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DESIGN, EVALUATION AND PREDICTION OF CORROSION RATES ON MILD STEEL IN SOME SELECTED ENVIRONMENTS

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ABSTRACT

The study investigates the rate of corrosion and its impact on mild steel. The test was carried out in different selected environments, to understand their environmental influence and the rate of corrosion in that environment namely: 0.1M of Hydrochloric acid, Underground (soil), Atmosphere, Salt water and Fresh water. A mild steel of diameter 1.2cm and 8.5cm long was used for this experiment and studied for a period of six weeks interval weighing and re-immersing. The weight losses were tabulated and analyzed graphically. It was observed that mild steel corroded in the different environment with decreasing intensity in the order of 0.1M of Hydrochloric acid, Underground (soil), Atmosphere, Salt water, Fresh water. This will help Mild Steel industries and/or companies that use mild steel as one of their major production materials and/or their major construction materials to understand the impact of the corrosion rate in the selected environments.

Index Terms: Mild steel, Atmosphere, Corrosion rate, Underground (soil), Fresh water, Salt water, Hydrochloric acid.

1. INTRODUCTION

Mild steel is used in several Engineering applications for the production of some automobile components, structural shapes (I beam and angle iron) and sheets that are used in pipelines, buildings, plants, bridges and tin cans (Callister, 1997). It is majorly used as construction materials. However, mild steel is known for its high carbon content of about 0.2% to 2.1%, manganese (1.65%), copper (0.6%), silicon (0.6%). It is produced from steel which is been extracted from pig iron and also less expensive to produce and it is readily available. It has outstanding ductility and toughness, high machinability and weldability which make its applications possible in the engineering fields (Achebo, Ezeliora & Umeh, 2019; Ezeliora, Mbanusi & Aguh, 2019). The application for which mild steel was developed generally did not involve corrosion resistance as a primary consideration; corrosion resistance of metals and alloys is a basic property related to the ease with which these metals react with a given environment. With the increased utilization of this metal in the manufacturing and construction firms, one of the major problems encountered is the control of corrosion rate when exposed to different corrosive environments. Corrosion is a natural process that reduces the binding energy in metals with the end result involving a metal being oxidized as the bulk metal losses one or more electrons. The lost electrons are conducted through the bulk metal to another site where they are reduced. In corrosion, the site where the metal atom losses electron is called the anode and the reducing species is called the cathode. Also, corrosion can be said to be the degradation of metallic materials properties due to interactions with its environments. Corrosion of most metals is inevitable while primarily associated with metallic materials; all material types are susceptible to degradation. Most metals in contact with water (and moisture in air), acids, bases salts, oils, oppressive metal polishes and other solid and liquid chemicals corrode as well as when exposed to gaseous materials like acid vapors, ammonia gas and sulphur containing gases. Corrosion processes are usually electrochemical in nature, having the essential features of a battery. When metal atoms are exposed to an environment containing water molecules they can give up electrons becoming themselves positively charged ions provided an electric circuit can be well extended across a wide area to produce general wastage. All metals exhibit the tendency to oxidize, some more easily than the others. A tabulation of the relative strength of this tendency is the galvanic series. The knowledge of a metal's position in this series helps in decision making for appropriate potential utility of a metal in structural and other applications. In a corrosion cell, the electron produced by the corrosion reaction will need to be consumed by a cathodic reaction in close proximity to the corrosion reaction itself. The electron and the hydrogen ions react to first

form atomic hydrogen and then molecular hydrogen gas. As the hydrogen forms, it tends to inhibit further corrosion by forming a very thin gaseous film at the surface of the metal. This film can be effective in reducing metal (Ezeliora, Umeh & Dilinna, 2020) to water contact and thus reducing corrosion rate. Dissolved oxygen in water will react with the hydrogen, converting it to water thus destroying the film. When the fresh metal is exposed to water, high water velocities can also sweep film away. Other corrosion accelerating actors includes; pH values and high temperature which increase virtually all chemical reactions. Thus a variety of natural and environmental factors can have significant effect on the corrosion rate of metals even when no other special conditions are involved (Amadi, 2000). In most situations its serviceability depends on the fact that following the initial corrosive attack, protective films formed that tend to reduce the corrosion rate to some acceptable level (Schweitzer, 1968). For the effective use of this steel in different engineering applications, there is the need to consider the corrosion rate engulfing this metal. The approach geared towards this phenomenon involves a basic knowledge of the structural features of the metal, the component data of the corrosion reaction that occurs at the metal environment interface. This enquiry is obviously necessary because corrosion reduces the useful life of plants and equipment and can often result in unscheduled shutdowns or in some cases, catastrophic failure (Ibert, 1970).

The objective of this study is to the rate of corrosion of the mild steel in five different environments namely: 0.1M of Hydrochloric acid, Underground (soil), Atmosphere, Salt water, Fresh water and.

Corrosion Fundamentals: Corrosion is the degradation of materials' properties due to interactions with their environments and corrosion of most metals is inevitable while primarily associated with metallic materials (Achebo, Ezeliora & Umeh, 2019; Ezeliora, Mbanusi & Aguh, 2019), all material types are susceptible to degradation. The corrosion of steel by natural and industrial waters is a complicated and many sided phenomenon, due to three main considerations involved;

i. The composition and surface condition of the steel
ii. The quality of the water
iii. The operating conditions

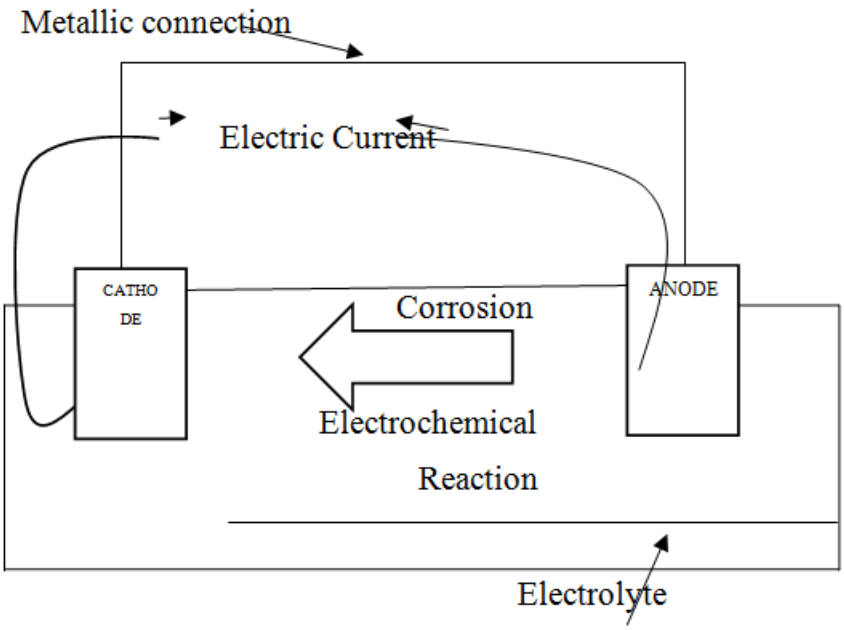

Figure 1: Basic Corrosion Cell.

Forms of Corrosion: There are several forms of corrosion also referred to as modes or mechanisms of corrosion. The different forms and sub-forms of corrosion are analogous to different failure mechanisms in the mechanical world (fast fracture, fatigue, ductile tearing, wear, etc.). Corrosion may occur depending upon the metal involved, its size and shape, the atmospheric conditions and the corrosion producing pollutants present. A popular classification of forms of corrosion has been made as in ASM Handbook volume 13 on "corrosion". However, corrosion can be divided into several forms and sub forms as shown below.

Uniform Corrosion: Uniform corrosion is weight loss corrosion whereby the area of the metal loss occurs over a relative large area so that the surface is uniformly attacked. This is common to carbon steels exposed to atmospheric corrosion and strong inhibited acids. Typically, uniform corrosion occurs gradually and failure takes longer to occur.

Galvanic corrosion: This occurs when two metals or alloys having different compositions are electrically coupled while exposed to an electrolyte. The less noble or more reactive metal in the particular environment will experience corrosion; the more inert metal, the cathode will be protected from corrosion.

Atmospheric corrosion: This is the corrosion of metal due to exposure of the metal to the humidity of the air or pollutants. In this project work, for the purpose of the subject under

study atmospheric, underground (soil), salt water, fresh water and hydrochloric environments shall be considered. Unprotected metals exposed to the atmosphere will inevitably experience damage due to atmospheric corrosion. Metals are mostly exposed to atmospheric environment than any other corrosive environment. The rusting of bare Steel in the atmosphere is controlled by the climatic condition at the exposure site. The main factors are the availability of moisture and the extent to which the air is polluted.

Moisture: Moisture can reach a steel surface directly in liquid form as a result of precipitation, that is rain and dew, and from water vapor in air. Rusting is minimal in pure air of less than 100% relative humidity, but that in the presence of minute concentration of impurities such as sulphur dioxide, serious rusting can occur.

Pollution: The most important impurity in industrial atmospheres is sulphur dioxide, although chlorides H_2S, NO_2 carbon compounds and ammonium salts may also have an effect. SO_2 in air originates from the combustion of fuel. Generally, chlorides have the most pronounced effects near the coast and as a rule, the chloride concentration in air Palls off rapidly with distance inland. Dust particles act as nuclei for the initial corrosion attack.

Temperature: It has effect on humidity and consequently an indirect effect on corrosion.

Effect of exposure condition: The orientation of the steel influences the rate of rusting through its effect on the amount of moisture and pollutants that can reach the surface.

Oxidation and tarnishing: This is corrosion attack caused by direct contact between the metal and these agents at high temperatures. However, certain areas of the metal surface corrode at higher rates than others due to heterogeneities in the metal, the environment or in the geometry of the structure as a whole.

Crevice corrosion: This occurs at places with gaskets, bolts and lap joints where crevices exist. Here oxygen inside a crevice is consumed more rapidly than the diffusion of fresh oxygen into the crevice. The difference in oxygen concentration creates a potential difference and causes corrosion in the oxygen deficient area of the crevice.

Pitting corrosion: This is termed "under deposit corrosion", and is a localized deep penetration on the metal or alloy surface, which forms passive oxide films where local film breakdown creates a small anode - large cathode combination. Due to surface deposits,

electrical imbalance or some other initiating mechanisms, all existing corrosion potential attacks a selected number of individual sites. In most cases, pitting is extended throughout the entire metal surface, creating an irregular or very rough surface profile. Pitting is the most common form of corrosion found where there are incomplete chemical protective films and insulating or barrier deposits of dirt, iron oxide and other foreign substances at the pipe surface. Also, localized microbiological corrosion is the most severe and threatening form of corrosion to pitting systems. This is caused by the presence of various microbiological agents or organisms under specific environmental conditions. In some cases it results in advanced and widespread failure of entire piping systems within a few years**.**

2. Factors that Influence Corrosion

There are factor that influence the cause of corrosion on metals. These factors are;

Mechanically assisted corrosion

These are corrosion attacks due to the synergistic action of a mechanically factor.

Erosion or Flow Induced Corrosion: Most metals depend on the formation and maintenance of a protective scale for corrosion resistance. Removal of the scale at local areas can lead to accelerated corrosion. High velocity flow or turbulence can erode away the protective scale to expose new metal surface to corrosive attack. The combination of the erosion of the scale and corrosion of the underlying metals is termed flow - enhanced corrosion or erosion.

Fretting Corrosion: This is a corrosion attack that is accelerated by the relative motion of contacting surfaces,

Cavitation and Water Drop Impingement Corrosion: Cavitation is caused by tee formation and collapse of vapor bubbles in fluids due to rapid change in pressure. It can occur when the absolute pressure at a point in the liquid is reduced to the vapor pressure of the fluid causing the bubbles to collapse. When the void walls collide, a tremendous shock wave is generated, this exerts a pressure up to $1.5GNln^{-2}$ on small adjacent areas of metal surface. This pressure plastically deforms the metal. The repetitive impact of bubble collapse within the fluid wears away the metal, this is Cavitation damage.

Corrosion Fatigue: This occurs in metals as a result of cyclic stress and corrosive environments.

Mechanism of Rusting of Iron (Mild Steel): In pure dry, air at normal temperatures a thin protective oxide film forms on the surface of polished mild steel. The oxide film is not protective in the presence of electrolytes and usually breaks down in air, water and soil.

The anodic reaction is

$Fe \longrightarrow Fc^{2+} + 2e^{-}$

In de-aerated solutions, the cathodic reaction is

$2H^{+} + 2e^{-}$

This occurs fairly rapidly in acids but very slowly in alkaline and neutral solutions. This is the common form of cathodic reaction in most environments. The OI-l- ions react with Fe^{2+} ions to form ferrous hydroxide.

$Fe^{2+} + OH \longrightarrow Fe(OH)_2$

This is oxidized to ferric hydroxide ($Fe(OH_3)$) which is a simple form of rust. The final product is the familiar reddish brown rust Fe_2O_3. H_2O of which there are a number of varieties, in situations where supply of oxygen is restricted Fe_3O_4 may be formed (Scheie, 1992).

Research Method: Similar sizes of mild steel will be exposed to different corrosive environments and will be left for a stipulated period of six weeks with a weekly interval of collection, weighing and re-immersing into the various environments (Ezeliora, Umeh & Dilinna, 2020; Chinwuko, Ezeliora & Ezeanyim, 2022; Ezeliora & Nwufo, 2021).

3 Shape and Size of Specimens

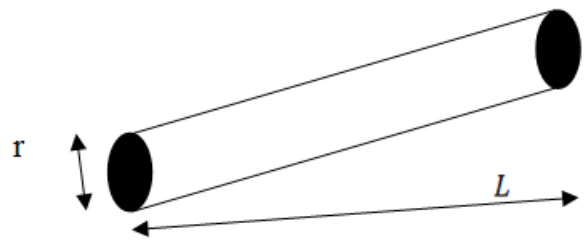

Figure 2: Shape of coupon. (Odio et al., 2014).

The shape of the mild steel rod is cylindrical, (Ezeliora, Umeh & Dilinna, 2020) therefore, the surface area of a cylinder,

$$A = 2\pi rL + 2\pi r^2 \quad (1)$$

Where; $L = Lenght of Coupon$= 85mm

$r = Radius of specimen$= 6mm

$A = Total Surface area of the Cylinder =$

$A = 2\pi \times 6 \times 85 + 2\pi \times 6^2$

$A = 3430.619\ mm^2$

$A = 34.306\ cm^2$

$\approx 34.31\ cm^2$

1. Number of Specimens and their Labeling

Five coupons were used for the experiment. Coupons were pulled out for weighing with ropes tied to them. The ropes were also looped about wooden sticks. On each string and test bottles, a masking tape with label name of the corrosive media was pasted. The following are the labeled names; 0.1M hydrochloric acid, Soil (Underground), Atmosphere, Salt water: The salt water used for this project work was gotten from a simple solution of table salt and water, Fresh water: The fresh water was gotten from River Niger, Onitsha.

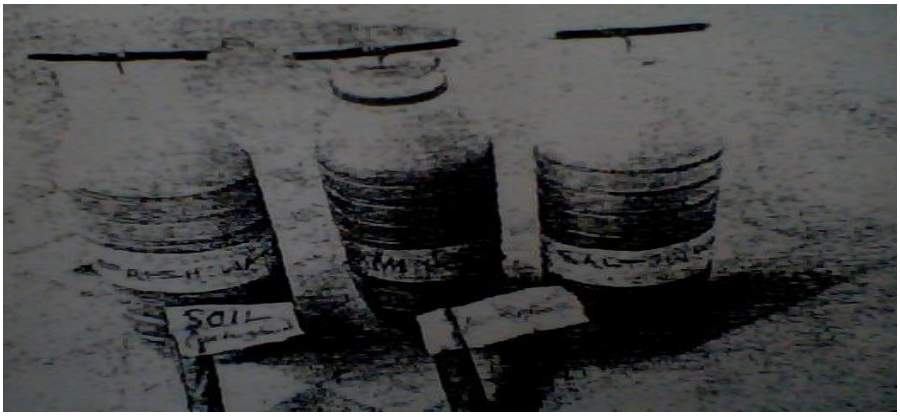

Figure 3: Number of Specimen and their labels (Fifth Week) (Odio, 2014).

Figure 4: Coupon buried in the soil (Odio, 2014).

2. Determination of Corrosion Rate

The most common method for estimating a corrosion rate from mass loss is to weight the corroding sample before and after exposure and divide by the total exposed area and the total exposure time making sure that appropriate conversion constants are used to get the rate in the required units. The method in mm/wk can be represented by the following equation (Freeman, 1988).

$$C_R = \frac{k \times \Delta w}{A \times T \times \rho} \qquad (2)$$

$C_R = Penetration(corossion) ratein\ (mm/wk)$

$\Delta w = Weightlossingram$

$A = ExposedSurfaceareaofCoupon = 34.31 \times 10^{-2} cm^2$

$\rho = DensityofmildSteel\ (g/cm^3)\ 7.86 g/cm^3$

$T = Timeofexposureinhours$

$k = Constantforunitconversion\ 8.76 \times 10^4$

To provide minimum uncertainty in the corrosion rate, this method implicitly assumes:

The corrosion rate does not vary with exposure time

The area does not change as mass is lost to corrosion

The projected and actual surface areas are the same

The penetration rate is uniform over the entire surface

The weight is unaffected by corrosion product removal

Even assuming that the above criteria are fulfilled, errors can still be propagated because of the uncertainty in the measurement of time, mass, and dimensions (Freeman, 1988)

Experimental Results: The results obtained from the experiment carried out as outlined in chapter three are presented and discussed in this chapter. The weight loss and corrosion rate of metal depend to a large extent on a number of factors. The weight loss and the corrosion rate of the different mild steel (Achebo, Ezeliora & Umeh, 2019; Ezeliora, Mbanusi & Aguh, 2019) samples were calculated and shown in the tables below. These values where then graphically represented in the figures below.

3. Tabulation of Results

Table 1: Weight of Coupons in Grams.

Media	Initial	Week 1 168 hr	Week 2 336 hr	Week 3 3504 hr	Week 4 672 hr	Week 5 840 hr	Week 6 1008 hr
0.1MHCL	76.5325	75.2320	75.0028	73.1639	71.2748	68.8039	65.9130
Soil	76.5325	76.5453	76.5188	75.4144	73.3532	72.4475	70.5309
Atmosphere	76.5325	76.5497	76.5337	76.5073	76.0835	76.0428	75.8394
Saltwater	76.5325	76.5232	75.5752	74.8098	73.8231	73.8072	73.4820
Freshwater	76.5325	76.5469	76.4828	75.8270	74.8439	73.9657	72.6629

Table 2: Weight Loss of Coupons (Wt).

Media	Week 1 168 hr	Week 2 336 hr	Week 3 504 hr	Week 4 672 hr	Week 5 840 hr	Week 6 1008 hr
0.1MHCL	1.3347	1.5639	3.4028	5.2919	7.7628	9.5333
Soil	0.0214	0.0479	1.1523	3.2135	4.1192	5.2744
Atmosphere	0.017	0.033	0.0594	0.4832	0.5239	0.7138
Saltwater	0.0435	0.9915	1.7569	2.7436	2.7595	2.7796
Freshwater	0.0198	0.0839	0.7397	1.7228	2.601	3.3724

Table 3: Rate of Corrosion of Samples in mm/wk.

Media	Week 1 168 hr	Week 2 336 hr	Week 3 504 hr	Week 4 672 hr	Week 5 840 hr	Week 6 1008 hr
0.1MHCL	2.5665	1.5099	2.1952	2.5621	3.0072	3.4011
Soil	0.0272	0.0443	0.7447	1.5575	1.5982	1.641
Atmosphere	0.01871	0.0299	0.0404	0.2377	0.2079	0.3193
Saltwater	0.0699	0.9566	1.1344	1.3303	1.6322	1.9116
Freshwater	0.0241	0.0791	0.4788	0.8369	1.0112	1.4133

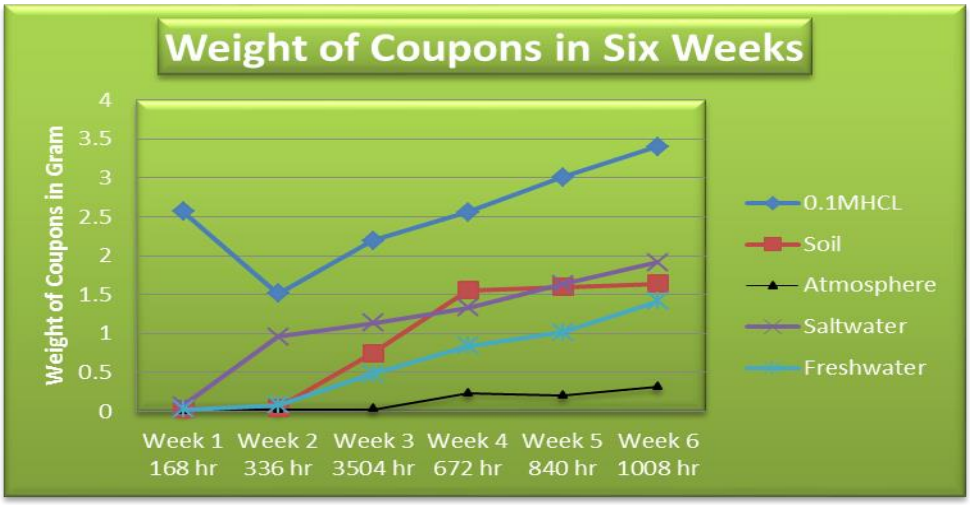

Figure 5: weight of coupons in six weeks.

Figure 6: Rate of weight Loss of coupons in six weeks.

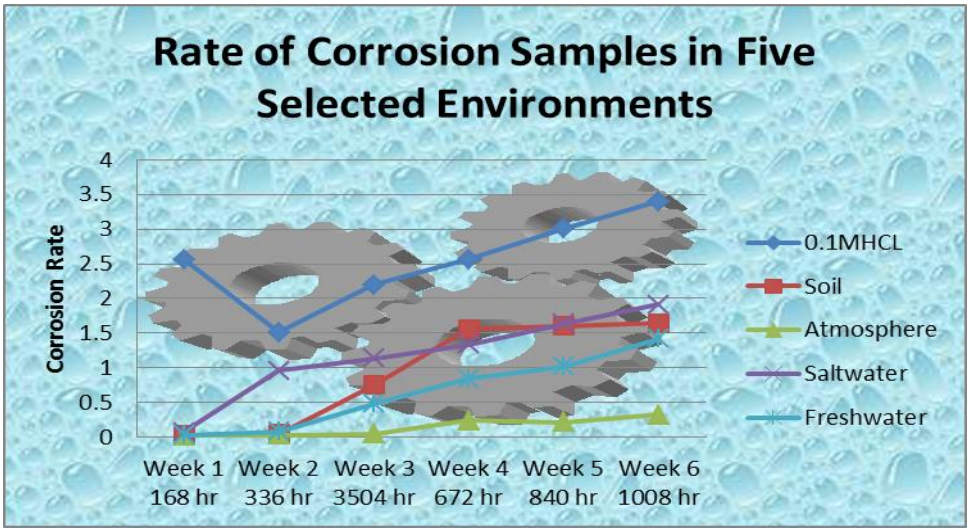

Figure 7: Rate of Corrosion Samples in Five Different Environments within Six Weeks.

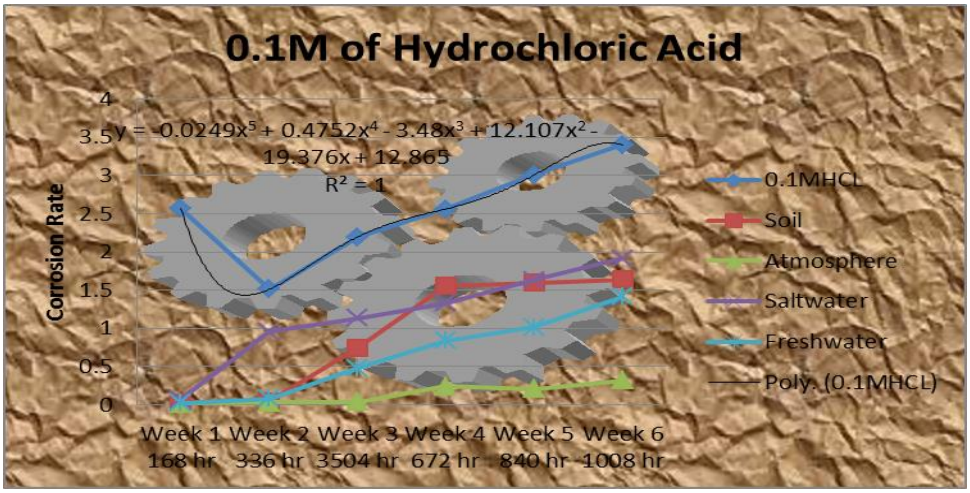

Figure 8: Predictive Model to Determine the Corrosion Rate of 0.1M of Hydrochloric Acid.

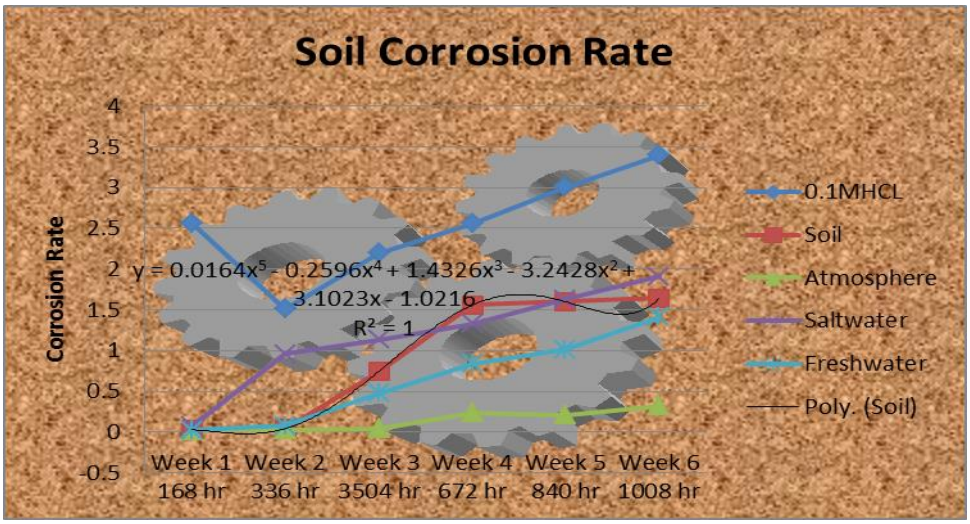

Figure 9: Predictive Model to Determine the Corrosion Rate of Underground Soil.

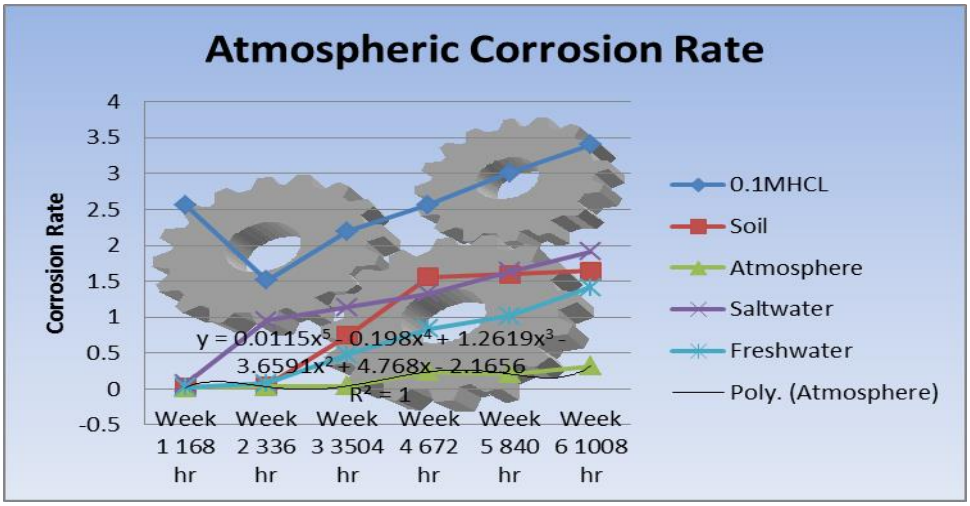

Figure 10: Predictive Model to Determine the Atmospheric Corrosion Rate.

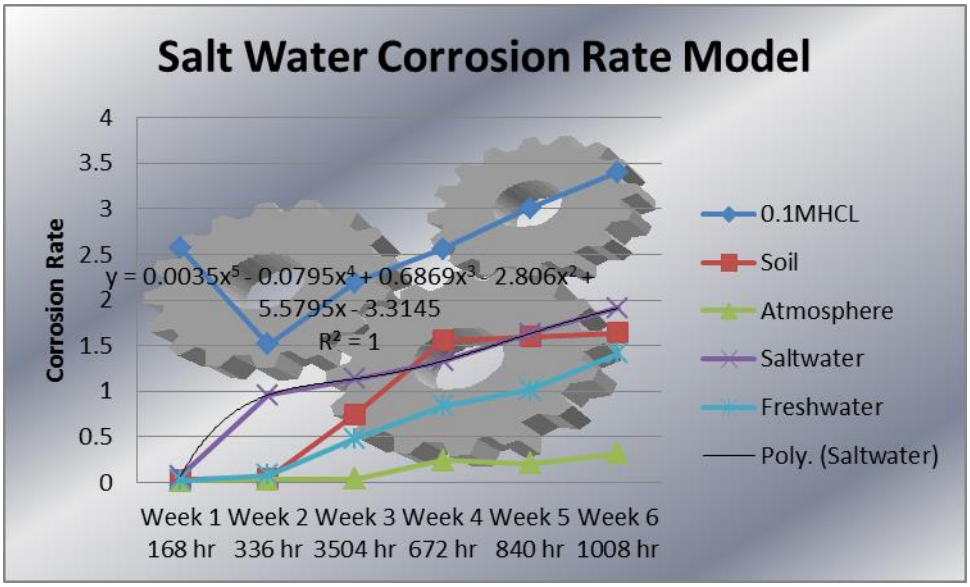

Figure 11: Predictive Model to Determine the Corrosion Rate of Salt Water.

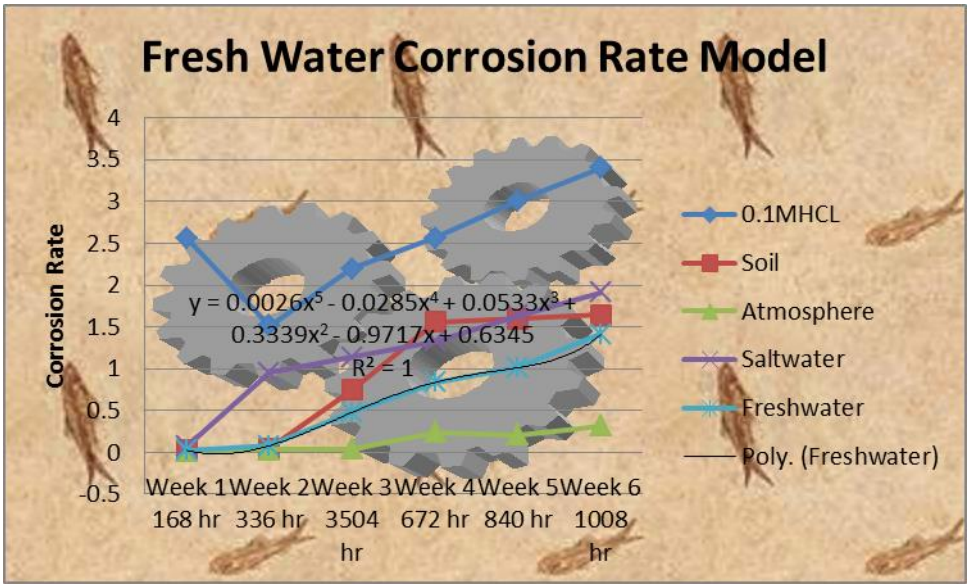

Figure 12: Predictive Model to Determine the Corrosion Rate of Fresh Water.

DISCUSSION

The results of the experiment show that corrosion occurred because weight losses were evident. But interestingly the rate of corrosion for the various specimens varied increasingly in the following trend: 0.1M hydrochloric acid, underground (soil), salt water, fresh water and atmosphere. The specimen in hydrochloric acid experienced what is considered in engineering literature as chloride aggressiveness. The presence of halide ions breakdown any passive films available and can some-times prevent passive films from forming on the mild steel rod. From figure 6, the specimen in the soil also experienced high corrosion rates towards the third week because of the presence of anaerobic bacteria and available oxygen

accounted. However, optimal rate of corrosion was observed between the third and fourth weeks for the soil and salt water. It is believed that in the first two weeks the micro-organisms present where making available the necessary corrosive media combined with the available oxygen and soil pH, corrosion increased at a rapid rate. The soil had a pH of 5. The corrosion rate observed for the specimen in the atmosphere was low; this was as a result of the components of the atmosphere, Constant processing of chemicals do not take place in the place where the mild steel rod was kept and so the emissions of various corrosion stimulating gases was reduce. From the first three weeks, the corrosion rate was really slow then became rapid between the third and fourth week, this occurred when the passive films that were formed between the first and third week broke down and thus corrosion commenced, but the weight loss in general was small when compared to the specimens in the rest of the environments. The types of salts present in salt water (salt solution) media were critically not accounted for and the corrosion rate was not too intense. For the fresh water the corrosion was slightly high at the start of the experiment then continued at an approximate constant rate with a small increase at the last week of the experiment, the low amount of ions in the water was responsible for this behavior since the available oxygen and the medium will form a corrosion ceil and initiate the corrosion process until passive films were formed when the rate became constant. Predictive models were developed to model, analysis and to predict the corrosion rate based on the selected environments. The models were developed using polynomial of fifth order which shows the best relationship. However, the correlations (R^2) of the dependent and the independent variables are hundred percent (100%). The models show that the independent variables can predict hundred percent of the dependent variables.

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CONCLUSION

The laboratory immersion test remains the best method of screening and eliminating from further consideration of those metals that should not be used for specific applications. But while these tests are the quickest and most economical means for providing a preliminary selection of best suited materials, there is no simple way to extrapolate the results obtained from this simple test to the predictions of systems service lifetime.

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