^{3-}), mg/l	25.10	3.50	Unacceptable
10	Suspended solid, mg/l	32.40	10	Unacceptable
11	Total silica (SIO_2), mg/l	32.80	17	Unacceptable

12	Sulphate (SO_4^{2-}), mg/l	13.80	1000	Acceptable
13	Total Hardness, mg/l	416	500	Acceptable
14	Calcium Hardness (Ca^{2+}),mg/l	224	75.0	Unacceptable
15	Magnesium Hardness, mg/l	192	0.2	Unacceptable
16	Acidity, mg/l	1.68	4.5-8.2	Acceptable
17	Total alkalinity, mg/l	6.20	100-200	Acceptable
18	Chloride (Cl), mg/l	16.45	250	Acceptable
19	Aluminium ($A1^{3+}$), mg/l	17.25	0.02	Unacceptable
20	Selenium (Se), mg/l	10.00	-	-
21	Copper (Cu^{3+}), mg/l	15.45	1	Unacceptable
22	Zinc (Zn), mg/l	29.20	3	Unacceptable
23	Barium, mg/l	14.40	0.7	Unacceptable
24	Fluoride (F), mg/l	14.65	1.5	Unacceptable
25	Dissolved Oxygen (O_2), mg/l	2.95	1.0-5.0	Acceptable

Finally, the total immersion of the iron bar was terminated at 49th day and the water quality parameters were tested as usual, the results obtained are presented in Table 4.8.

Table 4.8: Chemical Analysis Results Of Corrosive Water Sample after 49days of Iron Immersion.

S/NO.	PARAMETERS	RESULT	NSDWQ	REMARKS
1	Appearance	Not clear	Clear	Unacceptable
2	Temperature, (^oC)	39.40	Ambient	-
3	pH	4.60	6.5-8.5	Unacceptable
4	Turbidity, (NTU)	148.90	5	Unacceptable
5	Iron (Fe^{3+}), mg/l	26.9	0.3	Unacceptable
6	Salinity, (%)	0.60	0.50	Unacceptable
7	Electricity conductivity, µs/cm	396	1000	Acceptable

8	Total dissolved solid, mg/l	196.80	500	Acceptable
9	Phosphate (PO_4^{3-}), mg/l	28.60	3.50	Unacceptable
10	Suspended solid, mg/l	35.20	10	Unacceptable
11	Total silica (SIO_2), mg/l	34.40	17	Acceptable
12	Sulphate (SO_4^{2-}), mg/l	15.30	1000	Acceptable
13	Total Hardness, mg/l	468	500	Acceptable
14	Calcium Hardness (Ca^{2+}), mg/l	242	75.0	Unacceptable
15	Magnesium Hardness, mg/l	226	0.2	Unacceptable
16	Acidity, mg/l	1.96	4.5-8.2	Unacceptable
17	Total alkalinity, mg/l	5.40	100-200	Acceptable
18	Chloride (Cl), mg/l	18.80	250	Acceptable
19	Aluminium ($A1^{3+}$), mg/l	20.10	0.02	Unacceptable
20	Selenium (Se), mg/l	12.10	-	-
21	Copper (Cu^{3+}), mg/l	17.20	1	Unacceptable
22	Zinc (Zn), mg/l	32.40	3	Unacceptable
23	Barium, mg/l	17.80	0.7	Unacceptable
24	Fluoride (F), mg/l	14.30	1.5	Unacceptable
25	Dissolved Oxygen (O2), mg/l	2.65	1.0-5.0	Acceptable

The weight losses in iron bar after 7days immersion for a total of 49days were used to calculate the corrosion rates as shown in Appendix D and the results obtained were summarized and presented in Table 4.9

Table 4.9: Results of weight loss, corrosion with respect to duration in days.

Duration (Days)	Weight Loss (mg)	Corrosion Rate (mm/yr.)
0	0	0.00
7	2000	1656.38
14	2200	1822.02
21	2450	2029.07
28	2700	2236.11
35	2950	2443.16
42	3250	2691.62
49	3525	2919.37

Furthermore, it was observed that water quality does not have a specific parameter that defines it, rather it is defined in terms of Total Dissolved Solids (TDS), Iron concentration, pH value, temperature, dissolved oxygen (DO), chloride, sulphates, conductivity, total alkalinity, acidity and hardness (total calcium and magnesium hardness). All these parameters collectively define water quality and its relationship to corrosion. However, corrosion can be measured in terms of the material (iron bar) weight loss over time which was used to calculate the corrosion rate of the water works members using Equation 3.5. Thus, it would be important to establish a relationship between corrosion rate and each of the water quality parameters by plotting the graphs of each parameter (vertical axis) against corrosion rates (Horizontal axis) which will explain the relationship between water quality and corrosion.

Figure 4.1 shows the graphical representation of relationship between water quality in terms of Total Dissolved Solid (TDS) and Corrosion.

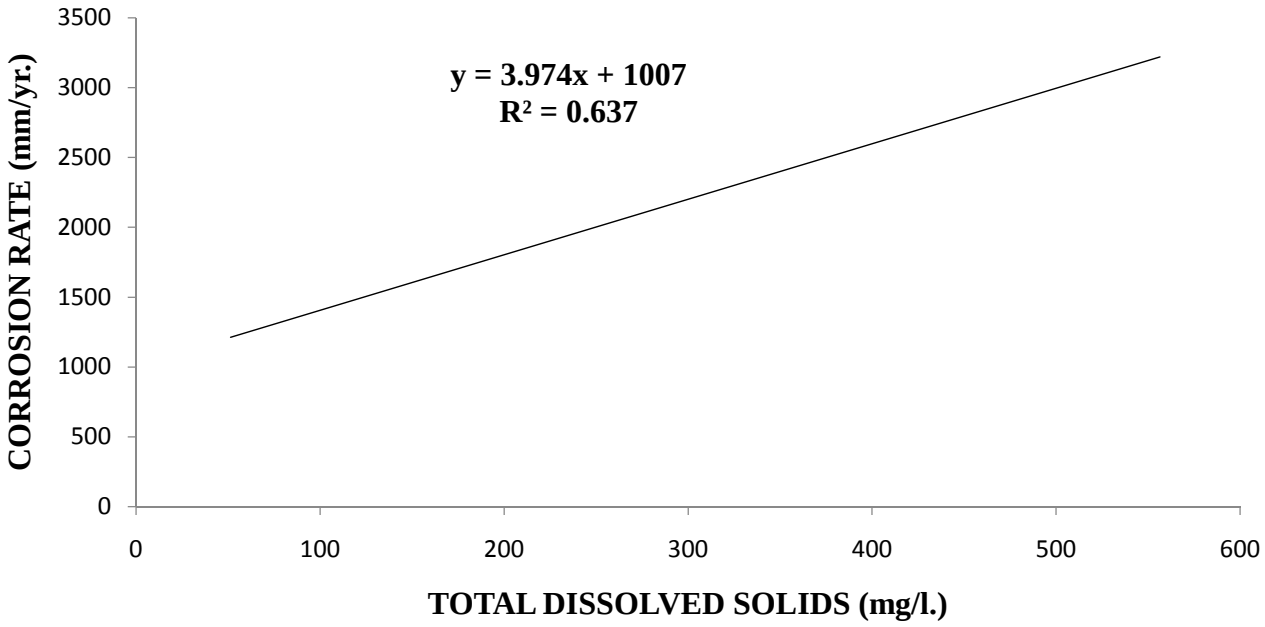

Fig. 4.1: Graph of Corrosion Rates (mm/yr.) against Total Dissolved Solid-TDS (mg/l.)

Iron concentration of water is one the parameters used to determine the water quality and corrosion. Figure 4.2 represent the graphical relationship between the iron concentration and corrosion.

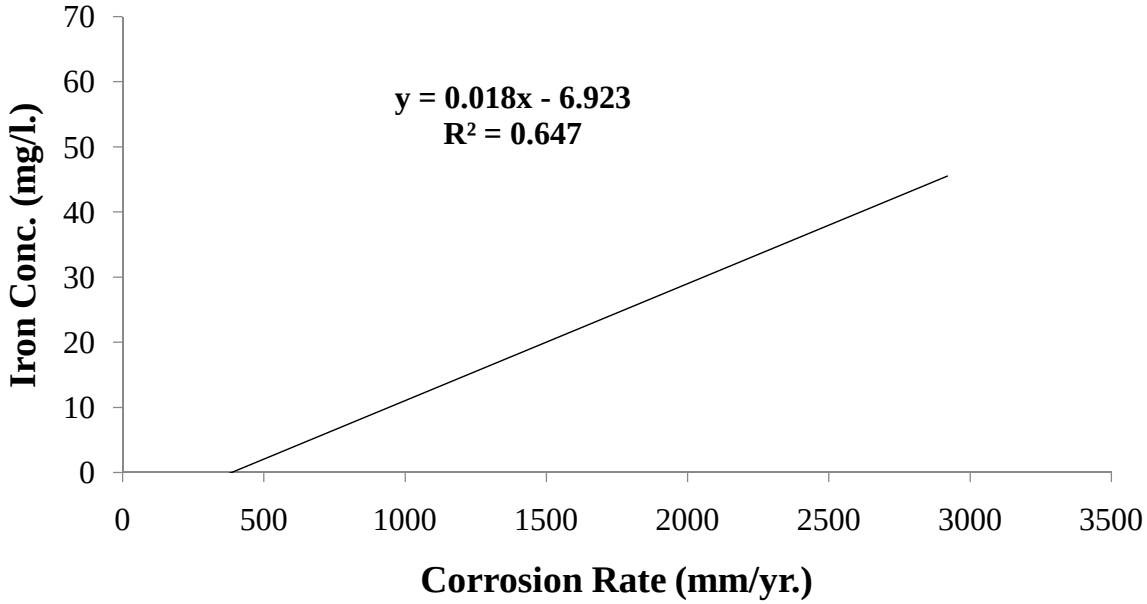

Fig. 4.2: Graph of Iron Concentration (mg/l.) against Corrosion Rate (mm/yr.)

The pH value of water is among the parameters that determine the quality of the water and its relationship to corrosion. Figure 4.3 shows the graph of pH values of the water sample and corrosion.

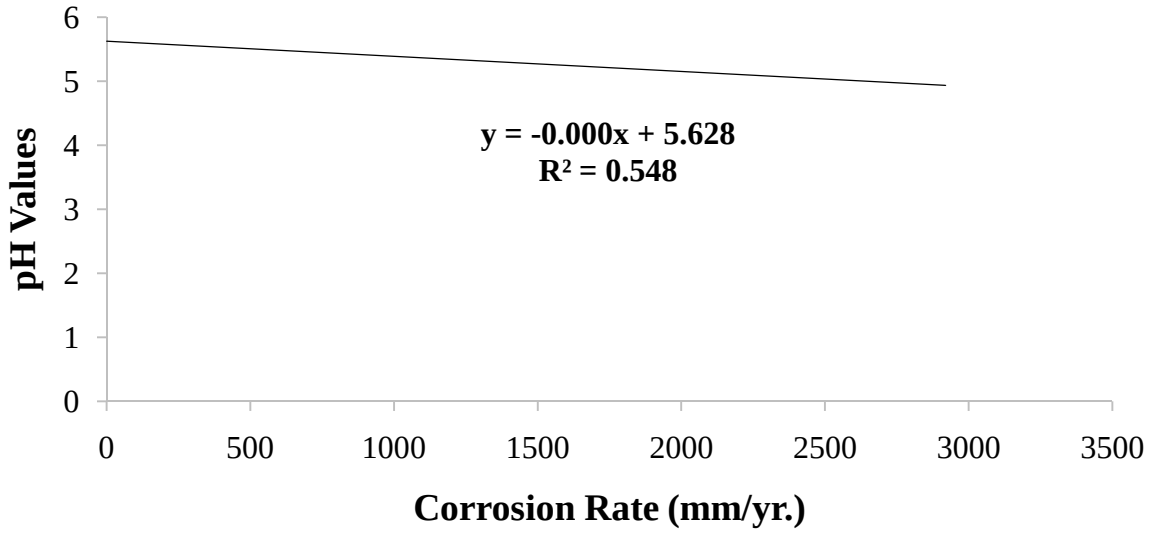

Fig. 4.3: Graph of pH values against Corrosion Rates (mm/yr.)

Temperature have an effect on the internal energy of a substance, this internal energy determines the rate at which the substance (water molecules) react with its environment. This internal energy is known as “Activation Energy”, thus, temperature of water sample affect the relationship between water quality and corrosion. Figure 4.4 shows this effect graphically.

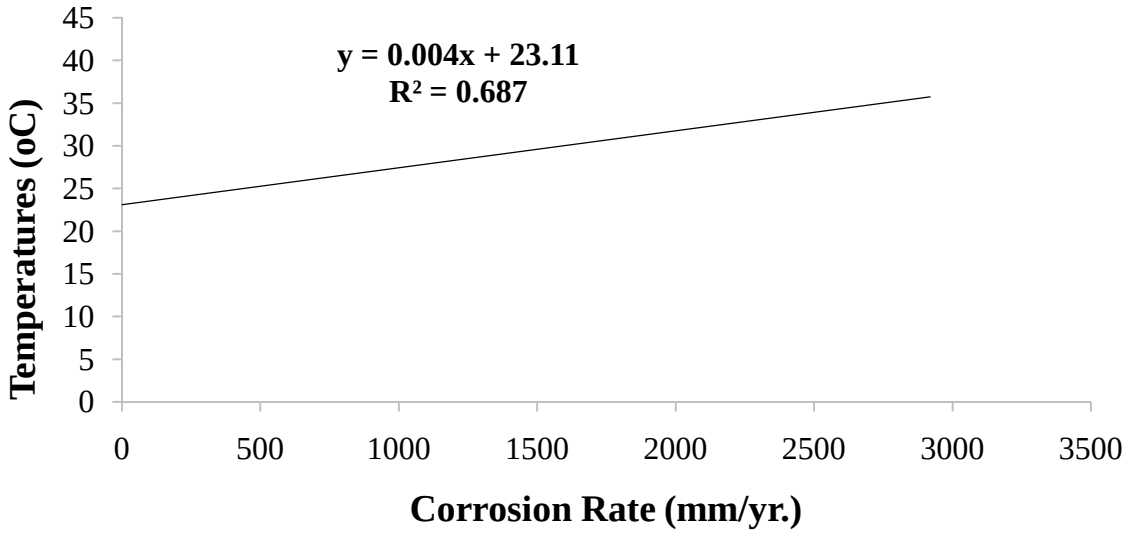

Fig. 4.4: Graph of Temperature (^{o}C) against Corrosion Rates (mm/yr.)

Corrosion is a redox (Reduction/Oxidation) reaction which has to do with oxygen; this means that the amount of dissolved oxygen will foster reaction of the water sample with its environment (Intake water works). And when this occurs, the reaction especially with metals (iron) will affect the water quality/corrosion relationship. Figure 4.5 shows the graphical representation of the dissolved oxygen (DO) and corrosion relationship.

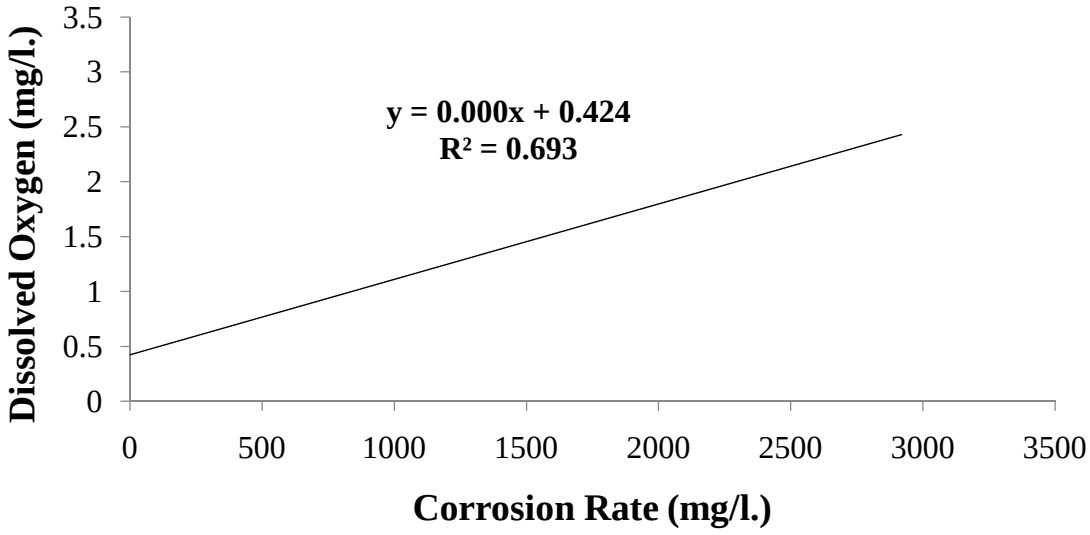

Fig. 4.5: Graph of Dissolved Oxygen (mg/l.) against Corrosion Rates (mm/yr.)

It has been shown by researchers that sulphates increases the total dissolved solid (TDS) of water. These sulphates have effect on the water quality and corrosion. Figure 4.6 shows the graphical representation of the sulphates and corrosion relationship.

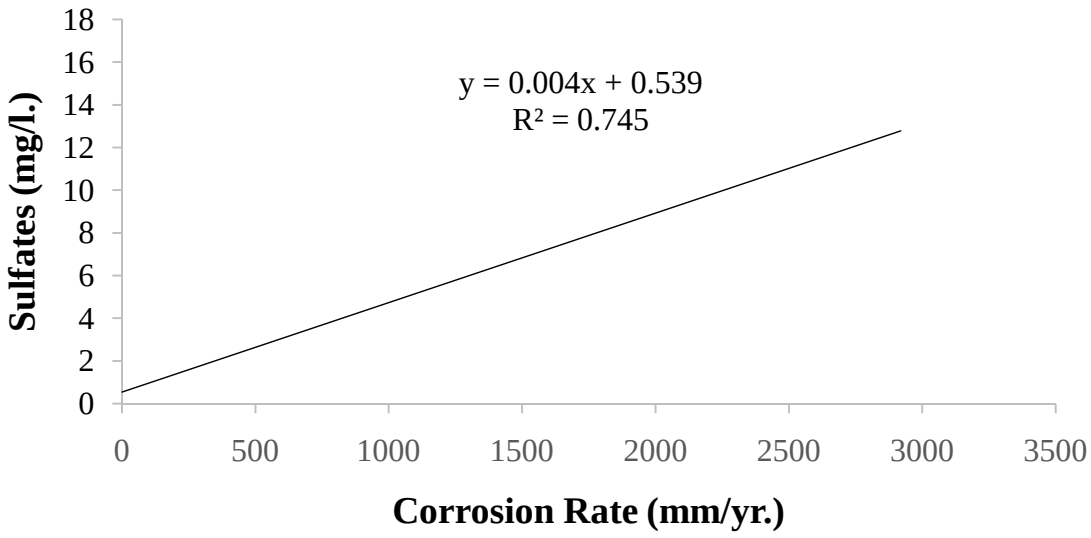

Fig. 4.6: Graph of sulphates (mg/l.) against Corrosion Rates (mm/y).

It has been shown also by researchers that chlorides increases the total dissolved solid (TDS) of water. These chlorides have effect on the water quality and corrosion. Fig shows the graphical representation of the chlorides and corrosion relationship.

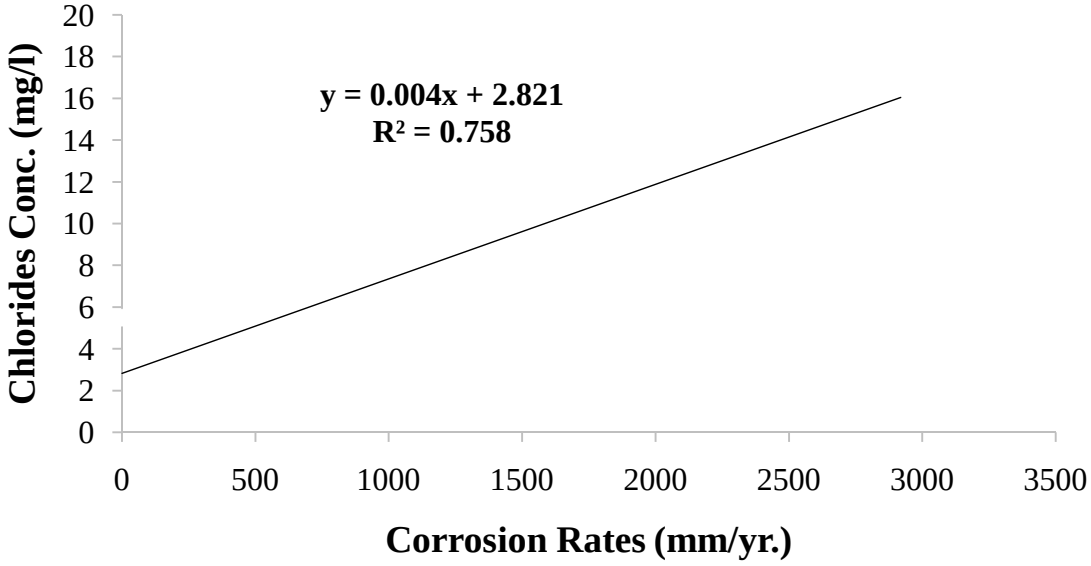

Fig. 4.7: Graph of chlorides (mg/l.) against Corrosion Rates (mm/yr.)

Because chlorides and sulphates increase TDS of the water, it was observed that the conductivity of the water also increases and this increase in conductivity increases the corrosion of the water. Figure 4.7 shows the relationship between the conductivity of the water sample and corrosion.

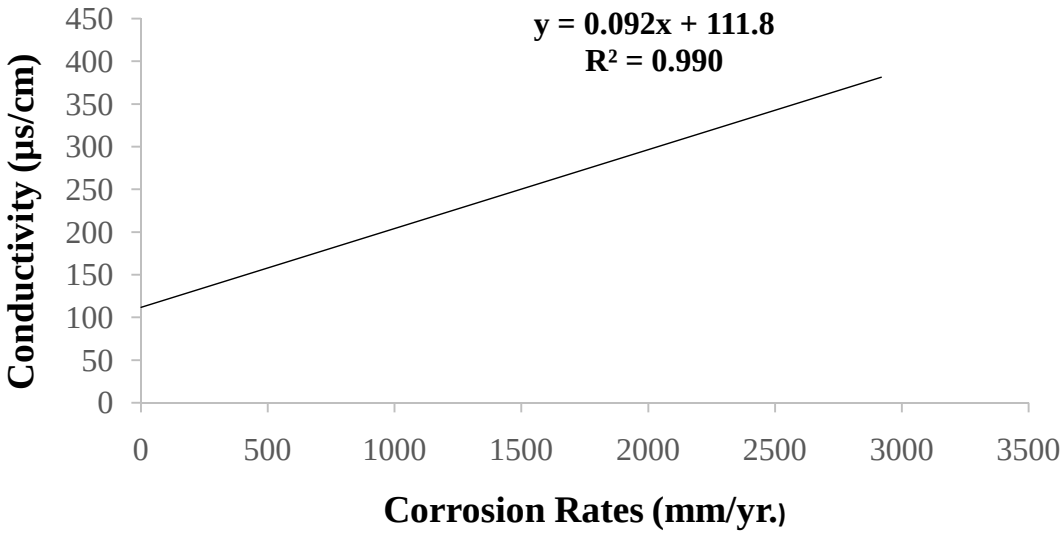

Fig. 4.8: Graph of Conductivity (µs/cm) against Corrosion Rates (mm/y).

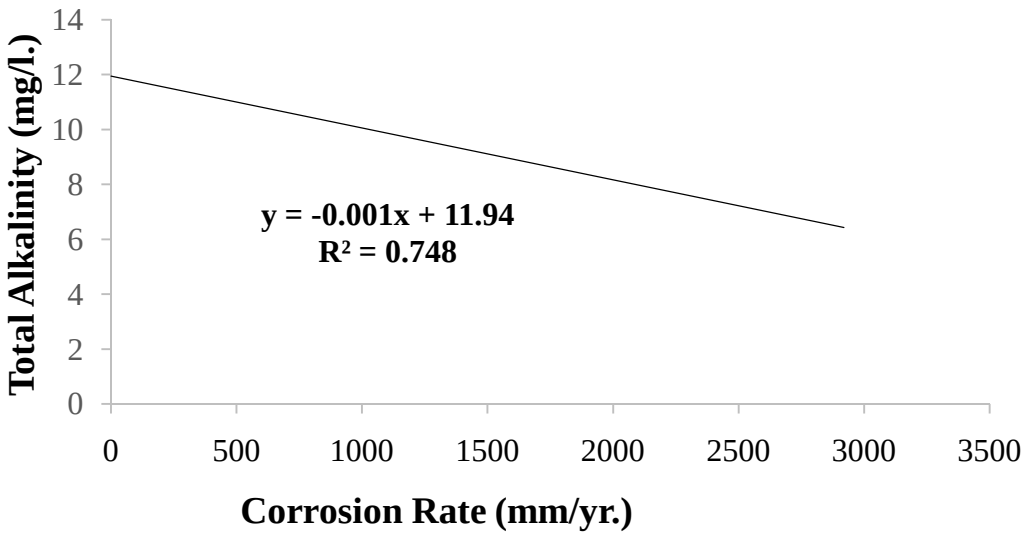

Fig. 4.9: Graph of Total Alkalinity (mg/l.) against Corrosion Rates (mm/y).

4.1.7 Mathematical Relationship between Corrosion Effect (Iron Conc.) and Water Quality (TDS).

Given the fact that water quality and corrosion can be defined in terms of the total dissolved solid (TDS) in mg/l. and iron concentration in mg/l; the results of the total dissolved solids (TDS) in mg/l. and iron concentration in mg/l. of the water sample over the period of immersion intervals were summarized in Table 4.10. These results were used for the mathematical modeling.

Table 4.10: Mathematical Modeling Values of TDS and Iron.

TOTAL DISSOLVED SOLID, TDS(x)	IRON CONCENTRATION (y)
51.4	6.8
71.9	9.2
107.5	13.4
167.6	20.3
236.2	28.8
324	37.2
432.9	49.8
556.4	62.9

For the mathematical modeling of the water quality in terms of TDS (mg/l.) and corrosion in terms of iron concentration (mg/l.), graph 4.11 shows the Ms-Excel plotting of TDS against Iron concentration and the generated Equation.

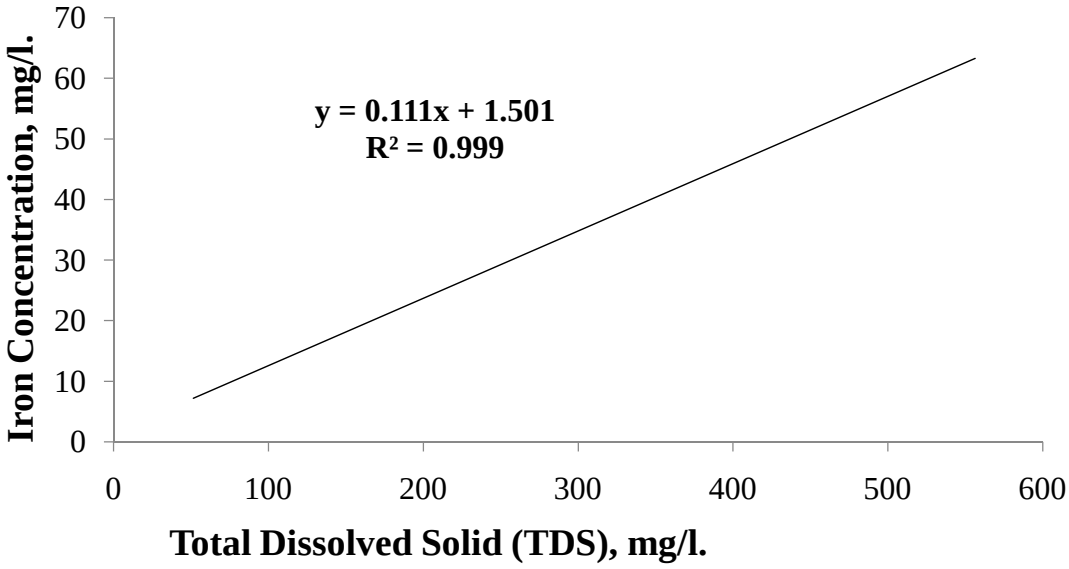

Fig. 4.11: Graph of Iron Conc. (mg/l.) against TDS (mg/l.) with the Equated relationship.

Now, the Equation of the relationship can be used for the future prediction of the water quality (TDS) and corrosion (Iron Conc.) of any water works system.

$$y = 0.111x + 1.501 \qquad (4.7)$$

Where;

$y =$ Iron concentration in mg/l.

$x =$ Water quality in terms of TDS (mg/l.)

4.1.8 Correlation check

The Equation of the relationship generated from Ms-Excel can be verified using secondary data of TDS (mg/l.) and Iron concentration (mg/l.) collected from Cross River State water board authority, Calabar, Cross River State. This is to check the correlation of Equation (4.7). Thus, using the data in Table A3 of the Appendice (pg 93), the value of iron

concentration y can be estimated and compared with the actual value in the Table B using Total Dissolved Solids TDS (mg/l.).

$$y = 0.111(32.7) + 1.501 = 3.630 + 1.501 = 5.1307$$

$$y = 5.1307 mg/l.$$

$$y = 0.111(24.8) + 1.501 = 2.7528 + 1.501 = 4.2538$$

$$y = 4.2538 mg/l.$$

Table 4.12: Verified Related Values of Iron y (mg/l.)

S/N	TDS (mg/l)	Iron Conc. (mg/l)		%
		Observed	Predicted	Percentage Error
1	21.90	3.46	3.93	13.6
2	24.80	3.97	4.25	7.1
3	28.50	4.56	4.66	2.2
4	32.70	5.05	5.13	1.6
5	35.80	5.61	5.47	2.5
6	40.20	5.90	5.96	1.0
7	42.80	6.20	6.25	0.8

4.1.9 Calculation of Weight Gained by the Iron Bar.

After the electrolysis of the water sample and cathodic protection of the corroded iron bar, the weight of iron bars were obtained both corroded and non-corroded iron bar by direct weighing.

Weight of corroded iron bar before electrolysis = 281g

Weight of non-corroded iron bar before electrolysis = 325g

Weight of the corroded iron bar after electrolysis = 307g

Weight of the non-corroded iron bar after electrolysis = 299g

By Faraday's second law of electrolysis;

Current recorded I = 7.9A

Time of current flow t = 3 hours.

Faraday constant = 96500 C.

Molar mass of Iron = 58.8g

Chemical Equation of the Electrolysis;

cathodic half reaction; $2Fe^{2+}(aq) + 4e^{+} \longrightarrow 2Fe(s)$

Anodic half reaction; $4OH^{-}(aq) \longrightarrow 2H_2O(l) + O_2(g) + 4e^{-}$

Electrolyte reaction; $4H^{+}Cl^{-}(aq) + O_2^{-}(g) \longrightarrow 2H_2O(l) + 2Cl_2(g)$

Overall reaction;

$2Fe^{2+}(aq) + 4OH^{-}(aq) + 4H^{+}Cl^{-}(aq) \longrightarrow 2Fe(s) + 4H_2O(l) + 2Cl_2(g)$

Quantity of electricity used = It = (7.9 x 5 x 60 x 60)C.

$2Fe^{2+}(aq) + 4e^{+} \longrightarrow 2Fe(s)$

$(2x58.8g) + 4F \longrightarrow (2x58.8g)$

$4 \times 96500\,C$ Electricity liberate $2 \times 58.8g$ of iron (117.6g of Fe)

$(7.9 \times 3 \times 60 \times 60)C$ Electricity liberates Xg of iron.

$$X = \frac{7.9 \times 5 \times 60 \times 60 \times 117.6}{4 \times 96500} = 43.32g$$

Final weight of the corroded iron after electrolysis = 281g + 43.32g = 324.32g. This shows that the additional weight of iron was as a result of iron content in the corrosive water which became clearer after the electrolysis, thus, the water work members can be cathodically protected.

4.2 DISCUSSION OF RESULTS

The result shows that corrosion effect has already been noticed in the assessed water parameters. This was evident when the concentrations of some minerals in mg/l. were matched with the standard permissible values in the Nigeria Standard for Drinking Water Quality (NSDWQ) and World Health Organization (WHO) standard. From the plots obtained in Figures 4.1 – 4.8, it is evident that water quality has a relationship with corrosion. From the pH scale, it could be observed that increase in pH values leads to increase in alkalinity and decrease in alkalinity leads to increase in corrosion. It was known from the literature review (Roberge,

2012) and observations of the laboratory test results of this work that water quality is defined in terms of its mineral constituents such as total dissolved solid (TDS), pH values, conductivity (ability to allow flow of electrical current), salts of chlorides and sulphates, alkalinity, temperature and dissolved oxygen (DO). The above listed minerals have a direct effect on the quality of any given water as they affect the concentration in milligram per litre (mg/l.) of the total dissolved solid TDS of the water sample. These mineral constituents of water are inter-related, that is, the value of one may affect the value of others. It may not be possible to remove these mineral constituents totally from water but they can be controlled to certain levels as established by Nigeria Standard for Drinking Water Quality (NSDWQ) and World Health Organization (WHO) according to Tables 4.1 – 4.8. Whenever mineral constituents of water quality exceed the recommended values by NSDWQ, the water quality will be altered and this alteration in water quality also affects corrosion. From Figures 4.1, 4.2, 4.4, 4.5, 4.6 and 4.7, it could be observed that corrosion increases with increase in total dissolved solid (TDS), iron concentration, temperature, dissolved oxygen, chloride/sulphate salts and conductivity, this means that the values of these mineral constituents are directly proportional to corrosion. However, Figures 4.3 and 4.8 shows that pH value and alkalinity of water are inversely proportional to corrosion meaning that decrease in their values lead to increase in corrosion.

Moreover, the major mineral constituent used to define water quality is total dissolved solid because iron concentration, concentration of chlorides/sulphates salts, dissolved oxygen and other minerals form part of total dissolved solid (TDS) and this TDS affect the conductivity of the water. And corrosion here can be defined by amount of iron concentration in the water sample. Based on these, mathematical modeling of the total dissolved solid (TDS) in mg/l. and iron concentration in mg/l. were carried

out using Ms-Excel package (see Figure 4.10) and a simple linear regression equation (Equation 4.7) was obtained. The Equation was verified in Subsection 4.1.6 (Correlation Check), this verification shows that the equation (Equation 4.7) can be used to predict the corrosion of any water works member in terms of iron concentration in mg/l. once the quality of the water sample in terms of total dissolved solid (TDS) in mg/l is known and vice verse by simply subtracting the known value in the modeled equation (Equation 4.7). From Tables 4.1 – 4.8, it could be observed that the rate of corrosion of Copper (Cu), Aluminium (Al) and Zinc (Zn) are lower than that of iron materials. This shows that copper, aluminium and zinc are better corrosion resistant materials than iron. And whenever copper, aluminium and zinc are used cathodically (coating) to protect the water intake work members, the quality of the water in that intake structures are preserved because it will take longer time before corrosion starts (Okafor and Ebenso, 2007). Furthermore, review of other researchers' literatures (Health Canada, 2016; Table A1 of Appendix A) shows that materials such as; polyethylene fiberglass, Epoxy or vinylester lined steel, polyvinylchloride (PVC), coated polyvinylchloride (CPVC) kynar, 316 stainless steel, viton or hypalon are corrosion resistants and can be used for storage tanks, feed system, pump liquid ends and piping. When these materials are used in the water intake structures, water quality can be sustained and the rate of corrosion of the intake water works can be reduced or possibly stopped. From the calculations in Appendix B and Table 4.1 – 4.8, it could be ascertained that increase in

corrosion causes increase in total hardness, calcium hardness and magnesium hardness of the water. The total hardness increases drastically from 58mg/l to 256mg/l after 7days of induced corrosion and continued to increase to 468mg/l at the 49days of corrosion induction. This increase in total hardness affected the calcium hardness as well as magnesium in like manner. From Tables 4.1 – 4.8, it could also be observed that the increase rate in the concentration of zinc and copper is lower than that of iron concentration; this increase rate described the elements (zinc, copper and iron) resistant to corrosion. But when comparing to the cost and availability of the zinc and copper (Table 2.2; the more density of a metal, the more expensive it becomes), it was observed that zinc is better metal to be used in the cathodic protection (coating) than copper in terms of cost and availability. When using zinc in the cathodic protection of mains intake water works, it is important to make the zinc anode in the electrolysis, this is because of the position of zinc in the electrochemical series which makes the zinc layers to break gradually (readily forms ions) and fill the pinhole caused by pitting corrosion. And this cathodic protection will foster the durability and elongate the lifespan of the intake structural members.

i. Furthermore, corrosion increases the iron concentration of the water and this changes the colour and taste of the water which is objectionable and must be removed, it needs treatment, this increases the cost of water treatment at the intake water works. But cathodic protection as a method of corrosion inhibition can reduce this colour and taste change or possibly stop it totally. However, in this work, the metal used as anode was iron

while the cathode was the corroded iron bar, this was because of the iron ions contained in the corrosive water sample which reacted with the chlorine gas produced from the reaction of the diluted hydrochloric acid (HCl) with dissolved oxygen (O_2) to form Ferric chloride ($Fecl_2$), this Ferric chloride acts as coagulant agent for both softening and chlorinification of the water sample. This makes the water sample clearer than it was before electrolysis. Also iron electrons flows from the anode to cathode (See Subsection 4.1.9, Overall reaction Equation), this flow of electron causes increase in the weight of the corroded iron thereby cathodically protecting (coating) the rusted iron bar. When corrosion of water intake structural members are inhibited either by cathodic/anodic protection or by any other methods such as selection and use of more corrosion resistant materials, special design of materials for particular intake water works, passivation of the metal surface etc., definitely, the durability and elongation of the intake structures' lifespan will be enhanced. Thus, the cost of water treatment at the intake water works will be drastically reduced provided that the quality of the water at the intake were improved and preserved as a result of corrosion inhibition.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

From the analysis of the results done in Chapter Four and observations of the water quality test results variations with regard to corrosion, the following conclusions were made:

ii. Total dissolved solid (TDS) is the major mineral constituent used to determine the quality of water because other mineral constituents such as; chlorides/sulphates salts, dissolved oxygen, iron, zinc, copper and aluminium concentrations add to the total dissolved solid (TDS) of water sample.

iii. And TDS increases the conductivity of the water, thus, increase in TDS lead to increase in the rate of corrosion (rust) on surface water intake members, this shows a linear relationship between water quality and corrosion.

iv. The tests of other water quality parameters such pH values and alkalinity showed an inverse relationship between water quality and corrosion, that is, increase in their values (pH values and Alkalinity) lead to decrease in corrosion and vice versa.

v. The mathematical modeling of water quality in terms of TDS in mg/l and corrosion in terms of iron concentration in mg/l gave a simple linear regression equation (Equation 4.7), this showed that when the total dissolved solid (TDS), x of the water sample is known, the iron concentration, y of the water sample can be determined. Thus, it can be deduced that increase in the total dissolved solid (TDS) affect the water quality negatively. This is applicable to any water sample.

vi. the results showed that corrosion increases the hardness of the water samples.

vii. Zinc is better and cheaper metal to be used in cathodic protection (coating) of the intake structures.

5.2 RECOMMENDATIONS

Based on the results of this study, the following recommendations were made:

i. The corrosiveness of the intake environment should be reduced by lowering the temperature, acidity, chloride concentration and oxidizer concentration.

ii. Stagnation of water at the intake water works should be avoided by increasing the water flow rate and draining of the intake structures when they are not in use. Flow rate increase can be made by channel improvement and dredging.

iii. The more corrosive resistant materials should be selected for the intake water work members, material like stainless steel 316 or 317 especially when the intake structural member are expected to be exposed to chloride.

iv. The use of protective coating paint such as zinc-rich paint should also be considered.

v. Pure iron (non-corroded iron) can be used in cathodic/anodic protection of intake structural members because of its cost efficiency and availability when compared with other metals. This also produced Ferric chloride that act as coagulant agent for both clearification and chlorinification of the corroded water sample.

5.3 CONTRIBUTIONS TO KNOWLEDGE

The study has shown that when the intake works member in the Cross River State water board are connected in series making them the cathode with the introduction of sacrificial anode, a simple electrolytic cell will be set up, and when the circuit is close, this will enable the cathode to gain weight in the process thereby becoming cathodically protected.

The study also has shown that the water quality at the intake point becomes purer, colourless, and free from iron concentration as they are being deposited at the cathode making the quality of water better at the intake point.

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APPENDICES

APPENDIX A

Table A1: Relationship of pH values To Corrosion and Incrustation for Selecting Piping Materials.

Materials	Target pH for Corrosion Control.	Comments
Steel/Cast Iron	7.5 – 9.0	Within this pH range, there is tendency for corrosion products to adhere in a hard, crusty deposit. At lower pH values, “red water” complaints are more common.
Copper	>7.0	In most waters, the critical pH value is about 7.0. For soft waters containing organic acids, the targeted pH value may be higher.
Lead	>7.0	Water are aggressive to lead if the pH is above 7.0.
Zinc	<10.5	Water with pH value above approximately 10.5 can be aggressive to zinc and will often remove galvanized coating.

Source: Health Canada, 2016a.

Table A2: Suitable Corrosion Resistant Materials and their uses.

Materials	Uses
Polyethylene, fiberglass, Epoxy or vinylester lined steel.	Storage tanks, feed systems and piping.
PVC, CPVC kynar, 316 stainless, Viton or hypalon.	For pumping liquid ends and piping.

Source: Health Canada, 2016b.

Table A3: TDS and Iron Conc. Values used for verification of the Modelled Equation (Correlation check)

TDS (mg/l.)	IRON CONC. (mg/l.)
21.9	3.46
24.8	3.97
28.5	4.56
32.7	5.05
35.8	5.61
40.2	5.9
42.8	6.2

Source: Secondary data from Cross River State Water Board Authority, Calabar.

APPENDIX B

Total Hardness Calculations.

a. Control Sample.

Initial reading = 23.4ml

Final reading = 20.5ml

Volume of sample = 50ml

$$Titre = 23.4 - 20.5 = 2.9$$

$$Total\ Hardness = \frac{Titre \times 1000}{Volume\ of\ sample}$$

(Equation 3.1, p.g 52)

$$Total\ Hardness = \frac{2.9 \times 1000}{50} = 58mg/l$$

b. 7days Immersion Sample.

Initial reading =33.2ml

Final reading = 20.4ml

Volume of sample = 50ml

$$Titre = 33.2 - 20.4 = 12.8$$

$$Total\ Hardness = \frac{12.8 \times 1000}{50} = 256mg/l$$

c. 14days Immersion Sample.

Initial reading = 34.6ml

Final reading = 20.2ml

Volume of sample = 50ml

$$Titre = 34.6 - 20.2 = 14.4$$

$$Total\ Hardness = \frac{14.4 \times 1000}{50} = 288mg/l$$

d. 21days Immersion Sample.

Initial reading = 35.5ml

Final reading = 19.6ml

Volume of sample = 50ml

$Titre = 35.5 - 19.6 = 15.9$

$$Total\ Hardness = \frac{15.9 \times 1000}{50} = 318mg/l$$

e. 28days Immersion Sample.

Initial reading = 36.5ml

Final reading = 19.4ml

Volume of sample = 50ml

$Titre = 36.5 - 19.4 = 17.1$

$$Total\ Hardness = \frac{17.1 \times 1000}{50} = 342mg/l$$

f. 35days Immersion Sample.

Initial reading = 39.1ml

Final reading = 19.8ml

Volume of sample = 50ml

$Titre = 39.1 - 19.8 = 19.3$

$$Total\ Hardness = \frac{19.3 \times 1000}{50} = 386mg/l$$

g. 42days Immersion Sample.

Initial reading = 40.7ml

Final reading = 19.9ml

Volume of sample = 50ml

$Titre = 40.7 - 19.9 = 20.80$

$$Total\ Hardness = \frac{20.8 \times 1000}{50} = 416mg/l$$

h. 49days Immersion Sample.

Initial reading = 43.9ml

Final reading = 20.5ml

Volume of sample = 50ml

$Titre = 43.9 - 20.5 = 23.4$

$$Total\ Hardness = \frac{23.4 \times 1000}{50} = 468mg/l$$

Calcium Hardness Calculations.

a. Control Sample.

Initial reading = 20.7ml

Final reading = 17.9ml

Volume of sample = 50ml

$$Titre = 20.7 - 17.9 = 2.8$$

$$Calcium\ Hardness = \frac{Titre \times 1000}{Volume\ of\ sample}$$

(Equation 3.2)

$$Calcium\ Hardness = \frac{2.8 \times 1000}{50} = 56mg/l$$

b. 7days Immersion Sample.

Initial reading =24.1ml

Final reading = 17.3ml

Volume of sample = 50ml

$$Titre = 24.1 - 17.3 = 6.8$$

$$Calcium\ Hardness = \frac{6.8 \times 1000}{50} = 136mg/l$$

c. 14days Immersion Sample.

Initial reading = 24.75ml

Final reading =17.5ml

Volume of sample = 50ml

$$Titre = 24.75 - 17.5 = 7.25$$

$$Calcium\ Hardness = \frac{7.25 \times 1000}{50} = 145mg/l$$

d. 21days Immersion Sample.

Initial reading = 25.3ml

Final reading = 17.2ml

Volume of sample = 50ml

$Titre = 25.3 - 17.2 = 8.1$

$$Calcium\ Hardness = \frac{8.1 \times 1000}{50} = 162mg/l$$

e. 28days Immersion Sample.

Initial reading = 26.4ml

Final reading = 17.6ml

Volume of sample = 50ml

$Titre = 26.4 - 17.6 = 8.8$

$$Calcium\ Hardness = \frac{8.8 \times 1000}{50} = 176mg/l$$

f. 35days Immersion Sample.

Initial reading = 27.6ml

Final reading = 17.2ml

Volume of sample = 50ml

$Titre = 27.6 - 17.2 = 10.4$

$$Calcium\ Hardness = \frac{10.4 \times 1000}{50} = 208mg/l$$

g. 42days Immersion Sample.

Initial reading = 28.3ml

Final reading = 17.1ml

Volume of sample = 50ml

$Titre = 28.3 - 17.1 = 11.2$

$$Calcium\ Hardness = \frac{11.2 \times 1000}{50} = 224mg/l$$

h. 49days Immersion Sample.

Initial reading = 28.9ml

Final reading = 16.8ml

Volume of sample = 50ml

$Titre = 28.9 - 16.8 = 12.1$

$$Calcium\ Hardness = \frac{12.1 \times 1000}{50} = 242mg/l$$

Magnesium Hardness Calculations.

$$Magnesium = Total\ hardness - Calcium\ hardness$$

(Equation 3.3)

a. Control Sample

Magnesium hardness = 58 – 56 = 2mg/l

7days Immersion Sample.

Magnesium hardness = 256 – 136 = 120mg/l

b. 14days Immersion Sample

Magnesium hardness = 288 – 145 = 143mg/l

c. 21days Immersion Sample

Magnesium hardness = 318 – 162 = 156mg/l

d. 28days Immersion Sample

Magnesium hardness = 342 – 176 = 166mg/l

e. 35days Immersion Sample

Magnesium hardness = 386 – 208 = 178mg/l

f. 42days Immersion Sample

Magnesium hardness = 416 – 224 = 192mg/l

h. 49days Immersion Sample

Magnesium hardness = 468 – 242 = 226mg/l

APPENDIX D

Total Alkalinity Calculations

a. Control Sample.

$$Total\ Alkalinity = \frac{Titre \times 0.1 \times 1000}{Volume\ of\ sample}$$

(Equation 3.4)

Initial reading = 37.2ml

Final reading = 31.8ml

Volume of sample = 50ml

$$Titre = 37.2 - 31.8 = 5.4$$

$$Total\ Alkalinity = \frac{5.4 \times 0.1 \times 1000}{50} = 10.8mg/l$$

b. 7days Immersion Sample.

Initial reading =36.3ml

Final reading = 31.2ml

Volume of sample = 50ml

$$Titre = 36.3 - 31.2 = 5.1$$

$$Total\ Alkalinity = \frac{5.1 \times 0.1 \times 1000}{50} = 10.2mg/l$$

c. 14days Immersion Sample.

Initial reading =35.7ml

Final reading = 30.9ml

Volume of sample = 50ml

$$Titre = 35.7 - 30.9 = 4.8$$

$$Total\ Alkalinity = \frac{4.8 \times 0.1 \times 1000}{50} = 9.6mg/l$$

d. 21days Immersion Sample.

Initial reading =36.9ml

Final reading = 32.4ml

Volume of sample = 50ml

$$Titre = 36.9 - 32.4 = 4.5$$

$$Total\ Alkalinity = \frac{4.5 \times 0.1 \times 1000}{50} = 9.0mg/l$$

e. 28days Immersion Sample.

Initial reading =36.4ml

Final reading = 32.5ml

Volume of sample = 50ml

$$Titre = 36.4 - 32.5 = 3.9$$

$$Total\ Alkalinity = \frac{3.9 \times 0.1 \times 1000}{50} = 7.8mg/l$$

f. 35days Immersion Sample.

Initial reading =35.8ml

Final reading = 32.3ml

Volume of sample = 50ml

$$Titre = 35.8 - 32.3 = 3.5$$

$$Total\ Alkalinity = \frac{3.5 \times 0.1 \times 1000}{50} = 7.0mg/l$$

g. 42days Immersion Sample.

Initial reading =35.3ml

Final reading = 32.2ml

Volume of sample = 50ml

$$Titre = 35.3 - 32.2 = 3.1$$

$$Total\ Alkalinity = \frac{3.1 \times 0.1 \times 1000}{50} = 6.2mg/l$$

h. 49days Immersion Sample.

Initial reading =34.2ml

Final reading = 31.5ml

Volume of sample = 50ml

$$Titre = 34.2 - 31.5 = 2.7$$

$$Total\ Alkalinity = \frac{2.7 \times 0.1 \times 1000}{50} = 5.4mg/l$$

Acidity Calculations.

a. Control Sample.

$$Acidity = \frac{Titre \times 0.2 \times 1000}{Volume\ of\ sample}$$

(Equation 3.5, pg 53)

Initial reading =20.53ml

Final reading = 20.50ml

Volume of sample = 50ml

$$Titre = 20.53 - 20.50 = 0.03$$

$$Acidity = \frac{0.03 \times 0.2 \times 1000}{50} = 0.12mg/l$$

b. 7days Immersion Sample.

Initial reading =20.45ml

Final reading = 20.40ml

Volume of sample = 50ml

$$Titre = 20.45 - 20.40 = 0.05$$

$$Acidity = \frac{0.05 \times 0.2 \times 1000}{50} = 0.20mg/l$$

c. 14days Immersion Sample.

Initial reading =20.40ml

Final reading = 20.30ml

Volume of sample = 50ml

$$Titre = 20.40 - 20.30 = 0.10$$

$$Acidity = \frac{0.10 \times 0.2 \times 1000}{50} = 0.40mg/l$$

d. 21days Immersion Sample.

Initial reading =20.55ml

Final reading = 20.40ml

Volume of sample = 50ml

$Titre = 20.55 - 20.40 = 0.15$

$Acidity = \frac{0.15 \times 0.2 \times 1000}{50} = 0.60 mg/l$

e. 28days Immersion Sample.

Initial reading =20.60ml

Final reading = 20.40ml

Volume of sample = 50ml

$Titre = 20.60 - 20.40 = 0.20$ $Acidity =$

$\frac{0.20 \times 0.2 \times 1000}{50} = 0.80 mg/l$

f. 35days Immersion Sample.

Initial reading =20.60ml

Final reading = 20.30ml

Volume of sample = 50ml

$Titre = 20.60 - 20.30 = 0.30$

$Acidity = \frac{0.30 \times 0.2 \times 1000}{50} = 1.20 mg/l$

g. 42days Immersion Sample.

Initial reading =20.70ml

Final reading = 20.30ml

Volume of sample = 50ml

$Titre = 20.70 - 20.30 = 0.40$

$Acidity = \frac{0.40 \times 0.2 \times 1000}{50} = 1.60 mg/l$

h. 49days Immersion Sample.

Initial reading =20.30ml

Final reading = 19.80ml

Volume of sample = 50ml

$Titre = 20.30 - 19.80 = 0.50$

$Acidity = \frac{0.50 \times 0.2 \times 1000}{50} = 2.00 mg/l$

APPENDIX E

Corrosion Rate Calculations

$$corrosion\ rate\ (mm/yr.) = 87.6 \times [W/(D * A * T)]$$

(Equation 3.4, pg 54)

Where:

W = weight loss in milligrams

D = Density of the metal in g/cm^3

A = Area of the metal sample in cm^2

T = Time of exposure of the metal sample in hours.

87.6 = Conversion factor.

Corrosion Rate expressed in millimeter per year (mm/yr.).

Trial 1:

W_1= Initial weight of the Iron bar before corrosion = 300g = 300000mg

W_2= Final weight of the Iron bar after 7 days of immersion = 298g = 298000mg

W = Weight loss = $W_1 - W_2$ =300000 – 298000 = 2000mg

D = Density of the Iron bar = $7.87 g/cm^3$ (Table 2.2, pg 45)

A = Total initial surface area of the Iron bar = $A = \pi r^2$

Where r = $\frac{Diameter\ d}{2} = \frac{32mm}{2} = 16mm = 0.16cm$, $\prod = 3.142$

Thus, A = 3.142 x $(0.16cm)^2$ = $0.08cm^2$

T = Reference time in hours = 7 days = 7 x 24 = 168 hours.

Corrosion rate (mm/y) = $87.6 \times \left(\frac{2000}{(7.87 \times 0.08 \times 168)}\right) = 1656.38 mm/yr.$

Trial 2:

W_1= Initial weight of the Iron bar at end of 7 days corrosion = 298g = 298000mg

W_2= Final weight of the Iron bar after 14 days of immersion = 295.8g = 295800mg

W = Weight loss = $W_1 - W_2$ =298000 – 295800 = 2200mg

D = Density of the Iron bar = 7.87g/cm^3 (Table 2.2, pg 45)

A = Total initial surface area of the Iron bar = $A = \pi r^2$

Where r = $\frac{Diameter\ d}{2} = \frac{32mm}{2} = 16mm = 0.16cm$, $\Pi = 3.142$

Thus, A = 3.142 x (0.16cm) ^{2}= 0.08cm^2

T = Reference time in hours = 14 - 7 days = 7 x 24 = 168 hours.

Corrosion rate (mm/y) = $87.6 \times \left(\frac{2200}{(7.87 \times 0.08 \times 168)}\right) = 1822.02 mm/yr.$

Trial 3:

W_1= Initial weight of the Iron bar at end of 14 days corrosion = 295.8g = 295800mg

W_2= Final weight of the Iron bar after 21 days of immersion = 293.35g = 293350mg

W = Weight loss = $W_1 - W_2$ =295800 - 293350 = 2450mg

D = Density of the Iron bar = 7.87g/cm^3 (Table 2.2,)

A = Total initial surface area of the Iron bar = $A = \pi r^2$

Where r = $\frac{Diameter\ d}{2} = \frac{32mm}{2} = 16mm = 0.16cm$, $\Pi = 3.142$

Thus, A = 3.142 x $(0.16cm)^2$ = 0.08cm^2

T = Reference time in hours = 21 - 14 days = 7 x 24 = 168 hours.

Corrosion rate (mm/y) = $87.6 \times \left(\frac{2450}{(7.87 \times 0.08 \times 168)}\right) = 2029.07 mm/yr.$

Trial 4:

W_1= Initial weight of the Iron bar at end of 21 days corrosion = 293.35g = 293350mg

W_2= Final weight of the Iron bar after 28 days of immersion = 290.65g = 290650mg

W = Weight loss = $W_1 - W_2$ = 293350 - 290650 = 2700mg

D = Density of the Iron bar = 7.87g/cm^3 (Table 2.2, pg 45)

A = Total initial surface area of the Iron bar = $A = \pi r^2$

Where r = $\frac{Diameter\ d}{2} = \frac{32mm}{2} = 16mm = 0.16cm$, $\prod = 3.142$

Thus, A = 3.142 x (0.16cm)^2 = 0.08cm^2

T = Reference time in hours = 28 - 21 days = 7 x 24 = 168 hours.

Corrosion rate (mm/y) = $87.6 \times \left(\frac{2700}{(7.87 \times 0.08 \times 168)}\right) = 2236.11 mm/yr.$

Trial 5:

W_1= Initial weight of the Iron bar at end of 28 days corrosion = 290.65g = 290650mg

W_2= Final weight of the Iron bar after 35 days of immersion = 287.7g = 287700mg

W = Weight loss = $W_1 - W_2$ = 290650 -287700mg = 2950mg

D = Density of the Iron bar = 7.87g/cm^3 (Table 2.2)

A = Total initial surface area of the Iron bar = $A = \pi r^2$

Where r = $\frac{Diameter\ d}{2} = \frac{32mm}{2} = 16mm = 0.16cm$, $\prod = 3.142$

Thus, A = 3.142 x (0.16cm)^2 = 0.08cm^2

T = Reference time in hours = 35 - 28 days = 7 x 24 = 168 hours.

Corrosion rate (mm/y) = $87.6 \times \left(\frac{2950}{(7.87 \times 0.08 \times 168)}\right) = 2443.16 mm/yr.$

Trial 6:

W_1= Initial weight of the Iron bar at end of 35 days corrosion = 287.7g = 287700mg

W_2= Final weight of the Iron bar after 42 days of immersion = 284.45g= 284450mg

W = Weight loss = $W_1 - W_2$ = 287700mg - 284450mg = 3250mg

D = Density of the Iron bar = 7.87g/cm^3 (Table 2.2)

A = Total initial surface area of the Iron bar = $A = \pi r^2$

Where r = $\frac{Diameter\ d}{2} = \frac{32mm}{2} = 16mm = 0.16cm$, $\prod = 3.142$

Thus, A = 3.142 x (0.16cm)^2 = 0.08cm^2

T = Reference time in hours = 42 - 35 days = 7 x 24 = 168 hours.

Corrosion rate (mm/y) = 87.6 × $\left(\frac{3250}{(7.87\times0.08\times168)}\right) = 2691.62 mm/yr.$

Trial 7:

W_1= Initial weight of the Iron bar at end of 42 days corrosion = 284.45g = 284450mg

W_2= Final weight of the Iron bar after 49 days of immersion = 280.925g= 280925mg

W = Weight loss = $W_1 – W_2$ = 284450mg - 280925mg = 3525mg

D = Density of the Iron bar = 7.87g/cm^3 (Table 2.2, pg 45)

A = Total initial surface area of the Iron bar = $A = \pi r^2$

Where r = $\frac{Diameter\ d}{2} = \frac{32mm}{2}$ = $16mm = 0.16cm$, $\Pi = 3.142$

Thus, A = 3.142 x $(0.16cm)^2$ = 0.08cm^2

T = Reference time in hours = 49 - 42 days = 7 x 24 = 168 hours.

Corrosion rate (mm/y) = 87.6 × $\left(\frac{3525}{(7.87\times0.08\times168)}\right) = 2919.37 mm/yr.$