EFFECT OF PARAMAGNETISM ON THE CORROSION ABATEMENT OF MILD STEEL

BY

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CERTIFICATION

This is to certify that the investigative research was carried out by UZOSIKE, CHIOMA EMMANUELLA (20094735698), in the department of Materials and Metallurgical Engineering. It satisfies in part, the requirements for the award of M. Eng. degree of the Federal University of Technology, Owerri.

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DEDICATION

This work is dedicated to my dear husband, Mr Moses Ahamba Njoku.

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ABSTRACT

The corrosion rates of magnetized mild steel coupons in HCl solutions were studied using the weight loss method. The coupons were magnetized with a laboratory electromagnet at 0.38T, 0.57T, 0.76T, 0.95T and 1.51T and immersed in HCl solutions of pH ranging from 2 to 6. Experimental results showed that coupons magnetized at 0.76T, 0.57T and 0.38T exhibited higher corrosion rates than their non-magnetized counterparts at pH values less than 5. At pH 5 and above however, they showed lower corrosion rates than the non-magnetized coupons. Coupons magnetized at 0.95T and 1.51T however, reduced the corrosion rate below those of the non-magnetized coupons for the entire pH range from 2 to 6 studied. Inhibition efficiency reached 87% and 96% for pH 5 and pH 6 respectively for the magnetized coupons, and, 80% and 94% at 0.95T and 1.51T respectively. Results were explained on the basis of the formation of paramagnetic Fe^{2+} and Fe^{3+} and the subsequent $FeCl_2$ and $FeCl_3$ species that adhered to the coupons as they become available in the system. This corrosion abatement technique using magnetized coupons to generate paramagnetic species in the electrolyte could be relevant in the oil industry. This could be specifically applicable to some crude oil and natural gas transporting pipelines that have CO_2, H_2S and microbes that generate corrosive acid media that will in turn produce paramagnetic species like $FeCO_3$, $FeSO_4$ and FeS.

Keywords: magnetized, mild steel, weight loss, laboratory electromagnet, pH, paramagnetic species.

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND INFORMATION

The present study is on metallic corrosion which had been defined as an attack on a metallic material by the reaction with its environment (Bardal, 2004). This attack is destructive and the reaction can either be chemical or electrochemical thus reversing the metal to its original or combined state.

Metals are extracted from their ores in which they occur in combined stable states as oxides, carbonates, sulphides, halides, silicates, sulphates. When they are exposed to the environment, they interact with it and inevitably and spontaneously revert back to their original states. This phenomenon is known as corrosion.

Corrosion has been implicated in the collapse of bridges with numerous fatalities (Chris, 2001). It is one of the causes of rupture of pipelines carrying crude oil and gases. This type of corrosion causes fatalities and extensive damage to the environment and requires huge financial outlays to clean up the environment, repair and replace damaged or destroyed equipment, and also pay compensations to affected communities. Jessica reported that in the year 2011, BP pipeline ruptures spewed 30,000 barrels per day of oil in Alaska, also that 5million barrel of oil were spewed into the Gulf of Mexico and these losses were all due to corrosion. Airplanes are not left out to the corrosion phenomenon, what might appear to be innocuous stains surface that were indeed tell-tale signs of pitting corrosion, had led to catastrophic plane crashes (Osaremen, 2012). The woes of corrosion are inexhaustible and span the entire spectrum of structures, machines and components. The cost of fighting corrosion is huge. The common findings of various cost of corrosion studies showed that the annual corrosion costs ranged from approximately 1 to 5 percent of the Gross National Product (GNP) of each nation. A closer examination of the National Association of Corrosion Engineers, NACE, and data indicates that corrosion costs in the U.S. now exceed $1 trillion dollars (NACE, 2011). Other studies done in China, Japan, the U.K, and Venezuela showed similar to even more costly results, leading to an estimated worldwide direct cost exceeding $1.8 trillion (Schmitt et al, 2009).

In response to the challenge, researches have been mounted to find solution and the science and engineering of corrosion has markedly progressed.

Magnetism application to corrosion mitigation is an area that may hold a good prospect of success in the battle against corrosion. The effect of magnetic field on corrosion rate has been studied and the obtained results were ambiguous (Chiba et al 1994, Chiba &Ogawa 1988(a), Chiba et al 1988b). On one hand, it was demonstrated that the corrosion rate of iron and copper in HNO_3 were distinctly reduced under constant magnetic field, and on the contrary, Kelly

(1977) established that magnetic field produced an adverse effect on the corrosion behaviour of Ti in 1N H_2SO_4 over the available range of magnetic flux density (0-2.1Tesla). Results from experiments done by Waskaas (1996) using combination of electrode materials (iron, nickel, platinum, zinc and copper) and electrolytes [iron (II) chloride, iron (II) sulphate, iron (II) oxide, copper (II) chloride], showed no effect of 600mT magnetic field. On the other hand, Yee and Bradford (1992) stated that 'it is still uncertain whether enhancement, retardation or both are the results of magnetic electrochemical interactions'. Nevertheless, the mechanism of the effect of magnetic field on the rate of corrosion processes remains to be fully understood (Pietrzak &Szatanik, 2010).

In this work, paramagnetism will be applied to corrosion mitigation.

1.2 PROBLEM STATEMENT

Great success has been achieved in protecting the exteriors of metallic facilities that contain or transport corrosive fluids. Coatings and additional barriers like polythene tapes, wrappings, concreting, etc., with further cathodic protection systems have been applied to the exteriors of such facilities to isolate them from contact with the environment. Their exteriors however, that are in contact with corrosive fluids like acids, or acid-forming species, for instance, are not similarly protected obviously because of collateral contamination of the fluids. Where these facilities are made of ferrous materials like carbon steel pipes that are extensively used for transporting crude oil and natural gas, corrosion protection has been limited largely to the use of corrosion inhibitors. This procedure has not been very effective in cases where acid-forming species like H_2S, CO_2 and microbes are integral with the fluids. An improvement in the existing corrosion mitigation by purposeful introduction of corrosion inhibitors into such acid-forming systems will be worthwhile, a novel.

In this work, the products of the reaction of acids with iron that are paramagnetic in nature will be induced to act as corrosion inhibitors by application of a magnetic field.

1.3 OBJECTIVE

The objective of this study is to determine the effect of paramagnetism on the corrosion abatement of mild steel:

1. To expose mild steel coupons magnetized at various magnetic field strengths to hydrochloric acid solutions of various pH values and thence determine the corrosion rates.
2. To establish the effect of magnetic field strength on the corrosion rate of the coupons.
3. To establish the effect of paramagnetism on the corrosion rates of mild steel coupons.

4. To establish the influence of pH on the corrosion rates of mild steel at various strengths of magnetization of the coupons.

1.4 JUSTIFICATION OF STUDY

The importance of this study lies on the fact that since corrosion must occur in metals and alloys because they want to revert back to their stable states, there must be controls/checks to be put in order to reduce the losses and costs incurred to the barest minimum. This idea of magnetizing the metal and creating a corrosion-inhibiting paramagnetic field was borne. The metallic pipes used in transporting acids, or those laid in seawater (containing much chloride ions) can be magnetized and corrosion inhibited. Also in oil reservoirs/gas wells where paramagnetic $FeSO_4$ and $FeCO_3$ are sometimes formed due to the presence of H_2S and CO_2, this study can be applied in the abatement of corrosion of mild steel pipelines.

1.5 SCOPE OF STUDY

This study/research is limited to mild steel and the corroding medium is that of an acid. The chemical analysis of the metal will be established and the electrolytes prepared with varying pH solutions will be used. The coupons will be magnetized at different magnetic field strengths and others kept non-magnetized. The corrosion rates will be plotted and compared, also from the latter; inhibition efficiencies will be calculated. The results will be related to the paramagnetic field effect on corrosion.

CHAPTER TWO

LITERATURE REVIEW

This project is based on the effect of the formation of paramagnetic compounds (Iron (II) chloride ($FeCl_2$) or Iron (III) chloride ($FeCl_3$)), in the abatement of corrosion of mild steel in HCl solutions.

2.1.1 PROPERTIES OF IRON (II) CHLORIDE

Iron (II) chloride, equally known as ferrous chloride, is a chemical compound of formula $FeCl_2$. It can exist in different forms such as; anhydrous, dihydrate, and tetrahydrate forms. The properties can be summarized in Table 2.1

Table 2.1 Typical properties for $FeCl_2$ (Wikipedia, 2011a)

PROPERTY	VALUE
Molar Mass	126.751g/mol (anhydrous) 198.8102g/mol (tetrahydrate)
Appearance	Tan solid (anhydrous) Pale green solid (di-tetrahydrate)
Density	3.16g/cm^3 (anhydrous) 2.30g/cm^3 (dihydrate) 1.39g/cm^3 (tetrahydrate)
Melting point	677 ^{o}C (anhydrous) 120 ^{o}C (dihydrate) 105 ^{o}C (tetrahydrate)
Boiling point	1023^{o}C (anhydrous)
Solubility in water	64.4g/100mL (10 ^{o}C) 68.5g/100mL (20 ^{o}C) 105.7g/100mL (100 ^{o}C)

2.1.2 PRODUCTION

Hydrated forms of $FeCl_2$ are obtained from the treatment of iron scraps with hydrochloric acid:

$$+2 \rightarrow + \qquad (2.1)$$

In the laboratory, $FeCl_2$ can also be prepared by the addition of iron powder to a solution of methanol and concentrated hydrochloric acid under an inert atmosphere. The reaction produces methanol solvate which when heated in a vacuum at about 160 ^{o}C gives anhydrous $FeCl_2$ (Wikipedia, 2011a).

Anhydrous Iron (II) chloride, $FeCl_2$, can also be prepared by passing a stream of dry hydrogen chloride over a heated iron coil, see equation (2.1) (Ababio, 1992).The ferrous chloride formed is a white deliquescent solid. When the iron coil is dissolved in dilute hydrochloric acid in an inert environment, a pale green solution is obtained from which the tetrahydrate, $FeCl_2.4H_2O$ crystallizes out.
The free energy of formation (ΔG) of $FeCl_f$ $_2$ at 298.15K is -37.18kcal/mol/K, and heat of formation (ΔH) at 298.15K_f is -33.70kcal/mol

2.1.3 APPLICATIONS

Ferrous chloride serves as a reducing flocculating agent in wastewater treatment. It is the precursor to hydrated iron (III) oxides that are magnetic pigments. Ferrous chloride acts as a reducing agent in many organic synthesis reactions.

2.2.1 PROPERTIES OF IRON (III) CHLORIDE

Iron (III) chloride or ferric chloride with the formula $FeCl_3$ can appear as dark green or purple red in colour, depending on the viewing angle.

Table 2.2 Typical properties for $FeCl_3$ (Wikipedia, 2011b)

PROPERTY	VALUE
Molar Mass	162.2g/mol (anhydrous) 270.3g/mol (hexahydrate)
Appearance	green-black by reflected light; purple-red by transmitted light hexahydrate: yellow solid aq. solutions: brown
Density	2.898 g/cm^3 (anhydrous)
Melting point	306°C(anhydrous) 37 °C (hexahydrate)
Boiling point	315 °C (anhydrous, decomp) 280 °C (hexahydrate, decomp) (partial decomposition to $FeCl_2 + Cl_2$)
Solubility in water	74.4 g/100 mL (0 °C) 92 g/100 mL (hexahydrate, 20 °C)

2.2.2 PRODUCTION

Anhydrous $FeCl_3$ is deliquescent and forms hydrated hydrogen chloride mists in moist air. When dissolved in water, it undergoes hydrolysis and gives off heat exothermically (Wikipedia, 2011b). Anhydrous Iron (III) chloride can be produced by heating an iron coil in a stream of dry chlorine gas.

Solutions of Iron (III) chloride are produced industrially both from iron and from ore, in a closed-loop process.

- Dissolving iron ore in hydrochloric acid

$$Fe_3O_4(s) + 8\ HCl(aq) \rightarrow FeCl_2(aq) + 2\ FeCl_3(aq) + 4\ H_2O \qquad (2.2)$$

- Upgrading the iron (II) chloride with chlorine

$$2\ FeCl_2(aq) + Cl_2(g) \rightarrow 2\ FeCl_3(aq) \qquad (2.3)$$

The free energy of formation (ΔG_f) of $FeCl_3$ at 298.15K is -59.24kcal/mol/K, and heat of formation (ΔH_f) at 298.15K is -60.50kcal/mol

2.2.3 APPLICATIONS

Industrially, Iron (III) chloride is used in sewage treatment and the production of drinking water. Also used as a leaching agent in chloride hydrometallurgy, but most importantly, the compound is used in the etching of copper to copper (I) chloride and then copper (II) chloride, used for producing printed circuits.

2.3 ADSORPTION

Adsorption is the adhesion of atoms, ions, or molecules from a gas, liquid, or dissolved solid to the surface (Brownfields, 2009). A film of the adsorbate (the material being adsorbed) is created on the surface of the adsorbent (the solid material being used as the adsorbing phase). In principle, adsorption can occur at any solid-fluid interface, which include; gas-solid interface or liquid-solid interface (Piero, 1999).

Adsorption is different from absorption in that in the latter, a fluid (the absorbate) dissolves in or permeates the liquid or solid (the absorbent). The process of adsorption is a surface-based process while absorption involves the whole volume of the material (Wikipedia, 2012a). The term ‘sorption’ is a general expression that encompasses both processes. Desorption is the reverse of adsorption.

Adsorption is present in many natural physical, biological and chemical systems, and adsorption operations employing solids such as activated carbon and synthetic resins are used widely in industrial applications and for purification of waters and wastewaters (Suzuki, 1990). Some common adsorbents used include activated carbon, silica gel, activated alumina, aluminosilicates (e.g. zeolites) etc. The reduction in interfacial tension between the fluid and the solid adsorbent due to the adsorption of the adsorbate on the surface of the solid is the driving force for adsorption. The surface atoms or molecules of the adsorbent are relatively unstable due to positive surface free energy. In the bulk, the molecules at the surface are not symmetrically surrounded by other molecules, hence they have tendency to attract adsorbate molecules and retain them to minimise the surface energy (Adichemistry, 2011).

Adsorption is an exothermic process as heat is liberated when new bonds are formed. Adsorption processes occur more at low temperatures.

Depending on the type of attractions between the adsorbate and adsorbent, the adsorption can be divided into two types: physisorption and chemisorption.

Physical adsorption or physisorption is caused by van der Waals forces and electrostatic forces between adsorbate molecules and the atoms which compose the adsorbent surface (Slejko, 1985). It is an exothermic reversible process with low enthalpy values due to weak van der Waals forces of attraction. Physical adsorption occurs readily at lower temperatures and the extent of adsorption increases with increase in pressure. Due to the universality of the van der Waals in physisorption, a given surface of an adsorbent does not show any preference for an adsorbate. The extent of adsorption depends on the nature of gas (adsorbate). Generally, easily liquefiable gases with higher critical temperatures are readily adsorbed as the van der Waals forces are stronger especially near the critical temperatures.

Chemical adsorption or chemisorption is a kind of adsorption which involves a chemical reaction between the surface and the adsorbate (Wikipedia, 2012b). Examples include obvious macroscopic phenomena like corrosion, and subtler effects associated with heterogeneous catalysis. The strong interaction between the adsorbate and the substrate surface creates new types of electronic bonds (Oura et al, 2003). Chemisorption follows the adsorption process. Initially, the adsorbate molecule comes into contact with the surface, and the particle will be trapped onto the surface by not possessing sufficient energy to leave the gas-surface potential well. If the collision with the surface is elastic, the particle would return to the bulk gas, but when it loses enough momentum through an inelastic collision, and then it adheres onto the surface forming a precursor state bonded to the surface by weak forces similar to physisorption. The particle diffuses on the surface until it finds a deep chemisorption potential well, then it reacts with the surface or simply desorbs after enough energy and time (Rettner & Auerbach, 1996).The chemical nature of the adsorptive(s) may be altered by surface dissociation or reaction in such a way that on desorption the original species cannot be recovered; meaning that chemisorption may not be reversible (IUPAC, 2002). The elementary step in chemisorption always involves activation energy. The energy of chemisorption is of the same order of magnitude as that of change in a chemical reaction between a solid and a fluid, thus chemisorption may be exothermic or endothermic and the magnitudes of the energy changes may vary from very small to very large. Chemisorption is highly specific and occurs only if there is some possibility of chemical bonding between adsorbent and adsorbate (Adichemistry, 2011).

So many factors affect adsorption and they include these: surface area of adsorbent, particle size of adsorbent, contact time or residence time, solubility of adsorbate in liquid, affinity of the adsorbate for the adsorbent, number of carbon atoms, size of the molecules with respect to size of the pores, degree of ionization of the adsorbate molecule and pH, etc. (Pierro, 1999).

2.4 BASICS OF MAGNETISM

For many centuries, magnetic phenomena have been exploited and known but the earliest experiences with magnetism involved magnetite, which occurs naturally as a magnetic material (Jakubovics, 1987). Due to its property of aligning itself in certain directions if allowed to rotate freely, and also the ability to attract or repel two pieces of it, it is known as Iodestone. It was realised that magnetite was able to attract iron. Some objects that can attract or repel each other are said to be magnets, but some others that are not attracted to or repelled by each other, can be said to consist of magnetic materials.

2.4.1 IMPORTANT MAGNETIC PROPERTIES

When an electric field is passed through a wire or coil, magnetic fields H are produced by the movement of charge (normally electrons). In anything that is magnetic, such as, a bar magnet, the electrons circle around the nuclei of the iron atoms, or spin about their own axis, and atoms like this are said to possess a magnetic moment m(Clarke, 2008). The magnetic moment of a system measures the strength and the direction of its magnetism, and the term itself is usually referred to as magnetic dipole moment. Electrons possess an electron magnetic dipole moment. A dipole is symmetric about the direction of its moment. This magnetic moment of an electron is generated by the electron's intrinsic property of spinning, or an electric charge in motion (Davis, 2010). The magnetic moment can be defined by referring to either a pair of magnetic charges (Figure 2.1a) or a loop of electrical current (Figure 2.1b). For the pair of magnetic charges, the magnitude of charge is q, and an infinitesimal distance vector, l, separates the plus charge from the minus charge. The magnetic moment, m, is

= (2.4)

For a loop with area A carrying electrical current I, the magnetic moment is

= (2.5)

where n is the unit vector perpendicular to the plane of the loop. The proper direction of n (and therefore m) is given by the right-hand rule (Butler, 1998). (Curl the fingers of your right hand in the direction of current flow and your right thumb points in the proper direction of the unit normal, n.)

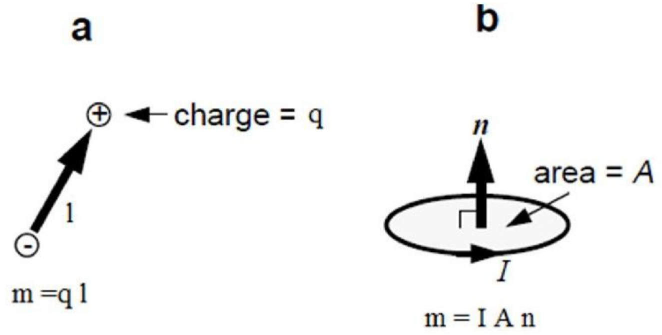


Fig. 2.1 (a) A magnetic dipole constructed from a pair of magnetic charges. The magnetic charge of the plus charge is q; the magnetic charge of the minus charge is –q; the distance vector from the minus charge to the plus charge is l. (b) A magnetic dipole constructed from a circular loop of electrical current. The electrical current in the circular loop is I; the area of the loop is A; the unit normal vector n is perpendicular to the plane of the loop.

Magnetic field, H, in a region is defined as the force experienced by a unit positive charge placed in that region.

The average field strength due to these moments at any particular point is known as magnetization, M or magnetic intensity. Magnetization is of two types: induced and remanent magnetization. Induced magnetization is that obtained when a material is placed in a magnetic field, but remanent magnetization is a recording of past magnetic fields that have acted on a material. For many materials, M is proportional to H (at least when H is large) and may be written as

$$= \qquad (2.6)$$

where χ, the magnetic susceptibility, is the property of the material. This magnetic susceptibility can be regarded as the magnetizability of a substance.

Another type of magnetic field which becomes important when considering electrical forces produced by magnetic phenomena is magnetic induction, B or magnetic flux density. This gives the energy of a dipole in a field.

The magnetization is related to B and H by

$$= \quad \mu\ (\quad + \quad) \qquad (2.7)$$

where μ_0, is the permeability of vacuum. Combining eqn. (2.6) with eqn. (2.7), we have

$$= \quad (1 + \chi) \qquad (2.8)$$

Thus 1 + χ express the proportionality of B and H.

Magnetic permeability can be defined as

$$= 1 + \qquad (2.9)$$

Eqns (2.8) and (2.9) give

$$= \qquad (2.10)$$

To characterise a material, either or μ may be used (Jakubovics, 1987).

According to Crangle (1977), some units in magnetism are given in Table 2.3

Table 2.3 Units in magnetism

Quantity	**SI**
Permeability of free space	= 4 × 10
Induction in free space (field)	tesla (T)
Magnetic force (field)	

Induction in free space (field)	=
Induction in medium	= +
Magnetization per unit volume	or
Magnetization per unit mass	= / =
Susceptibility per unit volume	κ = /
Susceptibility per unit mass	= κ/
Susceptibility per mole M	10
Bohr magneton	= $h/4$ = 9.2732 × 10
Relative permeability	= / = 1 +

2.4.2 CLASSES OF MAGNETIC PROPERTIES

Some materials are more magnetic than others, due to; there is a very strong collective interaction of atomic magnetic moments, whereas in others there is no collective interaction of atomic magnetic moments (Bruce 1991).

There are five major groups of classification of magnetic behaviour of materials. These are:

A. Diamagnetism

B. Paramagnetism

C. Ferromagnetism

D. Ferrimagnetism

E. Antiferromagnetism

Diamagnetic and paramagnetic materials exhibit no collective magnetic interactions and are not magnetically ordered. The remaining three groups of materials exhibit long-range magnetic order below a certain critical temperature.

A. DIAMAGNETISM

Diamagnetism is a very weak fundamental property of all matter. In diamagnetism, an external magnetic field H induces magnetic dipoles which are oriented antiparallel with respect to the exciting field (Mathias, 2008). The orbital shells of diamagnetic substances are filled and there are no unpaired electrons. The atoms have no net magnetic moments. Diamagnetic materials can easily be predicted. All noble gases, such as helium, neon, argon, all materials consisting of diatomic molecules, such as hydrogen, nitrogen, carbon monoxide; non-metallic elements such as boron, silicon and phosphorus; and also all materials consisting of ions with noble gas type electron configurations, such as sodium chloride; are diamagnetic (Jakubovics, 1987). The basic diamagnetism is independent of temperature and is due to the effect of applied magnetic fields on the motion of inner electrons of the atoms present (Crangle, 1977).

When we plot M vs H we see:

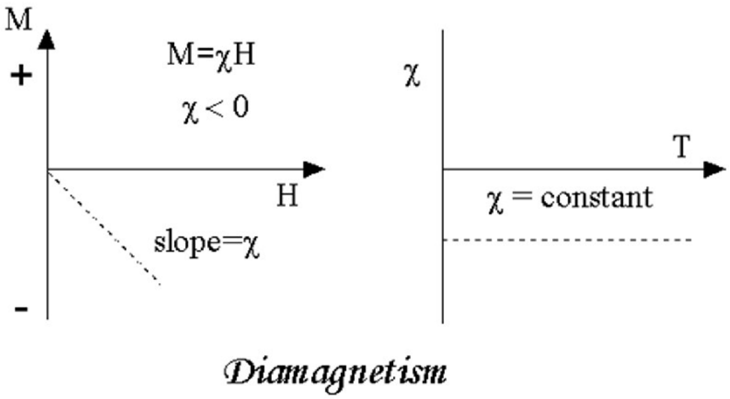


Figure 2.2 A plot of magnetization versus magnetic field for diamagnetism

The residual magnetic behaviour when materials are neither paramagnetic nor ferromagnetic is diamagnetism.

B. PARAMAGNETISM

Paramagnetism was first named and extensively investigated by the British scientist Michael Faraday in 1845. He realized that some materials are weakly repelled by a magnet, while some are weakly attracted or strongly attracted to magnet. The materials (elements or compounds) that are weakly attracted to the magnet exhibit paramagnetism and they have a certain atomic structure. In a paramagnet, some atoms inside the substance have unfilled inner shells, and also electrons are unpaired. This causes each of the electrons to spin on its own axis and align in a certain direction when the substance is placed in a magnetic field (Alex, 2013). If a substance containing such unpaired electrons is placed in a magnetic field, the field of the electron aligns with the field of the applied magnetic field and causes the electron to be slightly attracted to that magnetic field. When the magnetic field is removed, the net magnetic alignment is lost as the electrons relax back to their normal random motion (Dimitru et al., 1999).

Researchers have discovered that paramagnetic materials are beneficial in agriculture; in that most of the world's most fertile soils are highly paramagnetic, and that there is enhanced plant growth due to paramagnetism, either by influencing the plant roots directly, or by stimulating the microbiology that supports plant root development. Paramagnetic materials also appear to act as an antenna by collecting, and presumably storing ELF (extremely low frequency radio waves) from atmospheric lightening, and possibly other energy sources (TSP, 2006). There has been few or no documented application of paramagnetism to corrosion processes.

The paramagnetic property refers to an atom with one or more unpaired electrons.

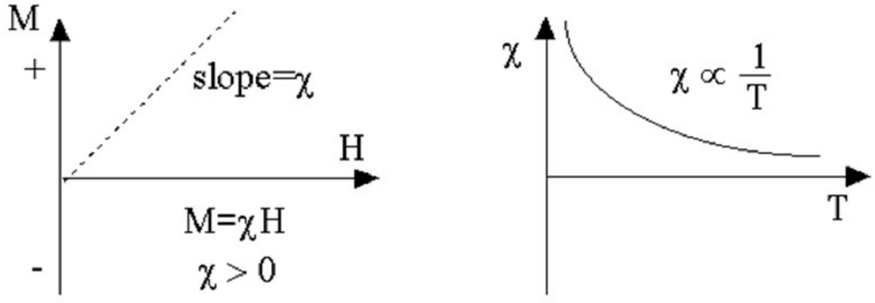
Some of the atoms in the paramagnetic material have net magnetic moments due to unpaired electrons in partially filled orbital. Since a paramagnetic substance has an unpaired electron, the electron can freely align its magnetic moment in any direction, and thus paramagnetic atoms are capable of being attracted to magnetic fields. In the presence of a field, H, a small magnetization, M, develops, but the susceptibility, is very small, and is inversely proportional to the absolute temperature (Jakubovics, 1987). When the applied magnetic field is removed, the atomic moments are equally distributed in all directions with zero resultant magnetization. The direction of the magnetic moments is almost completely random when field is applied (see figure 2.5). The randomizing effects of temperature oppose the efficiency of the field in aligning the moments, resulting in a temperature dependent susceptibility known as the Curie law, which states that the higher the temperature, the lower the magnetization. The Curie law is mathematically represented as

$$\chi = C/T \qquad (2.11)$$

where C is the Curie constant. χ is the magnetic susceptibility.

The paramagnetic susceptibility is small at normal temperatures and in moderate fields. It is independent of the applied field at very low temperatures (<<100K) and when the field is very high, but proportional to the total iron content in these conditions (Bruce 1991).

Plotting M vs H, we have



Paramagnetism

Figure 2.3 A plot of magnetization versus magnetic field for paramagnetism

Many of the salts of transition metals and rare earth metals, and also rare earth oxides are paramagnetic (Jakubovics, 1987). Oxygen is a typical example of a paramagnetic substance.

C. FERROMAGNETISM

In ferromagnetic materials, the atomic moments exhibit very strong interactions produced by electronic exchange forces. This results in a parallel or anti parallel alignment of atomic moments giving rise to a large net magnetization even in the absence of a magnetic field. The exchange forces are very large and the mechanical phenomenon is due to the relative orientation of the spins of two electrons (Bruce 1991). Ferromagnetic materials include magnetite, Fe, Ni, Co, Mn and their alloys and they possess atomic moments which are aligned below some critical temperature.

For a non magnetized piece of iron at room temperature placed in a small increasing field, its magnetization increases first slowly and reversibly. Beyond a critical field hysteresis develops (see figure 2.4). When the field is switched off, the magnetization does not return to zero, and if the field is cycled between small limits a minor hysteresis loop is followed (Crangle, 1977). As the magnetization raises with increasing field, at higher applied fields, saturation magnetization, M_s is reached. When saturation is reached, the magnetization increases very slowly and approximately linearly with increasing field and this is called intrinsic magnetization which is the value of the magnetization within a domain.

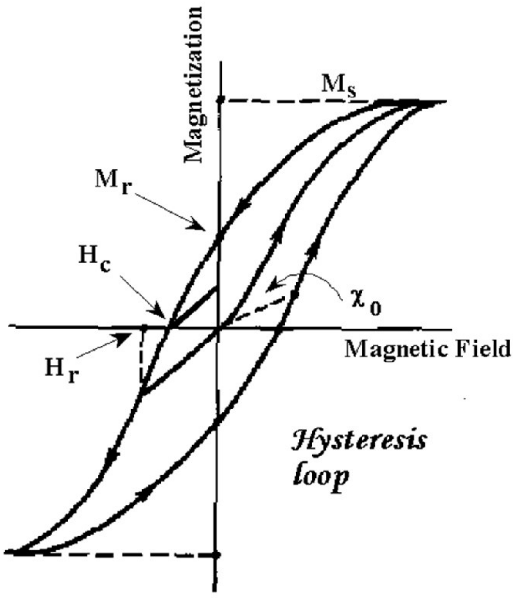


Figure 2.4 Hysteresis loop

This is the magnetization that remains when the different orientations of all the domains have been allowed for. There is a magnetization that remains when the field is switched off from saturation, known as remanence, M , and coercivity$_r$ H_c, is the reverse field required to reduce the magnetization to zero from saturation as shown in figure 2.4. In ferromagnets, the intrinsic magnetization does not become zero even when the applied field is removed, but it remains at a value a little below its value in a strong field. This is the spontaneous magnetization, which is spontaneously present within the domains when no field is applied externally (Crangle, 1977).

At a particular temperature called the Curie temperature (Tc), electronic exchange forces in ferromagnets produce a randomizing effect. Below the Curie temperature, the ferromagnet is ordered, at the Curie temperature, saturation magnetization becomes zero, and above the Curie temperature, the ferromagnets are disordered (the behaviour similar to that of paramagnets). Curie temperature is an intrinsic property, and also different magnetic minerals can have the same Curie temperature.

D. FERRIMAGNETISM

In ferrimagnetic materials, the magnetic moments of the atoms on different sublattices oppose each other and are not equal, also a spontaneous magnetization remains. At temperatures below their Curie temperature, Tc, they exhibit a spontaneous magnetic moment. Hysteresis and domain properties are observed in a similar way to ferromagnets and they become paramagnetic at temperature above Tc (Crangle, 1977). Ferromagnets are usually metallic

and ferrimagnets are usually non-metals. Oxides of iron combined with one or more of the transition metals such as manganese, nickel or zinc, e.g $MnFe_2O_4$ make up the ferrimagnetic materials. Magnetite is a well-known ferrimagnetic material. In ferrimagnets, the magnetic moments in one direction are weaker than the moments in the opposite direction leading to an overall magnetic moment. Most of the electronic equipment in use today contain some ferrimagnetic materials, these include: loudspeakers, motors, deflection yokes, antenna rods, recording heads, transformers, inductors, etc.

E. ANTIFERROMAGNETISM

In antiferromagnetic materials such as, chromium, manganese, MnO, NiO, the magnetic moments produced in neighbouring dipoles line up in opposition to one another in the magnetic field (Askeland, 1989). Owing to this, the magnetic moments are exactly equal and opposite, the net moment is zero. The interactions between neighbouring dipoles in ferromagnetism reinforce another, while as in antiferromagnetism, they oppose one another. Neel (between 1932 and 1936) was the first to show that some materials have a critical temperature, called the Neel temperature, below which the atomic moments are arranged alternately parallel and antiparallel, and above which the moments are disorderd paramagnetically (Crangle,1977). In a simple antiferromagnet, the crystal can be divided into two sublattices, A and B, such that the spins of one sublattice point one way, and those of the other point the opposite way. The spins of atoms which are nearest neighbours are usually antiparallel, and this can be associated with simple cubic and body-centred cubic crystal structures. The temperature at which there is non-zero magnetization in both sublattices in zero applied fields is the Neel temperature. The susceptibility at absolute zero is equal to the susceptibility at the Neel temperature (Jakubovics, 1987). As the temperature decreases from the Neel temperature to zero, the susceptibility gradually decreases to zero in fields applied parallel to the magnetic moments, but is constant in fields applied at right angles to them.

In summary, ordering of the magnetic dipole moments of some of the types of magnetic materials is as shown in figure 2.5

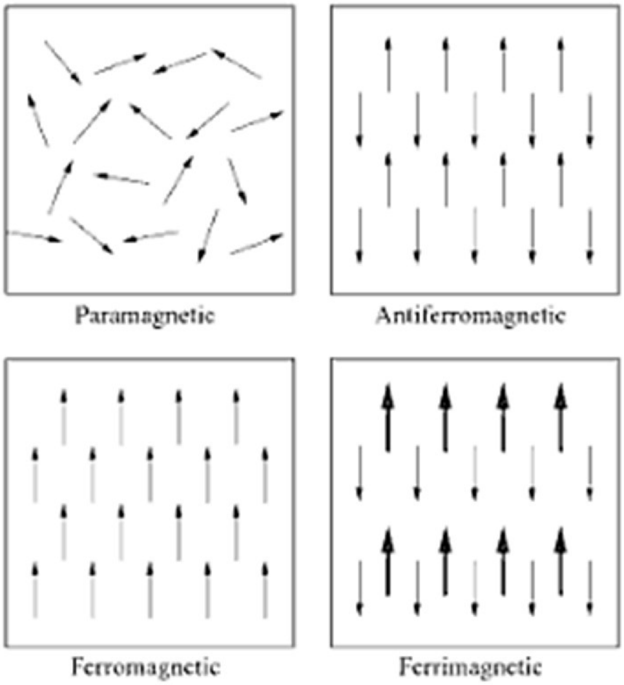


Fig 2.5 Ordering of magnetic moments in some types of magnetic materials

2.5 DEFINITION OF CORROSION

Corrosion in engineering can be defined as the deterioration of a material because of the interaction with its environment. This leads to the degradation of the material’s mechanical and physical properties (Kelly et al, 2003). The interaction can be in the form of electrochemical or chemical reaction. The dissolution of ceramic refractories by the molten slag; swelling or cracking of plastics by sunlight or chemicals; and rusting of iron or iron-based alloys are few examples of corrosion. Metals are susceptible to corrosion. Metallic corrosion can be defined as the destructive attack of a metal by chemical or electrochemical reaction by its environment (Roberge, 2000).

For the course of this study, few forms of corrosion are discussed:

2.5.1 CO_2 CORROSION

CO_2 (carbon dioxide) is the cause of most serious problems in oil and gas production. Though CO_2 is naturally present in crude oil and natural gas from oil reservoir/ gas well, it is also purposely injected into these wells for effective oil recovery (Ibraheem et al, 2012). CO_2 corrosion or sweet corrosion occurs when CO_2 dissolves in produced water or brine to form carbonic acid. The following key processes take place in CO_2 corrosion.

Weak carbonic acid is formed by the dissolution and hydration of CO_2:

$$( ) \rightarrow ( ) \qquad (2.12)$$

$$+ \rightarrow \qquad (2.13)$$

The carbonic acid then dissociates partially to form the bicarbonate which further dissociates to give the carbonate ion:

$$\rightarrow + \qquad (2.14)$$

At higher pH values (> 6), dissociates to give + .

According to George and Nesic (2007), solutions containing H_2CO_3 are more corrosive to mild steel than solutions of strong acids, such as HCl or H_2SO_4 at the same pH. Two possible cathodic reactions can occur during mild steel corrosion, which include:

$$+ \quad \rightarrow \quad {}^{+} + \qquad (2.15)$$

The hydrogen atoms adsorbed on the surface are thus combined with hydrogen molecules to form hydrogen gas:

$$2 \quad + 2 \quad \rightarrow \qquad (2.16)$$

At lower pH values (2-4), reduction of H^+ from reaction (2.16) may contribute, but at pH (>6), reduction of HCO_3^- is significant (Bardal, 2003).

The electrons needed to keep the process going are provided by an anodic reaction, iron dissolution:

$$\rightarrow \quad +2 \qquad (2.17)$$

The total reaction gives:

$$+ \quad \rightarrow \quad + \qquad (2.18)$$

During the corrosion of steel in CO_2 –saturated water, the solubility of $FeCO_3$ may be exceeded and precipitation sets in. The $FeCO_3$ precipitate may form a protective film depending on the solution composition, pressure and temperature of the system (George and Nesic, 2007). Increasing flow velocity causes increasing mass transport and consequently a higher extent of dissolution of corrosion products with increased corrosion rate as a result (Waard and Lotz, 1993).

2.5.2 H_2S CORROSION

Most oil/gas wells contain a lot of hydrogen sulphide that reacts with the structural materials to cause corrosion. Although in some fields, the H_2S is not present in large quantity, but the content may increase due to seawater injection in the wells. This is because bacteria can reduce sulphate (from injected water) to sulphide. Dissolved H_2S can form black iron sulphide film by reacting with steel in the following reaction (Dosunmu & Echendu, 2002):

$$(\ ) + \quad (\ ) \rightarrow \quad (\ ) + \quad (\ ) \qquad (2.19)$$

Surface scale formation plays an important role in controlling the corrosion rate. As there is poor knowledge of the mechanisms of H_2S corrosion, it is not easy to quantify the kinetics of the iron sulphide scale formed.

2.5.3 MICROBIAL CORROSION

Microbial corrosion which can also be called bacterial corrosion, bio-corrosion, microbiologically influenced corrosion, or microbial induced corrosion (MIC), is corrosion caused by the presence and activities of micro-organisms. The micro-organisms of interest in microbiologically influenced corrosion are mostly bacteria, fungi, algae, and protozoans (Pope et al, 1989). These organisms can produce electron flow, or modify the local environment to change from a non-corroding to a corrosive one. Some of the biological processes include; the formation of microbial deposits on the metal surface that results in metal dissolution and increased pitting, the deposits can produce organic and inorganic acids that will initiate corrosion on the metal surface, also some reactive bacteria directly reducing metal atoms to ions (Richard,1980; Schwermer et al., 2008).

Bacteria are the predominant cause of microbial corrosion, may be because they tend to live and grow under wide ranges of temperature, pH, and oxygen concentration. Sulphate-reducing bacteria (SRB) are the organisms most closely identified with microbial corrosion (Brenda &Jason, 2009). SRB thrive in near neutral environment (pH ≈ 5-8) at temperatures of 10-40 ^{o}C in the absence of air (anaerobic). They are called sulphate-reducing bacteria because they promote the reduction of present sulphate to sulphide. According to Metals Handbook (1987), a typical mechanism comprises the following reactions at/on the cathodes:

Dissociation of water: $8 \rightarrow 8 + 8$ (2.20)

Cathodic reaction: $8 + 8 \rightarrow 8$ (2.21)

Cathodic depolarization: $+ 8 \rightarrow + 4$ (2.22)

Ferrous ions from the anodic reaction: $\rightarrow + 2$ (2.23)

react with from the cathodic depolarization and from the water dissociation to form ferrous sulphide, FeS, and hydroxide, $Fe(OH)_2$. The ferrous sulphide can form a continuous protective covering on the metal surface, but when broken will cause local galvanic corrosion. SRB can cause corrosion in oil and gas wells, and in cases of anaerobic conditions in soils, sediments on sea and river beds, and beneath organic layers on metal surfaces in seawater.

Shreir and coworkers(2000) suggested that materials can be protected from microbial corrosion by:

(i) The use of coatings, particularly of resistant synthetic polymers or paints containing inhibiting salts (e.g. Cu $^{2+}$, Cr $^{3+}$, and Zn $^{2+}$).

(ii) Controlled dosing with appropriate biocides.

(iii) Changes in environmental conditions unfavourable for microbial growth.

(iv) Designs based on fundamental knowledge of microbial ecology.

2.6 RELEVANCE OF CORROSION STUDIES

The essence of corrosion studies is to militate against a lot of damages caused by corrosion which include:

i) MAINTENANCE /OPERATIONAL COSTS

The cost of repairing corroded structures and machinery or their components, such as pipelines, condenser tubes, is about six to ten times higher than when the operation is carried out under normal and planned conditions. Economic implication will arise from costs of procurement of the standard materials needed for replacement, repair works, and technical costs of experts required for the repair (Orukele, 1999).

ii) PRODUCT CONTAMINATION

The quality and purity of a product is of great importance especially to the user. A very small amount of corrosion products can contaminate a product and it will lose its market value. In the manufacture and handling of transparent plastics, pigments, drugs, foods, and semi-conductors, freedom from contamination is of vital concern (Onyemaobi & Amaghaghi, 1998).

iii) ENVIRONMENTAL POLLUTION

The destruction of the environment especially in a corroded pipeline causing spillages cannot be quantified. Such oil spills can cause a lot of damages to the environment; destruction of flora and fauna, fire outbreak and fatality.

iv) SAFETY EFFECTS

Corrosion can bring about the failure of operating equipment, thereby compromising its safety and that of the individuals in the work place. Some hazardous substances can be deposited in the environment from a corroded part such as, the equipment used in the disposal of wastes.

2.7 METHODS OF MEASURING CORROSION

Depending on the aims and objectives, many methods can be used to determine the amount of corrosion which includes:

i) Visual inspection
ii) Dye penetrant inspection
iii) Weight loss
iv) Electrical resistance probes
v) Ultrasonic
vi) Magnetic particle inspection
vii) Depth of pitting
viii) Radiography
ix) Hydrogen evolution
x) Potential difference method
xi) Electrochemical techniques

To determine the corrosion rates on metals and alloys, a quantitative approach is taken. A weight loss method is usually used to assess the corrosion damage and usually expressed in $g/cm^2/hr$:

Corrosion rate (CR) = W/At (2.24)

Where W = weight loss (g)

A= Total area of specimen (cm^2)

t= exposure time of the sample (hr)

This technique cannot give instantaneous corrosion rates, but a mean during a period of test. It is the most accurate method to quantify corrosion attack in laboratory experiments. Not minding that it is time-consuming and only applicable to laboratory studies, it is a useful tool to check the accuracy of some electrochemical techniques that measure corrosion rate more quantitatively.

2.8 MAGNETIC FIELD EFFECTS ON CORROSION

The effect of magnetic fields on electrochemical processes or behaviour of metallic materials in aqueous solutions has been mainly focused on the introduction of two additional forces into the electrolyte (Zhanpeng et al, 2003). The first of these is the magnetohydrodynamic (MHD) force which arises from the Lorentz force yielded by the transport of charged reactants and products through the magnetic field (Aogaki, 2001). The second force is the field gradient force which pulls paramagnetic ions in regions of high flux density, leading to concentration gradients at an electrode surface.

In the presence of magnetic field, any charged particle will be affected by the Lorentz force, F (Fig.2.5),

$$= \quad (\quad \times \quad) \tag{2.25}$$

where q (coulombs) is the charge on the species moving at velocity v (m/s)and B is the intensity of the applied external magnetic field.

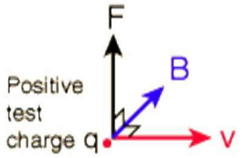


Fig.2.6 Schematic diagram of Lorentz force (Nave, 2013)

An external magnetic field can alter the ability of the rate of mass transport of electrochemical species which is known as the MHD effect. Such MHD flow in electrochemical systems is described by the force per unit volume acting on the solution. F_{MHD} (N/m^3).

$$= \times \qquad (2.26)$$

where J is the local flux of ions (coulombs/cm ^{2}s).

When the magnetic field is parallel and horizontal to the electrode surface, it will exert a Lorentz force and thus superimpose a MHD velocity (V_{mag}) by F_{MHD} on any charged particle moving in the interfacial diffusion layer is as shown in Fig. 2.7(Jing et al.,2010;Li et al.,2010). V_{mag} is perpendicular to the magnetic field direction and parallel to the electrode surface.

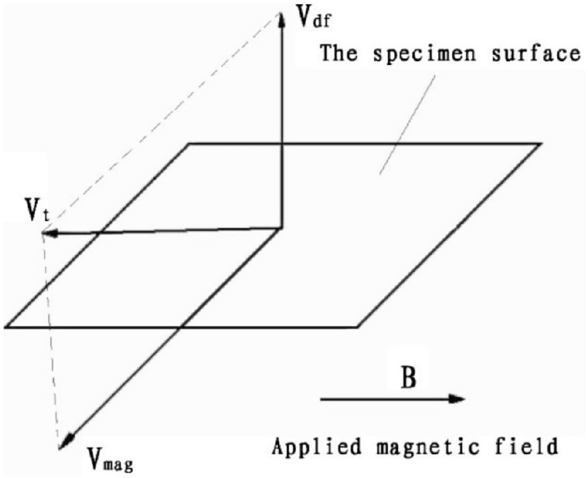


Fig 2.7 A schematic illustration of the combination of the velocity of ion in the magnetic field (Li et al, 2010)

The total velocity (V_T) of a charged particle in the presence of a magnetic field can be expressed as the vector sum

$$= \qquad + \tag{2.27}$$

where V_{df} is the velocity of the charged particle due to the concentration gradient (Jing et al,2010). There is $V_T > V_{df}$ in the presence of magnetic field, which implies that the mass transfer rate is increased by the magnetic field. According to Jianwei and his coworkers (2001), Lorentz forces do not apply to electrically non-conducting or low-conducting fluids, such as melts of organic oxides, organic solvents, and aqueous solutions with low conductivity.

On the other aspect of magnetic field effects, Waskaas and Kharkats (2001) on their study of the effect of magnetic fields on convection in solutions containing paramagnetic ions (Co^{2+}) verified experimentally that the observed magnetic field effect could not be explained only in terms of the Lorentz force. In the presence of a magnetic field in solution, where a gradient of concentration of paramagnetic ions exists due to some electrode reaction in which they participate, additional driving force acting on the solution will arise. This force which has the same direction as the gradient of the paramagnetic ions will cause a redistribution of velocities in the diffusion layer. As a result an additional convective transport of all the components of the solution will be generated. In correspondence, limiting currents of reactions proceeding in an electrochemical system will become a function of the applied magnetics flux density.

CHAPTER THREE

EXPERIMENTAL METHODS

3.1 MATERIALS PREPARATION

The alloy composition of the American Iron and Steel Institute (AISI) mild steel used is as follows; C 0.15-0.29wt%, Mn 0.6-0.9wt%, P≤0.04wt%, S≤0.05wt%, balance is Fe. The mild steel was prepared into coupons of four different sets with dimensions

i) 7.61cm x 2.22cm x 0.31cm
ii) 7.31cm x 2.22cm x 0.31cm
iii) 7.30cm x 2.20cm x 0.30cm
iv) 7.29cm x 2.22cm x0.31cm.

Each coupon was numbered and had two holes of 0.8cm each bored on both surfaces (see Fig.3.1).

Fig.3.1 The corrosion coupon

The surface of the coupons was polished with emery paper (a coarse paper was used initially and then finer grades were employed), cleaned and dried ready to be weighed.

3.2 MAGNETIZATION OF COUPONS

The coupons were used in the magnetized and non magnetized states. A laboratory electromagnet (LE) was used to magnetise the coupons. The LE is made up of a base and double casings (containing the solenoid) with handles, and a current regulator attached to it (Fig.3.2 (a) and (b) respectively).

Fig.3.2 (a) Laboratory electromagnet, (b) current regulator

A compass (Fig 3.3) was used to identify the earth’s poles and align the coupons in the same poles with that of the solenoid (i.e. North Pole against North Pole and South Pole against South Pole). The coupon was wrapped with a sheet of paper before inserting it into the solenoid so as to centralise the magnetic field around it (Fig.3.4). The device was switched off before inserting the coupon in the solenoid, when it was inserted, the device was switched on and current allowed to pass for 60 seconds, and the device switched off, then the coupon was brought out magnetized. The number of turns in the solenoid is 1000 turns per 2cm.

Fig.3.3 Compass

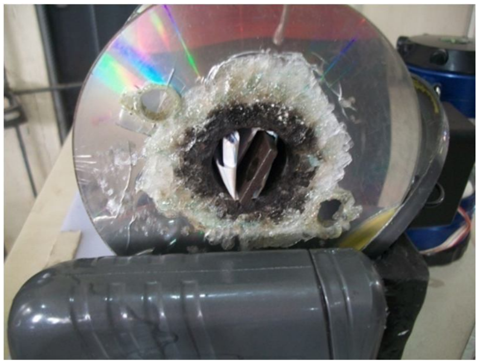


Fig.3.4 Coupon inside the solenoid

The strength of the magnetic field was varied by changing the current passing through the circuit using the relation:

$$ = \tag{3.1}$$

Where B is the magnetic field strength in Tesla, is the magnetic permeability of free space (4 x10^{-7}Weber/A), n is the number of turns per unit length and I is the current passing through the circuit in amperes.

3.3 TEST METHOD

The environment under corrosion study was a solution of distilled water and analytical grade HCl with varying pH ranging from 2-6. The acid (hydrochloric acid) has the following descriptions:

Type analysis	M.W. 36.46
Assay (acidimetric)	35-38%
Wt per ml at 20°C	about1.18g
Molarity	12M
Maximum limits of impurities	
Non-volatile matter	0.01%
Free chloride (Cl)	0.0005%
Sulphuric acid (H_2SO_4)	0.02%
Iron (Fe)	0.02%
Lead (Pb)	0.0005%

To prepare the solutions of different pH values, a lot of mathematical calculations were carried out;

From the acid description, there are 12M of the acid on the whole, thus;

$$1 \quad = 0.012 \quad , \qquad 1 \qquad \frac{1}{.012} = \qquad = 83.3 \quad , \qquad (3.2)$$

It implies that 83.3mls of HCl is needed to get 1liter or 1dm3 of acid solution for 1M. Due to practically 83.3ml cannot be easily measured out; 84mls is preferred and used.

From elementary chemistry, pH of a solution is the negative logarithm of the hydrogen ion concentration to the base 10. Mathematically,

$$= -\log[\qquad] \tag{3.3}$$

Assuming we have pH 2, and we want to know the hydrogen ion concentration in the solution, replacing 2 for pH in Eqn. (3.3) we have;

$$-2 = \quad [\quad]; \quad [\quad] = 10 \quad = 0.01 \qquad = 0.01 \tag{3.4}$$

This implies that for pH 2, we need 0.01M of acid in a litre of solution.

$$1 \quad = 84 \quad ,0.01 \quad = 0.84 \tag{3.5}$$

in a litre of solution.

Eqn (3.3) was used to calculate other pH values and their corresponding number of mls of acid gotten. Also the pH meter was used to confirm the pH of the solutions.

Six weighed coupons of the non-magnetised coupons were immersed into a rectangular bath with dimensions 28 x 28 x 26 cm containing the HCl solution at 0.5, 1, 1.5, 2, 2.5, and 3hrs at room temperature (23 ± 2 °C). Then the specimens were cleaned, dried and weighed. The above procedure was also carried out for the magnetised coupons with varying magnetic field strengths (0.38T, 0.57T, 0.76T, 0.95T, and 1.51T).

The corrosion rate (CR) of steel was calculated in g/cm^2/hr using the following equation:

$$= \quad / \qquad (3.6)$$

Where W is the weight loss, A is the area of coupon and t is the exposure time of coupon. All weight measurements were done using a 4-decimal place OHAUS digital weighing machine.

From the measured CR values, the inhibition efficiency was calculated using the relationship:

$$\% = \frac{}{} \times 100 \qquad (3.7)$$

Where CR_N and CR_M are non-magnetised and magnetised corrosion rate values of the coupons respectively.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 TABLES FOR CORROSION RATES

Table 4.1.1(a): Magnetised coupons at 0.38T for pH 2

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	10345	38.2732	38.9372	38.9188	0.0184	96.12
1	412	37.8771	37.2390	37.2086	0.0304	80.26
1.5	1211	37.9861	36.4844	36.4422	0.0422	74.06
2	1227	37.9861	36.0976	36.0544	0.0432	56.86
2.5	1206	37.9861	34.2355	34.1920	0.0435	45.81
3	21865	39.1620	36.8686	36.8290	0.0396	33.71

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate (g/cm^2/hr)x10^{-5}
0.5	10362	38.3775	37.6727	37.6564	0.0163	84.95
1	1119	37.9861	36.9315	36.9086	0.0229	60.30
1.5	10372	37.4324	37.0852	37.0567	0.0285	50.76
2	1109	37.9861	34.3674	34.3312	0.0237	31.20
2.5	367	37.8467	37.6194	37.5880	0.0314	33.19
3	1183	38.2732	35.5964	35.5649	0.0135	27.43

Table 4.1.2(a): Magnetised coupons at 0.38T for pH 3

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate (g/cm^2/hr)x10^{-5}
0.5	10354	38.7559	37.6865	37.6831	0.0034	17.55
1	1253	37.9861	36.5865	36.5819	0.0046	12.11
1.5	21896	38.8094	35.9794	35.9727	0.0067	11.51
2	10396	37.4321	32.9458	32.9381	0.0077	10.29
2.5	1232	37.9861	35.2893	35.2801	0.0092	9.688
3	21887	38.8573	35.9933	35.9797	0.0136	11.67

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	1231	37.9861	36.3087	36.3072	0.0015	7.898
1	21827	39.4240	37.8195	37.8162	0.0033	8.37
1.5	10363	37.9861	36.4394	36.4360	0.0034	5.967
2	1223	37.9861	36.2905	36.2870	0.0035	4.605
2.5	678	37.9682	35.7512	35.7458	0.0054	5.689
3	1479	37.3160	33.1183	33.1120	0.0063	5.628

Table 4.1.3(a): Magnetised coupons at 0.38T for pH 4

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	415	37.8973	36.5030	36.4984	0.0046	24.28
1	412	37.8771	37.2434	37.2399	0.0035	9.24
1.5	1227	37.9861	36.1012	36.0982	0.003	5.265
2	1047	37.9861	35.4194	35.4169	0.0025	3.291
2.5	1404	37.6567	33.5120	33.5090	0.003	3.187
3	670	37.9861	36.6267	36.6238	0.0029	2.55

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate $(g/cm^2/hr)x10^{-5}$
0.5	10371	37.8973	38.0722	38.0683	0.0039	20.58
1	10352	37.9861	37.1496	37.1486	0.0010	2.633
1.5	1220	37.9861	36.7326	36.7312	0.0014	2.457
2	678	37.9862	35.7574	35.7563	0.0011	1.448
2.5	1163	37.9861	36.0349	36.0330	0.0019	2.00
3	1125	37.9861	36.1325	36.1314	0.0011	0.965

Table 4.1.4(a): Magnetised coupons at 0.38T for pH 5

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate $(g/cm^2/hr)x10^{-5}$
0.5	21814	39.1620	37.2529	37.2487	0.0041	21.03
1	1166	37.9861	36.0003	35.9993	0.0010	2.675
1.5	10378	37.7961	35.0460	35.0441	0.0019	3.325
2	1156	37.9861	36.4261	36.4241	0.0020	2.65
2.5	1307	37.9861	35.7367	35.7318	0.0049	5.16
3	10365	37.9479	37.3046	37.3012	0.0034	2.987

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	429	37.9861	38.4416	38.4368	0.0048	25.3
1	1058	37.9861	36.1710	36.1681	0.0029	7.65
1.5	21865	39.1620	37.7548	37.7516	0.0032	5.45
2	10366	37.9861	38.1938	38.1892	0.0046	6.055
2.5	21881	39.0635	37.4998	37.4921	0.0077	7.89
3	365	37.8467	37.4098	37.4031	0.0067	5.90

Table 4.1.5 (a): Magnetised coupons at 0.38T for pH 6

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	21882	39.4240	37.0736	37.0686	0.005	25.3
1	1230	37.9861	35.9992	35.9929	0.0063	16.59
1.5	21891	38.8094	36.0345	36.0319	0.0026	4.466
2	10375	37.9175	37.7611	37.7583	0.0028	3.69
2.5	21888	39.0635	37.2083	37.2081	0.0002	0.205
3	364	37.8467	36.5439	36.5401	0.0038	2.72

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	1149	37.9861	35.9580	35.9522	0.0058	30.45
1	10347	37.8973	37.2542	37.2457	0.0085	22.4
1.5	10350	37.9861	38.4126	38.4062	0.0065	11.41
2	1228	37.9861	36.2342	36.2292	0.005	6.581
2.5	1148	37.9862	35.0013	34.9961	0.0052	5.476
3	10342	37.9861	37.7796	37.7725	0.0071	6.196

Table 4.1.6(a): Magnetised coupons at 0.57T for pH 2

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	10365	37.9479	37.2934	37.2779	0.0155	81.7
1	1232	37.9861	35.2811	35.2546	0.0265	69.8
1.5	10345	38.2732	38.9186	38.8989	0.0197	34.3
2	1404	37.6567	33.5061	33.4819	0.0242	32.21
2.5	1307	37.9861	35.7285	35.6999	0.0286	30.12
3	10336	38.2732	36.7388	36.7166	0.0222	19.3

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr)x10^{-5}$
0.5	429	37.9861	38.4363	38.4192	0.0171	90
1	10371	37.8973	38.0559	38.0252	0.0307	81
1.5	1223	37.9861	36.2808	36.2387	0.0241	73.9
2	365	37.8467	37.4040	37.3743	0.0297	39.2
2.5	10374	37.9861	37.2920	37.2506	0.0414	43.6
3	21881	39.0635	37.4863	37.4533	0.033	28.15

Table 4.1.6(a): Magnetised coupons at 0.57T for pH 3

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr)x10^{-5}$
0.5	10354	38.7559	37.6822	37.6764	0.0058	30
1	1166	37.9861	35.9954	35.9925	0.0029	7.63
1.5	670	37.9861	36.6227	36.6177	0.005	8.78
2	1227	37.9861	36.0564	36.0517	0.0047	6.19
2.5	1206	37.9861	34.1928	34.1874	0.0054	5.67
3	21882	39.4240	37.0616	37.0516	0.0100	8.50

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr)x10^{-5}$
0.5	1149	37.9861	35.9518	35.9497	0.0021	11.1
1	10372	37.4324	37.0443	37.0432	0.0011	2.94
1.5	678	37.9862	35.7444	37.7412	0.0032	5.62
2	10350	37.9861	38.3991	38.3963	0.0028	3.69
2.5	10347	37.8973	37.2327	37.2290	0.0037	3.91
3	1479	37.3160	33.1082	33.1016	0.0066	5.9

Table 4.1.7(a): Magnetised coupons at 0.57T for pH 4

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr)x10^{-5}$
0.5	412	37.8771	37.2093	37.2088	0.0005	2.64
1	21887	38.8573	35.9797	35.9787	0.0010	2.57
1.5	1253	37.9861	36.5816	36.5810	0.0006	1.05
2	1156	37.9861	36.4195	36.4188	0.0007	0.92
2.5	364	37.8467	36.5342	36.5333	0.0009	0.95
3	21891	38.8094	36.0287	36.0271	0.0016	1.37

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr)x10^{-5}$
0.5	10366	37.9861	38.1799	38.1796	0.0003	1.58
1	21865	39.1620	37.7433	37.7427	0.0006	1.53
1.5	10362	38.3775	37.6444	37.6440	0.0004	0.695
2	1119	37.9861	36.8939	36.8934	0.0005	0.658
2.5	1228	37.9861	36.2222	36.2217	0.0005	0.527
3	1125	37.9861	36.1171	36.1161	0.0010	0.878

Table 4.1.8: Magnetised coupons at 0.57T for pH 5

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr)x10^{-5}$
0.5	1211	37.9861	36.4412	36.4410	0.0002	1.05
1	10396	37.4324	32.9291	32.9235	0.0006	1.60
1.5	21866	39.1620	36.8349	36.8342	0.0007	1.19
2	10378	37.7961	35.0325	35.0320	0.0005	0.661
2.5	10375	37.9175	37.7531	37.7522	0.0009	0.949
3	21814	39.1620	37.2356	37.2342	0.0014	1.19

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	10342	37.9861	37.7656	37.7641	0.0015	7.9
1	1220	37.9861	36.7242	36.7233	0.0009	2.37
1.5	10352	37.9861	37.1383	37.1371	0.0012	2.11
2	1231	37.9861	36.2972	36.2961	0.0011	1.45
2.5	21827	39.4240	37.8105	37.8089	0.0016	1.62
3	367	37.8467	37.5895	37.5866	0.0029	2.60

Table 4.1.9a: Magnetised coupons at 0.57T for pH 6

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	21888	39.0635	37.2072	37.2069	0.0003	1.54
1	415	37.8973	36.4960	36.4959	0.0001	0.264
1.5	21896	38.8094	35.9687	36.9682	0.0005	0.896
2	1047	37.9861	35.4105	35.4096	0.0009	1.19
2.5	1230	37.9861	35.9896	35.9888	0.0008	0.842
3	1285	37.9861	35.6479	35.6415	0.0011	0.965

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	1163	37.9861	36.0263	36.0245	0.0018	9.48
1	1148	37.9861	34.9909	34.9803	0.0079	2.10
1.5	1183	38.2732	35.5584	35.5574	0.0010	1.74
2	10363	37.9861	36.4295	36.4275	0.0020	2.63
2.5	1058	37.9861	36.1597	36.1579	0.0018	1.9
3	1109	37.9861	34.3272	34.3238	0.0034	2.98

Table 4.1.10a: Magnetised coupon at 0.76T for pH 2

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	21887	38.8573	35.9747	35.9623	0.0124	63.8
1	10378	37.7961	35.0297	35.0057	0.0240	63.5
1.5	10336	38.2732	36.7013	36.6753	0.0260	45.3
2	21888	39.0635	37.2065	37.1728	0.0337	43.1
2.5	1156	37.9861	36.4162	36.3739	0.0423	44.5
3	415	37.8973	36.4960	36.4492	0.0468	41.2

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	10352	37.9861	37.1350	37.1184	0.0166	87.4
1	10347	37.8973	37.2240	37.1955	0.0285	75.2
1.5	1228	37.9861	36.2196	36.1782	0.0414	72.7
2	21865	39.1620	37.7400	37.6964	0.0436	55.7
2.5	10363	37.9861	36.4273	36.3699	0.0574	60.44
3	10372	37.4324	37.0370	36.9732	0.0638	56.81

Table 4.1.11a: Magnetised coupons at 0.76T for pH 3

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	1253	37.9861	36.5789	36.5752	0.0037	19.48
1	10354	38.7559	37.6696	37.6661	0.0035	9.03
1.5	21896	38.8094	35.9686	35.9617	0.0069	11.85
2	364	37.8467	36.5303	36.5235	0.0068	8.98
2.5	412	37.8771	37.2064	37.2008	0.0064	6.76
3	1230	37.9861	35.9850	35.9726	0.0124	10.9

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	429	37.9861	38.4084	38.4053	0.0031	16.3
1	1223	37.9861	36.2306	36.2278	0.0028	7.37
1.5	1119	37.9861	36.8886	36.8835	0.0051	8.95
2	10371	37.8973	38.0164	38.0124	0.004	5.28
2.5	21881	39.0635	37.4190	37.4142	0.0048	4.92
3	1220	37.9861	36.7212	36.7142	0.007	6.14

Table 4.1.12a: Magnetised coupon at 0.76T for pH 4

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	10396	37.4324	32.9196	32.9173	0.0023	12.29
1	10375	37.9175	37.7455	37.7434	0.0021	5.54
1.5	1047	37.9861	35.4072	35.4038	0.0034	5.97
2	1166	37.9861	35.9922	35.9893	0.0029	3.82
2.5	1285	37.9861	35.6381	35.6353	0.0028	2.95
3	1404	37.6567	33.4631	33.4596	0.0035	3.10

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate (g/cm^2/hr)x10^{-5}
0.5	1058	37.9861	36.1548	36.1529	0.0019	10
1	10342	37.9861	37.7582	37.7570	0.0012	3.16
1.5	10374	37.9861	37.2478	37.2455	0.0023	4.04
2	678	37.9682	35.7384	35.7372	0.0012	1.58
2.5	367	37.8467	37.5872	37.5855	0.0017	1.8
3	10366	37.9861	38.1792	38.1789	0.0016	1.4

Table 4.1.13a: Magnetised coupons at 0.76T for pH 5

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate (g/cm^2/hr)x10^{-5}
0.5	1227	37.9861	36.0495	36.0458	0.0026	13.69
1	21866	39.1620	36.8289	36.8274	0.0015	3.83
1.5	21814	39.1620	37.2292	37.2263	0.0029	4.94
2	21882	39.4240	37.0552	37.0537	0.0015	1.90
2.5	1206	37.9861	34.1925	34.1885	0.004	4.21
3	1211	37.9861	36.4376	36.4338	0.0038	3.34

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr)x10^{-5}$
0.5	1148	37.9861	34.9894	34.9861	0.0033	17.38
1	10350	37.9861	38.9841	38.3911	0.003	7.90
1.5	1231	37.9861	36.2934	36.2895	0.0039	6.85
2	365	37.8467	37.3706	37.3672	0.0034	4.49
2.5	1109	37.9861	34.3299	34.3228	0.0071	7.48
3	21827	39.4240	37.8090	37.8009	0.0081	6.85

Table 4.1.14a: Magnetised coupons at 0.76T for pH 6

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr)x10^{-5}$
0.5	1232	37.9861	35.2527	35.2517	0.0008	4.21
1	10345	38.2732	38.8965	38.8957	0.0008	2.09
1.5	10365	37.9479	37.2744	37.2733	0.0011	2.00
2	670	37.9861	36.6174	36.6164	0.0010	1.32
2.5	21891	38.8094	36.0263	36.0250	0.0013	1.34
3	1307	37.9861	38.8921	35.6855	0.0013	1.14

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	1183	38.2732	35.5582	35.5570	0.0012	6.27
1	1479	37.3160	33.0992	33.0978	0.0014	3.75
1.5	1125	37.9861	36.1165	36.1147	0.0018	3.09
2	1149	37.9861	35.9480	35.9458	0.0022	2.9
2.5	1163	37.9861	36.0224	36.0202	0.0028	2.32
3	10362	38.3775	37.1374	37.1364	0.0025	2.17

Table 4.1.15a: Magnetised coupons at 0.95T for pH 2

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	1047	37.9861	35.3801	35.3616	0.0185	97.4
1	10375	37.9175	37.7392	37.7158	0.0234	61.7
1.5	1285	37.9861	35.6076	35.5679	0.0397	69.7
2	1404	37.6567	33.4314	33.3885	0.0429	57
2.5	1307	37.9861	35.6645	35.5949	0.0696	73.3
3	1211	37.9861	36.4119	36.3357	0.0762	66.9

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr)x10^{-5}$
0.5	1163	37.9861	36.0057	36.9852	0.0205	108
1	1231	37.9861	36.2757	36.2432	0.0325	85.6
1.5	1149	37.9861	35.9319	35.8887	0.0432	75.82
2	21827	39.4240	37.7969	37.7399	0.0570	72.3
2.5	365	37.8467	37.3630	37.2872	0.0758	80.11
3	1125	37.9861	36.0974	36.0290	0.0848	74.4

Table 4.1.15a: Magnetised coupons at 0.95T for pH 3

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr)x10^{-5}$
0.5	21891	38.8094	36.0054	36.0043	0.0011	5.67
1	1230	37.9861	35.9549	35.9532	0.0017	4.48
1.5	1206	37.9861	34.1606	34.1570	0.0036	6.32
2	1166	37.9861	35.9774	35.9738	0.0036	4.74
2.5	1253	37.9861	36.5698	36.5639	0.0059	6.21
3	10396	37.4324	32.8938	32.8927	0.0011	0.98

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	10374	37.9861	37.2259	37.2230	0.0020	10.5
1	1220	37.9861	36.7074	36.7053	0.0021	5.53
1.5	21865	39.1620	37.6922	37.6876	0.0046	7.83
2	1183	38.2732	35.5388	35.5339	0.0049	6.40
2.5	1109	37.9861	34.2962	34.2896	0.0066	6.95
3	10350	37.9861	38.3899	38.3854	0.0045	3.95

Table 4.1.16a: Magnetised coupons at 0.95T for pH 4

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	364	37.8467	36.5193	36.5191	0.0002	1.06
1	21814	39.1620	32.2177	32.2170	0.0007	1.79
1.5	10336	38.2732	36.6763	36.6759	0.0004	0.697
2	21887	38.8573	35.9590	35.9580	0.0012	1.29
2.5	412	38.8771	37.1966	37.1958	0.0008	0.823
3	21866	39.1620	36.8275	36.8266	0.0009	0.766

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate (g/cm^2/hr)x10^{-5}
0.5	10366	37.9861	38.1708	38.1698	0.001	5.27
1	10363	37.9861	36.4030	36.4019	0.0017	2.90
1.5	10371	37.8973	38.0060	38.0052	0.0008	1.41
2	21881	39.0635	37.4095	37.4081	0.0041	1.79
2.5	10372	37.9861	37.0062	37.0057	0.0015	1.58
3	1223	37.9861	36.2202	36.2182	0.002	1.76

Table 4.1.17a: Magnetised coupons at 0.95T for pH 5

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate (g/cm^2/hr)x10^{-5}
0.5	21888	39.0635	37.1669	37.1667	0.0003	1.54
1	10365	37.9479	37.2566	37.2560	0.0006	1.58
1.5	1227	37.9861	36.0403	36.0394	0.0009	1.58
2	10345	38.2732	38.8878	38.8872	0.0006	0.96
2.5	1232	37.9861	35.2402	35.2401	0.0001	0.105
3	21882	39.4240	37.0465	37.0461	0.0004	0.338

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr)x10^{-5}$
0.5	10362	38.3775	37.6320	37.6316	0.0004	2.09
1	10352	37.9861	37.1037	37.1029	0.0008	1.84
1.5	1119	37.9861	36.8751	36.8740	0.0011	1.93
2	1148	37.9861	34.9677	34.9667	0.001	1.32
2.5	429	37.9861	38.4032	38.4027	0.0005	0.527
3	678	37.9682	35.7263	36.7256	0.0007	0.615

Table 4.1.18a: Magnetised coupons at 0.95T for pH 6

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr)x10^{-5}$
0.5	670	37.9861	36.6104	36.6095	0.0009	4.74
1	1156	37.9861	36.3684	36.3680	0.0004	1.05
1.5	10354	38.7559	37.6628	37.6625	0.0003	0.516
2	21896	38.8094	35.9571	35.9568	0.0003	0.386
2.5	415	37.8773	36.4435	36.4431	0.0004	0.422
3	10378	37.7961	34.9988	34.9983	0.0005	0.441

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	10342	37.9861	37.7522	37.7500	0.0022	11.6
1	367	37.8467	37.5754	37.5741	0.0013	3.44
1.5	10347	37.8973	37.1915	37.1905	0.001	1.76
2	1228	37.9861	36.1698	36.1688	0.001	1.32
2.5	1479	37.3160	33.0938	33.0925	0.0013	1.39
3	1058	37.9861	36.1412	36.1399	0.0013	1.14

Table 4.1.19a: Magnetised coupons at 1.51T for pH 2

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	1230	37.9861	35.9515	35.9365	0.015	79
1	21866	39.1620	36.8333	36.8172	0.0161	41.1
1.5	364	37.8467	36.5203	36.5042	0.0161	28.4
2	21891	38.8094	36.0038	35.9736	0.0302	38.9
2.5	415	37.8973	36.4480	36.4313	0.0167	17.6
3	412	38.8771	37.1970	37.1741	0.0229	19.6

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate (g/cm^2/hr)x10^{-5}
0.5	1228	37.9861	36.1735	36.1568	0.0167	87.9
1	10366	37.9861	38.1736	38.1438	0.0298	78.5
1.5	10347	37.8973	37.1981	37.1739	0.0242	42.6
2	1223	37.9861	36.2210	36.1818	0.0392	51.6
2.5	429	37.9861	38.4063	38.3747	0.0316	33.4
3	10372	37.9861	37.0174	36.9853	0.0321	28.2

Table 4.1.20a: Magnetised coupons at 1.51T for pH 3

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate (g/cm^2/hr)x10^{-5}
0.5	1307	37.9861	35.5893	35.5799	0.0094	49.5
1	1227	37.9861	36.0408	36.0355	0.0053	14.0
1.5	1166	37.9861	35.9738	35.9611	0.0127	22.3
2	670	37.9861	36.6113	36.6005	0.0108	14.2
2.5	1404	37.6567	33.3884	33.3736	0.0148	15.7
3	21888	39.0635	37.1725	37.1605	0.012	10.2

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr)x10^{-5}$
0.5	1163	37.9861	35.9815	35.9700	0.0115	60.6
1	1220	37.9861	36.7087	36.7008	0.0079	20.7
1.5	1109	37.9861	34.2926	34.2755	0.0171	30.0
2	367	37.8467	37.5754	37.5621	0.0133	17.5
2.5	1183	38.2732	35.5386	35.5173	0.0213	22.3
3	10363	37.9861	36.4220	36.4070	0.0173	15.2

Table 4.1.21a: Magnetised coupons at 1.51T for pH 4

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr)x10^{-5}$
0.5	10375	37.9175	37.7162	37.7078	0.0084	44.3
1	10336	38.2732	36.6808	36.6749	0.0059	15.42
1.5	10345	38.2732	38.8914	38.8879	0.0035	6.10
2	10396	37.4324	32.8975	32.8865	0.0110	14.69
2.5	1232	37.9861	35.2383	35.2320	0.0063	6.63
3	1253	37.9861	36.5665	36.5652	0.0013	1.14

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate (g/cm^2/hr)x10^{-5}
0.5	10362	38.3775	37.6398	37.6300	0.0098	51.07
1	10350	37.9861	38.3897	38.3811	0.0086	22.64
1.5	10371	37.8973	38.0113	38.0051	0.0062	10.91
2	21865	39.1620	37.6950	37.6835	0.0151	19.28
2.5	1479	37.3140	33.0961	33.0863	0.0098	10.51
3	10374	37.9861	37.2243	37.2200	0.0043	3.77

Table 4.1.22a: Magnetised coupons at 1.51T for pH 5

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate (g/cm^2/hr)x10^{-5}
0.5	1156	37.9861	36.3685	36.3655	0.003	15.8
1	1047	37.9861	35.3593	35.3565	0.0028	7.37
1.5	1211	37.9861	36.3310	36.3291	0.0019	3.34
2	1285	37.9861	35.5677	35.5554	0.0123	16.2
2.5	10354	38.7559	37.6662	37.6610	0.0052	5.37
3	21882	39.4240	37.0487	37.0479	0.0008	0.676

(b) Magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate (g/cm^2/hr)x10^{-5}
0.5	365	37.8467	37.3428	37.3336	0.0092	48.6
1	429	37.9861	38.4172	38.4024	0.0048	12.64
1.5	21881	39.0635	37.4183	37.4141	0.0042	7.17
2	1125	37.9861	36.0323	36.0177	0.0146	19.2
2.5	1223	37.9861	36.2226	36.2143	0.0083	8.74
3	1149	37.9861	35.8968	35.8924	0.0044	3.86

Table 4.1.23: Magnetised coupons at 1.51T for pH 6

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate (g/cm^2/hr)x10^{-5}
0.5	10378	37.7961	34.9998	34.9928	0.007	37.0
1	21887	38.8573	35.9640	35.9608	0.0032	8.24
1.5	1206	37.9861	34.1521	34.1519	0.0002	0.351
2	10365	37.9479	37.2603	37.2547	0.0056	7.38
2.5	21896	38.8094	35.9608	35.9541	0.0067	6.91
3	21814	39.1620	37.2154	37.2148	0.0006	0.511

(b) Non magnetised coupons

Time (hr)	Coupon No	Area (cm^2)	Initial wt (g)	Final wt (g)	Wt loss (g)	Corr. Rate ($g/cm^2/hr$)x10^{-5}
0.5	21827	39.4240	37.7425	37.7272	0.0153	77.6
1	1231	37.9861	36.2441	36.2376	0.0065	17.11
1.5	678	37.9682	35.7291	35.7258	0.0033	5.79
2	1148	37.9861	34.9697	34.9586	0.0111	14.61
2.5	1119	37.9861	36.8792	36.8606	0.0186	19.59
3	1058	37.9861	36.1404	36.1331	0.0073	6.41

4.2 TABLES FOR INHIBITION EFFICIENCIES

Table 4.2.1: Inhibition efficiency for pH 5 at different magnetic field strengths (MFS)

Time(hr)	EI(%) at diff MFS				
	0.38T	0.57T	0.76T	0.95T	1.51T
0.5	16	86.71	21.23	26.32	67.49
1	64.88	32.49	51.52	14.13	41.69
1.5	38.90	43.60	27.88	18.14	53.42
2	56.27	54.48	57.68	30.30	15.63
2.5	34.60	41.36	43.72	79.25	38.56
3	49.32	54.23	51.24	45.16	82.38

Table 4.2.2: Inhibition efficiency for pH 6 at different magnetic field strengths (MFS)

Time(hr)	EI(%) at diff MFS				
0.38T	0.57T	0.76T	0.95T	1.51T	
0.5	16.78	83.76	32.86	59.14	52.32
1	25.94	87.62	44.27	69.48	51.84
1.5	60.82	50.58	35.28	70.46	93.96
2	43.92	54.75	54.48	70.46	49.49
2.5	96.17	55.79	42.24	70.00	64.64
3	56.13	67.45	47.47	61.40	92.04

Table 4.2.3: Inhibition efficiency for 0.95T at different pH levels

Time(hr)	EI(%) at diff pH levels				
pH2	pH3	pH4	pH5	pH6	
0.5	9.82	46.00	79.89	26.32	59.14
1	27.92	18.99	38.28	14.13	69.48
1.5	8.07	19.29	50.36	18.14	70.46
2	2.12	25.94	27.93	30.30	70.46
2.5	8.50	10.65	48.10	79.25	70.00
3	10.08	75.19	56.25	45.16	61.40

Table 4.2.4: Inhibition efficiency for 1.51T at different pH levels

Time(hr)	EI(%) at diff pH levels				
pH2	pH3	pH4	pH5	pH6	
0.5	10.13	18.32	14.29	67.49	52.32
1	47.64	32.37	31.89	41.69	51.84
1.5	33.33	25.67	44.09	53.42	93.96
2	24.61	19.18	23.81	16.63	49.49
2.5	47.15	29.60	36.92	38.56	64.64
3	30.50	32.90	69.76	82.38	92.04

4.3 INHIBITIVE MECHANISM OF PARAMAGNETISM ON CORROSION RATES

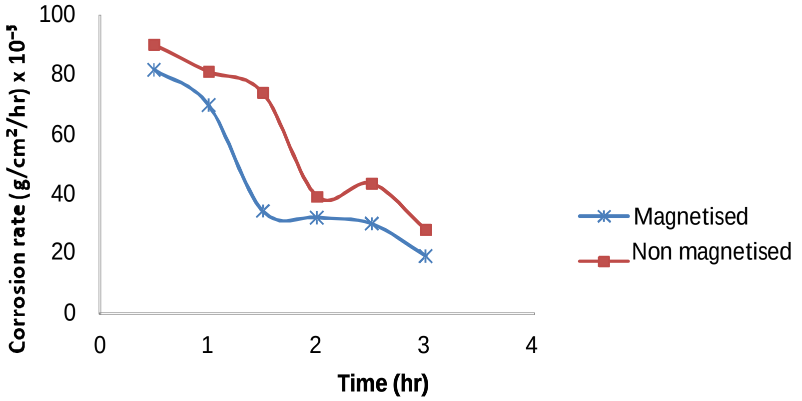


Fig.4.3a: Corrosion rate against time for pH 2 at 0.57T

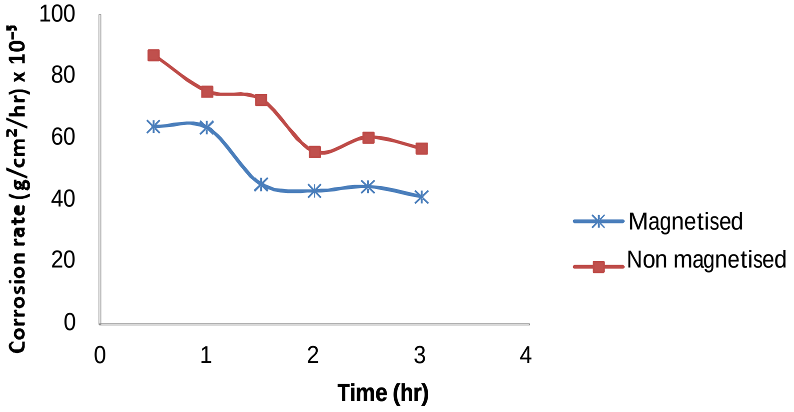


Fig.4.3b: Corrosion rate against time for pH 2 at 0.76T

Figures 4.3a and b show that the corrosion rates of magnetized coupons reduced less than the values obtained in those of the non magnetized coupons. This could be attributed to the adsorption of paramagnetic substances, $FeCl_2$ and $FeCl_3$ on the metal surface, thus inhibiting corrosion. It has been shown (Davis, 2010) that ions for example Fe^{2+} and Fe^{3+} interact with magnetic fields. Two possible mechanisms may be involved; the first mechanism is that there is a formation of Fe^{2+} or Fe^{3+} which interact with the field before being linked to the chloride ion (Cl^-) to form iron chloride compound. It is very probable that the corroding metallic surface would have initially established an electrical double layer between the ions and the associated electrons on the metal surface. Thereafter, being paramagnetic, the ions are attracted to the surface of the magnetized coupons. This tendency is possibly assisted by the Lorentz force additive that engenders motion in ionic species in the presence of a magnetic field. The paramagnetic Fe^{2+} and Fe^{3+} formed are attracted to the surface of the metal by magnetic and Lorentz forces. This may explain the comparative rapid reduction in corrosion rates of magnetized coupons in the first few minutes of initiation of the experiments.

From the periodic table (see appendix), iron a transition element (meaning an element with partially filled orbital) with atomic number 26 and electronic configuration $1s^2 2s^2 2p^6 3s^2 3p^6 3d^6 4s^2$, when placed in an electrolyte ionizes and loses mainly 2 electrons to become Fe^{2+} or 3 electrons to give Fe^{3+}. The Fe^{2+} has the electronic configuration of $1s^2 2s^2 2p^6 3s^2 3p^6 3d^6$, with 4 unpaired electrons and Fe^{3+} has the electronic configuration of $1s^2 2s^2 2p^6 3s^2 3p^6 3d^5$ with 5 unpaired electrons. Fe^{3+} is more stable than Fe^{2+} because all the five 3d orbital are singly filled ($3d^5$), and this electronic configuration gives the iron (III) ion a special stability. Iron (II) compounds are easily oxidized to iron (III) compounds (Ababio, 1992). The presence of these unpaired electrons makes iron (II) and iron (III) ions paramagnetic (Davis, 2010; Molholt et al., 2012).

Having established that the two ions formed are paramagnetic and can be attracted to the magnetized coupon, the corrosion abatement could be that iron (II) and iron (III) ions adhered to the metal surface due to magnetic attraction before chloride ions become attached to the metal ions to form iron chloride compounds.

The second mechanism is that Fe^{2+} or Fe^{3+} reacts with chloride ion to form unstable $FeCl_2$ or stable $FeCl_3$ before adhering to the metal surface and inhibiting corrosion. Iron (II) chloride and Iron (III) chloride have positive magnetic susceptibilities (see Figure 2.3) of $+14750/10^{-6} cm^3 mol^{-1}$ and $+13450/10^{-6} cm^3 mol^{-1}$ respectively (Landolt,1992; Waskaas,1996) and are thus paramagnetic; implying that they can be attracted to the magnetic field produced by the magnetized mild steel coupon. The iron compound gets adhered to the metal surface and covers some of the anodic sites, thus bring about the reduction in corrosion rates as compared to the non magnetized coupons.

4.4 INFLUENCE OF LOW pH ON CORROSION RATES AT 0.38T

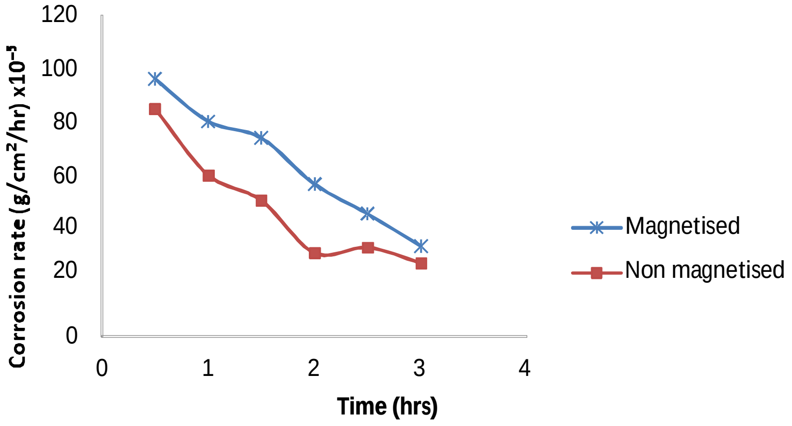


Fig. 4.4a: Corrosion rate against time for pH 2 at 0.38T

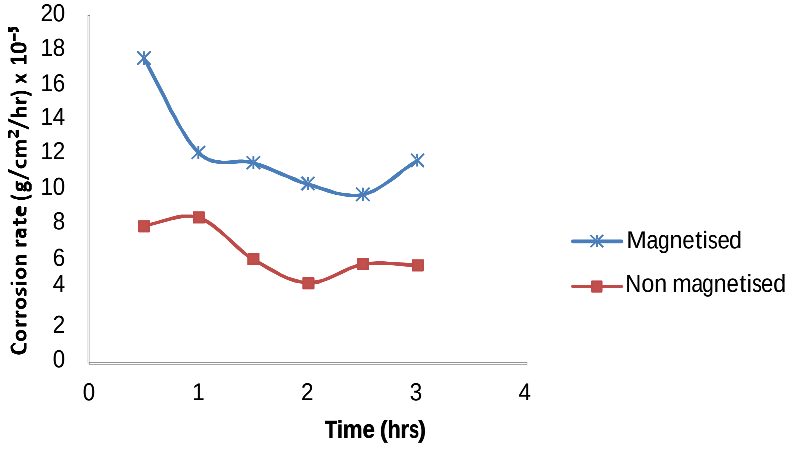


Fig. 4.4b: Corrosion rate against time for pH 3 at 0.38T

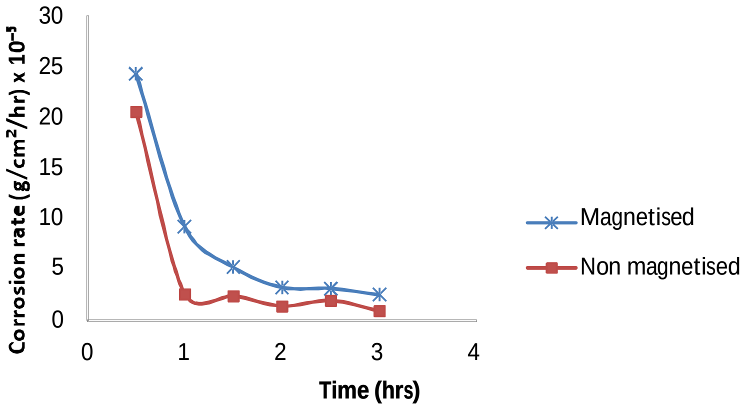


Fig.4.4c: Corrosion rate against time for pH 4 at 0.38T

At these low pH values, pH 2, pH 3 and pH 4 as shown in Figures 4.4a, b and c respectively for MFS 0.38T, the corrosion rates of the non magnetized coupons were less than those of the magnetized. This is because the magnetic field was not strong enough to keep the formed paramagnetic substances on the surface of the magnetized coupon. The paramagnetic substances formed detached from the metal surface and thus more anodic sites were made available for corrosion attack.

4.5 INFLUENCE OF HIGH pH ON CORROSION RATES AT 0.38T

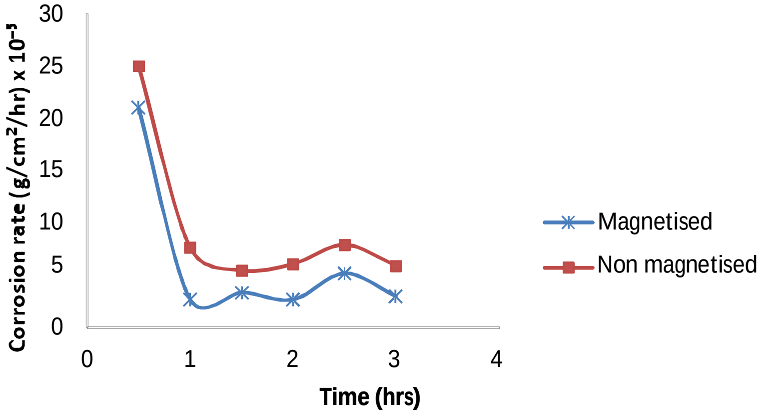


Fig.4.5a: Corrosion rate against time for pH 5 at 0.38T

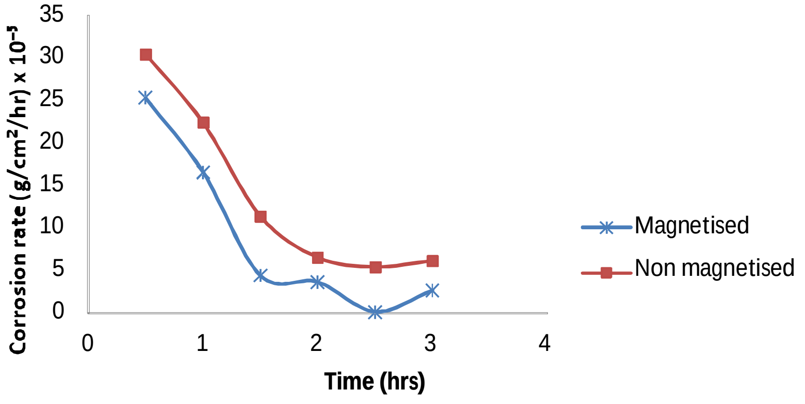


Fig. 4.5b: Corrosion rate against time for pH 6 at 0.38T

Figures 4.5a and b show that there is a reduction in corrosion rates in the magnetized coupons as compared to the non magnetized. In Figure 4.5a, the magnetized coupons attained the inhibition efficiency of 65% at 1hr.

In Figure 4.5b there is a noticeable difference in the corrosion rates of the magnetized to the non magnetized, the inhibition efficiency of 96% at 2.5hrs was attained.

4.6 INFLUENCE OF LOW pH ON CORROSION RATES AT 0.57T

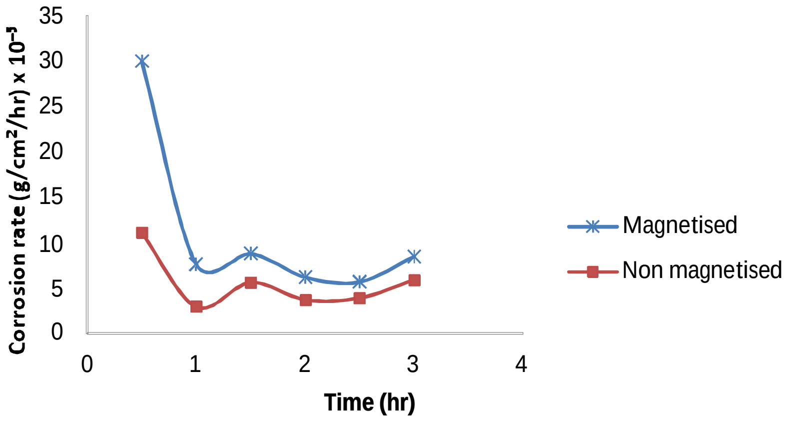


Fig.4.6a: Corrosion rate against time for pH 3 at 0.57T

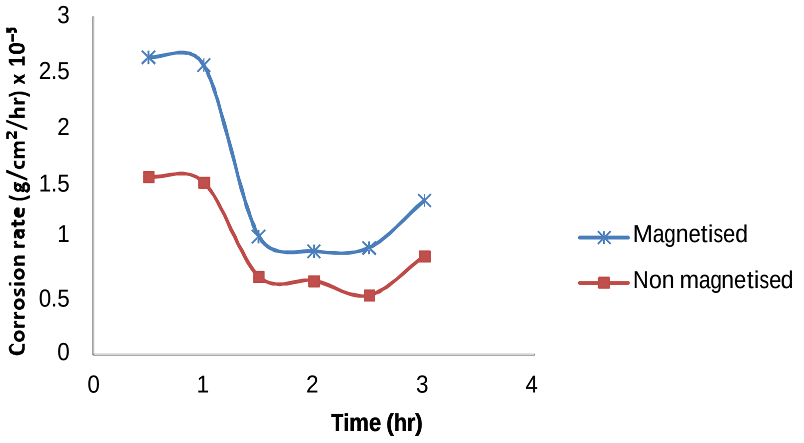


Fig.4.6b: Corrosion rate against time for pH 4 at 0.57T

The corrosion rates of non magnetized coupons are less than the values obtained for magnetized coupons as shown in Figures 4.6a and b. The paramagnetic species were formed but could not firmly adhere to the surface of the magnetized coupons, thus the increase in corrosion rates.

4.7 INFLUENCE OF HIGH pH ON CORROSION RATES AT 0.57T

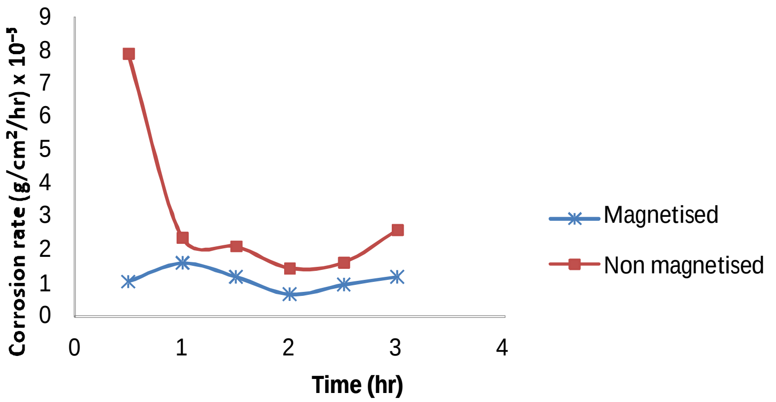


Fig. 4.7a Corrosion rate against time for pH 5 at 0.57T

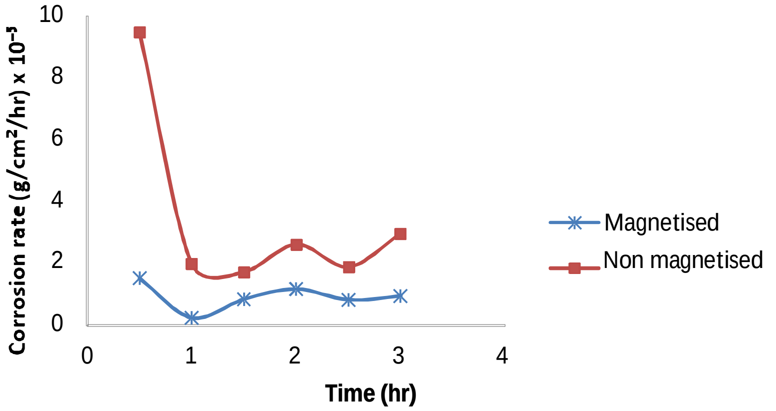


Fig. 4.7b Corrosion rate against time for pH 6 at 0.57T

In Figure 4.7a and b, an appreciable reduction in corrosion rates was obtained for the magnetized coupons, giving the inhibition efficiency of 87% at 0.5hr for Figure 4.7a and 88% at 1hr for Figure 4.7b.

4.8 INFLUENCE OF LOW pH ON CORROSION RATES AT 0.76T

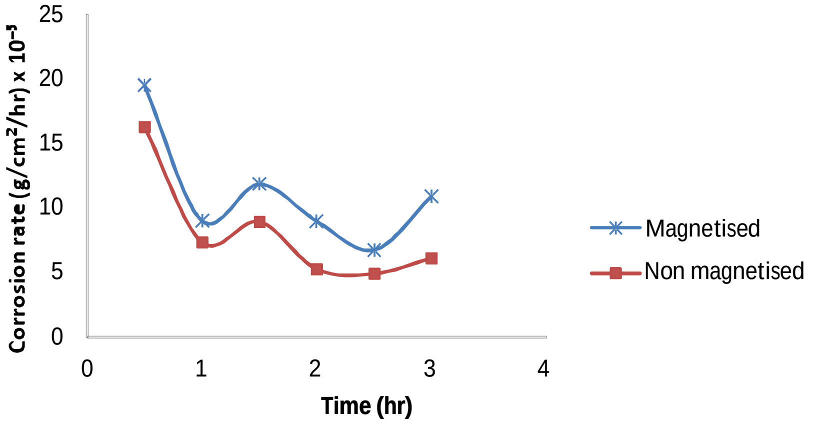


Fig.4.8a Corrosion rate against time for pH 3 at 0.76T

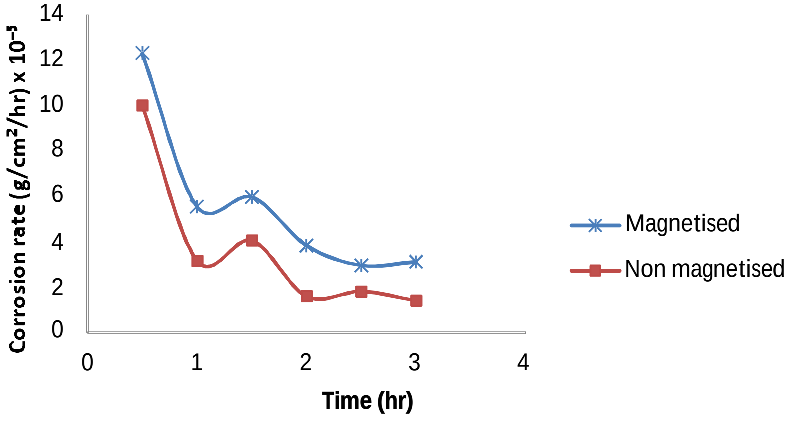


Fig.4.8b Corrosion rate against time for pH 4 at 0.76T

In Figures 4.8a and b, the corrosion rates of magnetized coupons were more than the values obtained for magnetized coupons. The magnetic field was not strong enough to keep the formed paramagnetic species on the surfaces of the magnetized coupons, thus an increase in corrosion rate.

4.9 INFLUENCE OF HIGH pH ON CORROSION RATES AT 0.76T

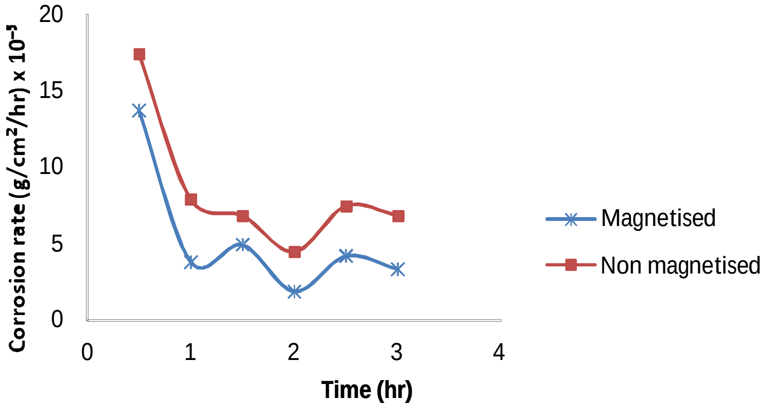


Fig.4.9a Corrosion rate against time for pH 5 at 0.76T

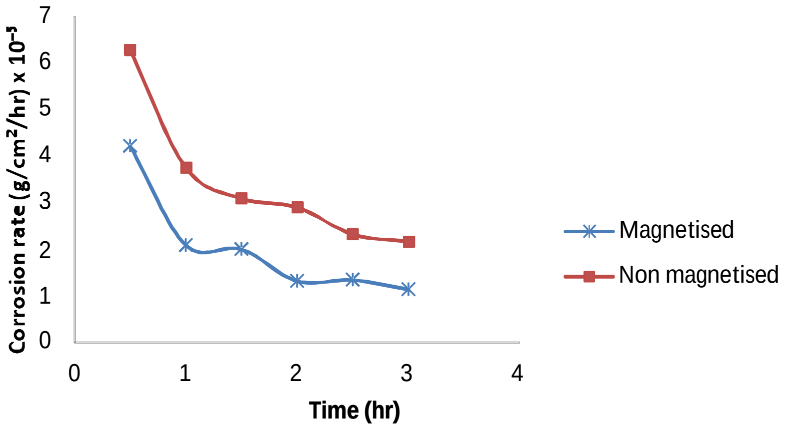


Fig.4.9b Corrosion rate against time for pH 6 at 0.76T

The magnetized coupons in both Figure 4.9a and b have corrosion rate values less than those of the non magnetized. The inhibitive effects of the formed paramagnetic species were most effective at 2hrs, with Figure 4.9a attaining 58% and Figure 4.9b 55%.

4.10 INFLUENCE OF HIGH pH ON CORROSION RATES AT 0.95T

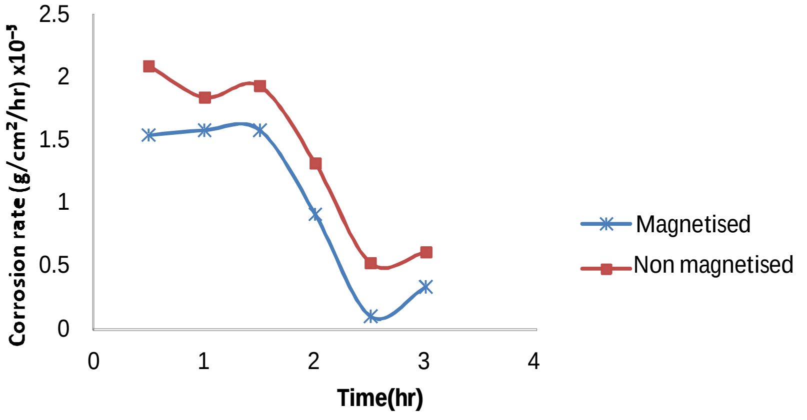


Fig.4.10a Corrosion rate against time for pH 5 at 0.95T

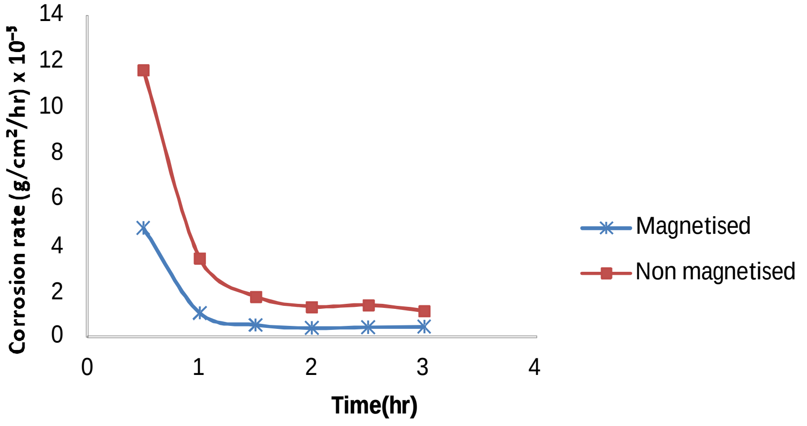


Fig.4.10b Corrosion rate against time for pH 6 at 0.95T

In Figure 4.10a, a decrease in corrosion rate is noticeable, and at 2.5hrs, a79% inhibition efficiency was attained.

In Figure 4.10b, a drastic reduction in corrosion rate is seen for the magnetized coupons leading to constancy in corrosion rate, and the inhibition efficiency of 71% was attained at 2hrs.

4.11 INFLUENCE OF HIGH pH ON CORROSION RATES AT 1.51T

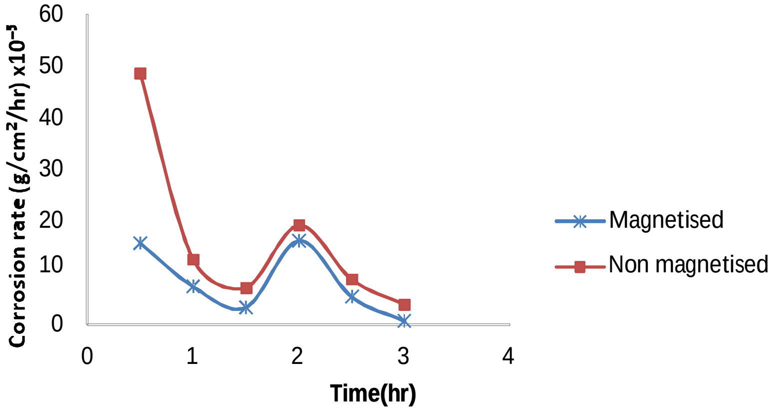


Fig.4.11a Corrosion rate against time for pH 5 at 1.51T

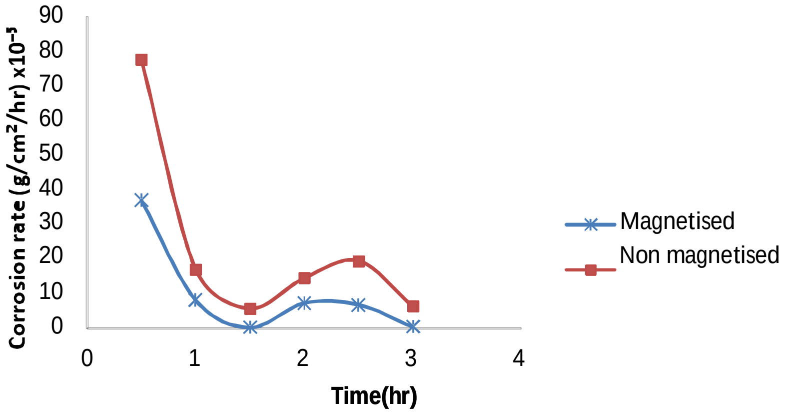


Fig.4.11b Corrosion rate against time for pH 6 at 1.51T

The magnetized coupons inhibited corrosion in Fig 4.11a and b and the inhibitive efficiency attained in Figure 4.11a is 82% at 3hrs and, 94% at 1.5hrs in Figure 4.11b. At these times the paramagnetic compounds adhered strongly to the surface of the metal.

4.12 EFFECT OF MAGNETIC FIELD STRENGTH ON CORROSION RATES AT 0.95T

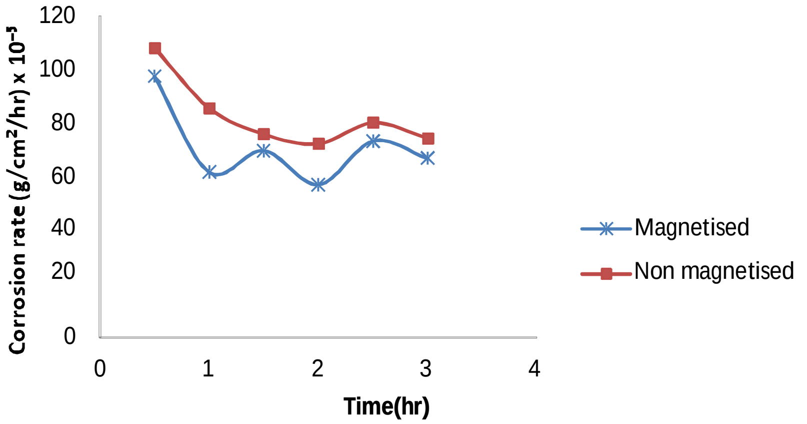


Fig.4.12a Corrosion rate against time for pH 2 at 0.95T

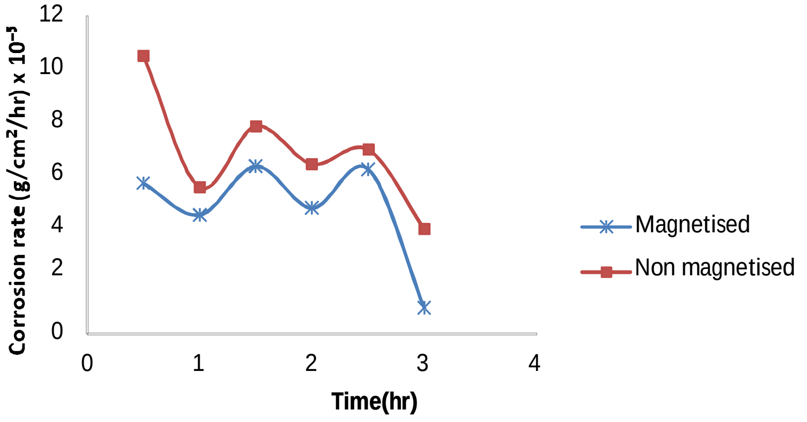


Fig.4.12b Corrosion rate against time for pH 3 at 0.95T

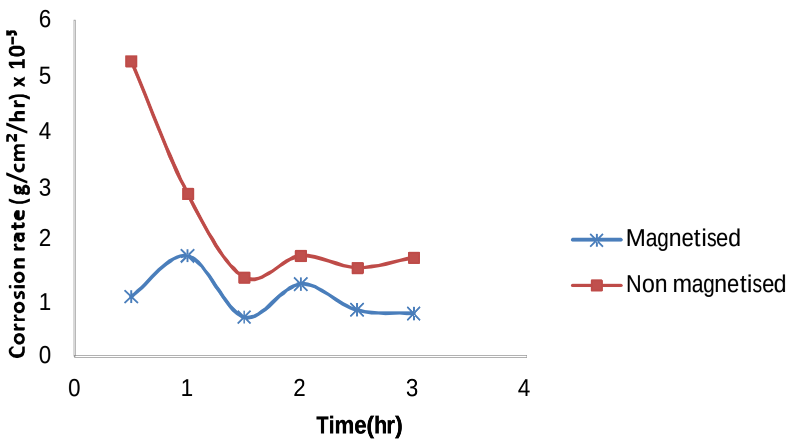


Fig.4.12c Corrosion rate against time for pH 4 at 0.95T

(Graphs for pH 5 and 6 have been shown in Figures 4.10a&b)

At the low pH level seen in Figure 4.12a, there will be marked attack on the metal leading to an attained low inhibition efficiency of 28% at 1hr. But in Figure 4.12b and c, the attained inhibition efficiencies are 75% at 3hrs and 80% at 0.5hr respectively.

In Figure 4.12a, b and c, the magnetic field on the magnetized coupons was strong enough to attract the paramagnetic species in the highly corrosive medium, and the latter adhered to the metal surface resulting to an inhibitive effect.

4.13 EFFECT OF MAGNETIC FIELD STRENGTHS ON CORROSION RATES AT 1.51T

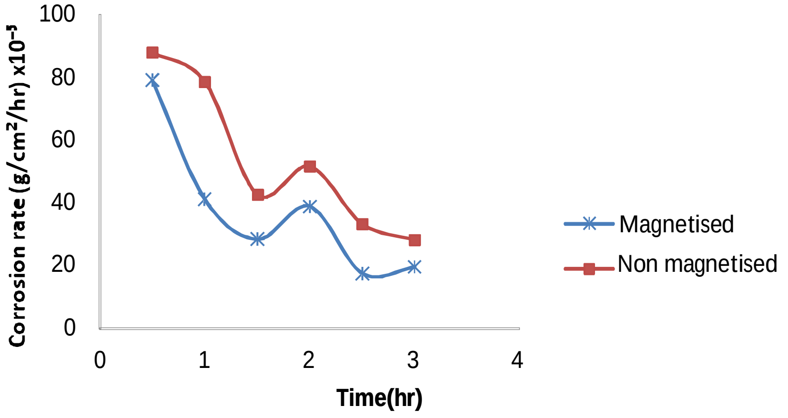


Fig.4.13a Corrosion rate against time for pH 2 at 1.5T

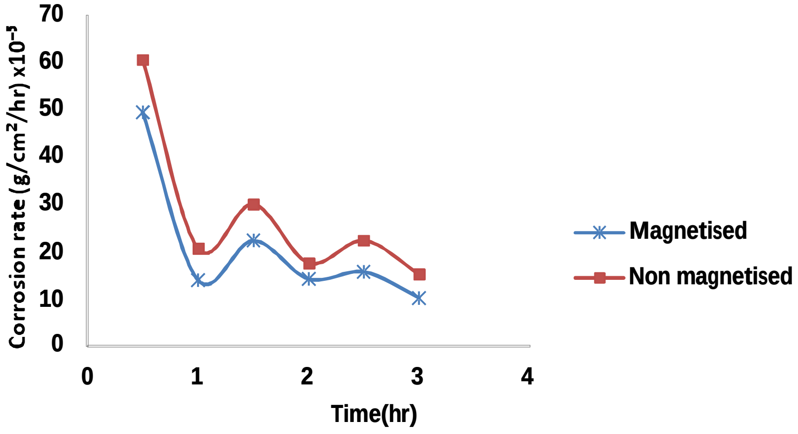


Fig.4.13b Corrosion rate against time for pH 3 at 1.51T

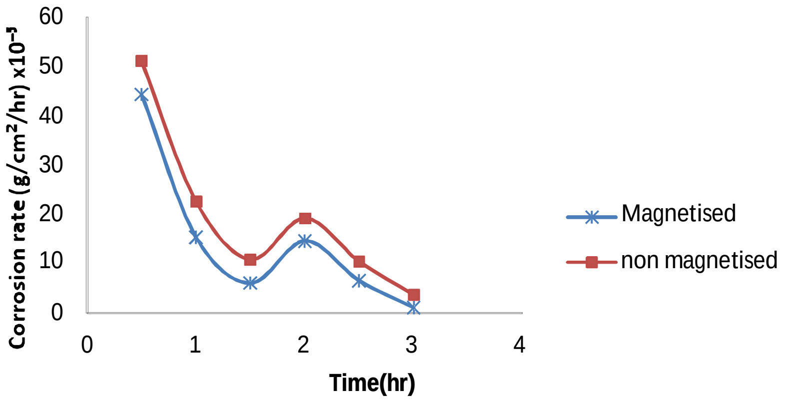


Fig.4.13c Corrosion rate against time for pH 4 at 1.51T

(Graphs for pH 5 and 6 has been shown in Figures 4.11a&b)

In Figure 4.13a, a low inhibition efficiency of 48% at 1hr was obtained; Figure 4.13b and c were 33% and 70% respectively, both at 3hrs. Notwithstanding that the acidic content is high in these; paramagnetic species were able to cause corrosion abatement on the magnetized coupons.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Under the conditions in which the experiments were carried out, the following conclusions are made.

- The magnetized AISI mild steel coupons exhibited lower corrosion rates than the non magnetised coupons for pH 5 and pH 6 for all the magnetic field strengths (MFS) investigated, and this is attributed to formation and adhesion of paramagnetic substances on the metal surface.
- The coupons magnetized at MFS 0.95T and 1.51T had more corrosion resistance than the non magnetized coupons for all the pH levels investigated, also attributed to appreciable tenacious adhesion of formed paramagnetic species on metal surface as to withstand the high corrosive action of the acid at low pH values.
- Some of the coupons magnetized at MFS 0.38T, 0.57T, and 0.76T had higher corrosion rates at pH 2,pH 3 and pH 4 than those of the non magnetized due to detachment of adhered paramagnetic species on the metal surface, thus creating more anodic sites for more corrosion attack.
- Inhibition efficiency reached 87% and 96% for pH5 and pH6 respectively for the magnetised coupons at all the MFS investigated.

- Inhibition efficiency reached 80% and 94% for 0.95T and 1.51T respectively for the magnetised coupons at all pH levels investigated.
- Results of this work may find application in the oil and gas industry where the oil and gas are known in some instances to be associated with acid forming species like CO_2, H_2S and microbes that lead to attack of the pipeline to form paramagnetic substances like $FeCO_3$, $FeSO_4$ and FeS (Landolt, 1992).

5.2 CONTRIBUTIONS TO KNOWLEDGE

- Paramagnetic species $FeCl_2$, $FeCl_3$ have been employed in the corrosion abatement of mild steel in an acid medium.
- Corrosion abatement of mild steel coupons magnetized at 0.38T, 0.57T and 0.76T in acid medium was best achieved at pH values from 5 and above.
- In this work, a novel technique was used in which the magnetic field contiguous with the corroding acid medium was generated by the magnetized mild steel coupons that at the same time induced the paramagnetic effect on the Fe^{2+} and Fe^{3+} ions. This is distinct from previous works where the corrosion experiments were carried out in externally generated magnetic fields.

5.3 RECOMMENDATIONS

- The study can be carried out for a longer period of time.
- Higher magnetic field strengths can be used in magnetizing the coupons.
- The laboratories in the universities should be properly equipped to enhance more research work being carried out by both students and staff.

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APPENDIX

APPENDIX A: PERIODIC TABLE

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period 1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57- 71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89- 103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Periodic Table Key

X Synthetic Elements

X Liquids or melt close room temp.

at**X** to Solids

X Gases

Alkali Metals	Alkali Earth Metals	Transition Metals	Other Metals	Metalloids	Other Non Metals	Halogens	Noble Gases	Lanthanides & Actinides
■	■	■	■	■	■	■	■	■