KINETICS AND THERMODYNAMICS OF CARBON STEEL CORROSION IN DIFFERENT TYPES OF SOIL SOLUTION

AMY WAHIDA BINTI MOHAMAD SA'ADAN

UNIVERSITI TEKNOLOGI MALAYSIA

KINETICS AND THERMODYNAMICS OF CARBON STEEL CORROSION IN DIFFERENT TYPES OF SOIL SOLUTION

AMY WAHIDA BINTI MOHAMAD SA'ADAN

A thesis submitted in fulfillment of the
requirements for the award of the degree of
Master of Science (Chemistry)

Faculty of Science
Universiti Teknologi Malaysia

SEPTEMBER 2012

For my beloved…

Mom and Dad - thanks for your support, understanding and concern. I will always love you.

Brothers and Sisters- thanks for your advice and support.

Supervisor, Prof. Dr. Madzlan Aziz, and Co-Supervisor, Dr. Rita Sundari - thank you for giving me the opportunity to do this research under your supervision and for the priceless knowledge you gave me.

My dearest friends thanks for your encouragement and support.

Even thousand words could not express my gratitude…

ACKNOWLEDGEMENT

In the name of God, Most Gracious, Most Merciful...

First and foremost, all praise is to Allah, the Almighty, the Benevolent for His blessings and guidance for giving me the inspiration and strength to finish this master project successfully.

In preparing this thesis, I was in contact with many people. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my project supervisor, Prof. Dr. Madzlan Aziz, and co-supervisor, Dr. Rita Sundari for their encouragement, guidance, critics, and friendship.

To the staff at Chemistry Lab and Geotechnical Lab, thanks for advise and help given to me during my day at the lab. My sincere appreciation also extends to all my colleagues, who has been such a wonderful friend and were so supportive along the way.

Thanks to the most important person in my life, my beloved parent, Mohamad Sa'adan bin Hj. Mohamad and Ilmiah bt Hj. Shafaat, for their prayers and unconditioned love towards me.

Lastly, a thankful expression will be passed to the Research Management Center (RMC) Universiti Teknologi Malaysia, Skudai Johor and National Science Fellowship (MOSTI) for funding support of this study.

Thank you.

ABSTRACT

The fundamental cause of deterioration of buried pipeline is soil corrosion. Factors that influence soil corrosion includes soil type, moisture content, supply of oxygen, redox potential, pH value, soil resistivity, and microbial activity. This study investigated the effect of soil types on the corrosion of carbon steel. Three types of soil namely, laterite, yellow soil, and kaolin were taken as soil of interest. The corrosion rates of carbon steel in various types of soil solutions were studied by applying weight loss method in the temperature range of 30^oC – 90^oC for 1-5 days and electrochemical method based on Tafel polarization measurements. The results obtained from weight loss method and Tafel polarization measurement revealed that yellow soil has the highest corrosion rate. High corrosion rate is due to the low pH and high conductivity of yellow soil solution. The corrosion rates also increased with increasing temperature and decreased with increasing immersion time. Kinetic functions in terms of activation energy, E_a indicates that yellow soil solution has the lowest activation energy followed by laterite and kaolin which is 3.33 kJ mol^{-1}, 5.48 kJ mol^{-1}, and 8.82 kJ mol^{-1} respectively. The positive value of heat of reaction, ΔH indicates that the process of interaction of chemical species in the solution of soil samples on the steel surface is endothermic. The negative value of entropy of reaction, ΔS implies that the system is less disorder and decrease in randomized motion. The positive values of Gibbs free energy, ΔG suggested that the corrosion reactions by chemical species in the soil solutions did not occur spontaneously. This investigation showed that the corrosion of laterite soil solution on carbon steel surface can be described as pitting corrosion which follows the Frumkin adsorption isotherm.

ABSTRAK

Punca utama berlakunya pengaratan paip bawah tanah ialah kakisan tanah. Faktor yang mempengaruhi kakisan tanah termasuk jenis tanah, kandungan kelembapan, bekalan oksigen, keupayaan redoks, nilai pH, kerintangan tanah, dan aktiviti mikrob. Kajian ini dijalankan untuk mengkaji kesan pelbagai jenis tanah terhadap kakisan keluli karbon. Tiga jenis tanah iaitu laterit, tanah kuning, dan kaolin telah dipilih. Kadar kakisan keluli karbon dalam pelbagai jenis larutan tanah telah dikaji dengan menggunakan kaedah kehilangan berat dalam julat suhu $30^{o}C$ – $90^{o}C$ untuk tempoh masa 1-5 hari dan kaedah elektrokimia berdasarkan pengukuran pengutuban Tafel. Keputusan yang diperolehi daripada kaedah kehilangan berat dan pengukuran pengutuban Tafel menunjukkan bahawa tanah kuning mempunyai kadar kakisan tertinggi. Kadar kakisan yang tinggi adalah disebabkan oleh nilai pH yang rendah dan kekonduksian larutan tanah kuning yang tinggi. Kadar kakisan juga meningkat dengan peningkatan suhu dan menurun dengan peningkatan masa rendaman. Fungsi kinetik dari segi tenaga pengaktifan, E_a menunjukkan bahawa larutan tanah kuning mempunyai tenaga pengaktifan terendah diikuti oleh laterit dan kaolin iaitu 3.33 kJ mol^{-1}, 5.48 kJ mol^{-1}, dan 8.82 kJ mol^{-1} masing-masing. Nilai positif haba tindak balas, ΔH menunjukkan bahawa proses interaksi spesies kimia dalam larutan sampel tanah pada permukaan keluli adalah endotermik. Nilai negatif entropi tindak balas, ΔS menunjukkan bahawa sistem tersusun dan kerawakan sistem menurun. Nilai-nilai positif tenaga bebas Gibbs, ΔG mencadangkan bahawa kakisan oleh spesis kimia dalam larutan tanah tidak berlaku secara spontan. Kajian ini juga mendapati bahawa kakisan larutan tanah laterit di atas permukaan keluli karbon adalah jenis kakisan liang yang mematuhi isoterma penjerapan Frumkin.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A	-	Pre-exponential factor
A	-	Ampere
Al	-	Aluminium
Au	-	Gold
C	-	Carbon
Cl	-	Chlorine
Cr	-	Chromium
C_R	-	Corrosion rate
E_a	-	Activation energy
F	-	Fluorine
Fe	-	Iron
J	-	Joule
K	-	Potassium
K	-	Kelvin
L	-	Liter
Mg	-	Magnesium
O	-	Oxygen
R	-	Universal gas constant
R^2	-	Correlation coefficient
S	-	Surface area
S	-	Sulfur
Si	-	Silica
T	-	Temperature
Ti	-	Titanium
V	-	Volt

cm	-	Centimeter
g	-	Gram
m	-	Meter
mL	-	Milliliter
mm	-	Millimeter
E_{corr}	-	Corrosion potential
K_{ads}	-	Equilibrium constant of the corrosion process
N	-	Avogadro's number
b_a	-	anodic
b_c	-	cathodic
f	-	Factor of energetic in homogeneity
h	-	Plank constant
i_{corr}	-	Current density
t	-	Immersion period
w_o	-	Moisture content
%	-	Percent
ΔG	-	Gibbs free energy
ΔH	-	Heat of reaction
ΔS	-	Entropy of reaction
^oC	-	Degree Celsius
θ	-	Surface coverage
Ω	-	Ohm

LIST OF ABBREVIATIONS

AC	-	Alternate Current
ASTM	-	American Society for Testing and Materials
EDX	-	Energy Dispersive X-ray Spectrometer
FESEM	-	Field Emission Scanning Electron Microscopy
GDS	-	Glow Discharge Spectrometer
GPES	-	General Purpose Electrochemical System
MIC	-	Microbiological Influenced Corrosion
PVC	-	Polyvinyl Chloride
SCE	-	Saturated Calomel Electrode
SEM	-	Scanning Electron Microscopy
SRB	-	Sulfate-reducing Bacteria
XRD	-	X-ray Diffraction
XRF	-	X-ray Fluorescence

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Corrosion can be defined in a number of ways but the chemical or electrochemical reaction of a metal or an alloy with its environment provides a reasonable explanation of the term corrosion. It is one of the common causes of metal deterioration, the other being the mechanical loss of the metal by erosion, and abrasion or wear. Sometimes there is a joint action of corrosion and erosion (Chandler, 1985). Corrosion and cracking on the external or internal surfaces of in-service pipes, tanks, or other industrial assets reduce the integrity of the material and potentially reduce the service life of the equipment. Defects may have various forms and may be initiated by one or more mechanisms potentially resulting in corrosion and cracking. These factors affect a wide range of materials in many industries including industrial, aerospace, pipeline, power generation, and marine (Ginzel and Kanters, 2002).

Many structures affected by soil corrosion around the world, such as crude oil, natural gas, and water mains pipelines. Pipelines are widely used as engineering structures for the transportation of fluid from one place to another. In many instances pipelines are placed underground, under runways, railways, and roadways (Ahammed and Melchers, 1997). The deterioration of buried pipeline is commonly caused by soil corrosion (Ismail and El-Shamy, 2009). Underground steel structures are designed to have a long working life. Continuous inspection and maintenance are required in order to secure the lifetime and reliability. Failure in underground structures can have severe consequences economically and environmentally (Li *et al.,* 2007). Therefore, corrosion prevention and control is a matter of options to fit in with the many other requirements to be taken into account by the design team.

Soil type, moisture content, supply of oxygen, redox potential, pH value, soil resistivity, and microbial activity are some factors that influence corrosion in soil (Rim-rukeh *et al.,* 2006). From engineering aspects, an increase in soil water content has a number of disadvantages such as swelling, shrinkage, and cohesion decreases which affected directly on the interaction of pipelines, causing deterioration of pipelines materials and also caused damage on the top soil due to the occurrence of general and localized corrosion which was present in different sites of steel structures (Ismail and El-Shamy, 2009).

Carbon steels are widely used as constructional material due to its excellent mechanical properties, high strength, low cost, and weldability (Abdallah *et al.* 2006). The response of carbon steel to soil corrosion depends primarily on the nature of the soil and other environmental factors, such as moisture and oxygen. These factors can lead to extreme variations on corrosion (Rim-rukeh *et al.,* 2006).

1.2 Problem Statement

Carbon steel is a common material for many industrial units because of its low cost and excellent mechanical properties. However carbon steel suffers severe attack in service particularly in oil and gas production systems. Although corrosion inhibitors are the most effective and flexible mean of corrosion control in oil and gas production systems, the selection and application of inhibitors are actually complicated because of variable corrosive environment in these systems. Corrosion occurred widely through all specific types of pipeline.

Corrosion in soil is the fundamental cause of the deterioration of metal structures in soil. Metal structures corrode in soil by complex electrochemical processes due to the presence of different types of electrolyte. Soils with high moisture content, high electrical conductivity, high acidity, and high dissolved salts will be most corrosive. Many industries tend to expose to various type of soil in Malaysia that can cause corrosion.

To date, there is no report in the literature regarding the effect of laterite, yellow soil and kaolin on the corrosion of carbon steels. On account of this reasons, the corrosion study of carbon steel in different types of soil was carried out by using weight loss and electrochemical method to measure the corrosion rate in terms of temperature and time.

1.3 Research Objectives

The objectives of this research are:

1. To study the kinetic and thermodynamic aspects of corrosion caused by different types of soil solutions.

2. To investigate the effects of temperature and immersion time on the corrosion rate of carbon steel in different types of soil solutions.

1.4 Scope of the Study

The scope of this study is to identify the kinetic and thermodynamic parameters on corrosion of carbon steel in three different types of soil solutions (laterite, yellow soil, kaolin). The measurement technique for corrosion rate has been studied using weight loss method and electrochemical method based on Tafel polarization measurements. The effect of temperature on the corrosion rate of carbon steel in soil solution was studied in the temperature range of 30^oC-90^oC for 1-5 days of immersion time. The effect of concentrations of soil solution on corrosion rate was focused on laterite at temperature 30^oC for 3 days of immersion time. The kinetic and thermodynamic parameters are determined based on the Arrhenius based equation.

1.5 Significant of Research

Corrosion of metals is a serious problem related to material application. There are numerous factors that influence metal corrosion in soil such as the degree of oxidation, pH of the corrosion environment, soluble salts, and the water content of soil (Wang, 2009). These make the prediction of corrosion rates very complex. Hence, the study of kinetics and thermodynamics of the corrosion would give a better understanding of corrosion of carbon steel in particularly the soil solution samples studied.

REFERENCES

Abboud, Y., Abourriche, A., Saffaj, T., Berrada, M., Charrouf, M., Bennamara, A., Hannache, H. (2009). A Novel Azo Dye, 8-quinolinol-5-azoantipyrine as Corrosion Inhibitor for Mild Steel in Acidic Media. *Journal of Desalination.* 237: 175-189.

Abdallah, M., Helal, E. A., Fouda, A. S. (2006). Aminopyrimidine Derivatives as Inhibitors for Corrosion of 1018 Carbon Steel in Nitric acid Solution. *Corrosion Science*. 48: 1639-1654.

Ahammed, M. and Melchers, R. E. (1997). Probabilistic Analysis of Underground Pipelines Subject to Combined Stresses and Corrosion. *Journal of Engineering Structures.* 19: 988-994.

Amin, M.A., Ahmed, M.A., Arida, H.A., Arslan, T., Saracoglu, M., & Kandemirli, F. (2011). Monitoring Corrosion and Corrosion Control of Iron in HCl by non-ionic Surfactants of the TRITON-X series – Part II. Temperature Effect, Activation Energies and Thermodynamics of Adsorption. *Corrosion Science*, 53: 540–548.

Ashman, M. and Puri, G. (2002). *Essential Soil Science: A Clear and Concise Introduction to Soil Science.* (1st edition). Australia. Blackwell Science Ltd.

ASTM G31-72 (2004). United State: Standard Practice for Laboratory Immersion Corrosion Testing of Metals.

ASTM D2216-10 (2010). United State: Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass.

Atkins, P. and Paula, J. D. (2002). Physical Chemistry. (7th edition). Oxford University Press.

Baize, D. (1993). *Soil Science Analyses: A Guide to Current Use.* (1st edition). England. John Wiley & Sons Ltd.

Rajani, B. and Kleiner, Y. (2003). Protection of Ductile Iron Water Mains against External Corrosion: Review of Methods and Case Histories. *Journal American Water Works Association.* 95: 110-125.

Revie, R. W., and Uhlig, H. H. (1971). *Corrosion and Corrosion Control: an Introduction to Corrosion Science and Corrosion Engineering.* (2st edition). New York: John Wiley & Sons, Inc.

Rim-rukeh, Akpofure, Awatefe and Kehinde, J. (2006). Investigation of Soil Corrosivity in the Corrosion of Low Carbon Steel Pipe in Soil Environment. *Journal of Applied Science Research.* 2: 466-469.

Roberge, P. R. (1999). *Handbook of Corrosion Engineering*. (1st edition). New York: McGraw-Hill Companies, Inc.

Sastri, V. S., Ghali, E., Elboujdaini, M. (2007). *Corrosion Prevention and protection.* (1st edition). England: John Wiley & Sons Ltd.

Sigh, S. K. and Mukherjee, A. K. (2010). Kinetics of Mild Steel Corrosion in Aqueous Acetic Acid Solutions. *Journal Material Science Technology.* 26(3): 264-269.

USDA (1987). Textural Soil Classification. Soil Conversation Service. United State Department of Agriculture.

Whitmire, K. H., Machnikova, E., Hackerman, N. (2008). Corrosion Inhibition of Carbon Steel in Hydrochloric Acid by Furan Derivatives. *Journal of Eleltrochemical Acta*. 53: 6024-6032.

Zaki, A. (2006). *Principles of Corrosion Engineering and Corrosion Control.* (1st edition). UK. Elsevier Ltd.

Zhang, S., Tao, Z., Li, W., Hou, B. (2009). Corrosion Inhibition of Mild Steel in Acidic Solution by some oxo-triazole Derivatives. *Corrosion Science.* 51: 2588-2595.

Bayliss, D. A. and Deacon, D. H. (2002). *Steelwork Corrosion Control.* (2nd edition). London: Spon Press.

Benabdellah, M., Touzani, R., Dafali, A., Hammouti, B., and Kadiri, S. E. (2007). Ruthenium-ligand Complex, an Efficient Inhibitor of Steel Corrosion in H_3PO_4 Media. *Material Letters.* 61: 1197-1204.

Booth, G. H. (1971). *Microbiological Corrosion*. (1st edition). London: Mills and Boon Ltd.

Bouklah, M., Hammouti, B., Lagrenee, M., and Bentiss, F. (2006). Thermodynamic Properties of 2,5-bis(4-methoxyphenyl)-1,3,4-oxadiazole as a Corrosion Inhibitor for Mild Steel in Normal Sulfuric Acid Medium. *Corrosion Science.* 48: 2831-2842.

Brondel, D., Edwards, R., Hayman, A., Hill, D., Mehta, S., Semerad, T. (1994). Corrosion in the Oil Industry. *Oilfield Review.* 6: 4-18.

Caleyo, F., Velazquez, J. C., Valor, A., Hallen, J. M. (2009). Probability Distribution of Pitting Corrosion Depth and Rate in Underground Pipelines: A Monte Carlo Study. *Corrosion Science.* 51:1925-1934.

Chandler, K. A. (1985). *Marine and Offshore Corrosion.* (1st edition). U.S.: Butterworth & Co (publisher) Ltd.

Chilton, J. P. (1968). *Principles of Metallic Corrosion.* (1st edition). London: The Chemical Society.

Davis, J. R. (2000). *Corrosion: Understanding the Basics.* (1st edition). U.S.A.: The Materials Information Society.

Delinder, L. S. V., Dillon, C. P., Snograss, J. S. Webster, H. A. (1984). *Corrosion Basics An Introduction.* (1st edition). Texas: National Association of Corrosion Engineers.

Eddy, N. O., Ekwumemgbo, P., and Odoemelam, S. A. (2008). Inhibition of the Corrosion of Mild Steel in H_2SO_4 by 5-amino-1-cyclopropyl-7-[(3*R*, 5*S*) 3, 5 dimethylpiperazin- 1-YL] -6, 8-difluoro-4-oxo-uinoline-3-carboxylic acid (ACPDQC). *International Journal of Physical Sciences.* 3 (11): 275-280.

El-Dein, S. W. A., Al-Sarawy, A. A., Fouda, A. S. (2008). Some thiozole Derivatives as Corrosion Inhibtors for Carbon Steel in Acidic Medium. *Journal of Desalination.* 229: 279-293.

El-Maksoud, S. A. and Fouda, A. S., (2005). Some Pyridine Derivatives as Corrosion Inhibitors for Carbon Steel in Acidic Medium. *Materials Chemistry and Physics*. 93: 84-90.

Emeregul, K. C. and Hayvali, M. (2006). Studies on the Effect or a Newly Corrosion of Steel in 2M HCl. *Corrosion Science.* 48: 797-812.

Escalante, E. (1979). *Underground Corrosion, ASTM STP 741,* Philadelphia: American Society for Testing and Materials.

Evans, U. R. (1981). *An Introduction to Metallic Corrosion.* (3rd edition). London: Edward Arnold Limited.

Foth, H. D. (1990). *Fundamentals of Soil Science.* (8th edition). Canada: John Wiley & Sons.

Garverick, L. (1994). Corrosion in the Petrochemical Industry. (1st edition). UK. Elsevier Ltd.

Ginzel, R. K. and Kanters, W. A. (2002). Pipeline Corrosion and Cracking and the Associated Calibration Considerations for Same Side Sizing Applications. *Eclipse Scientific Products Inc.,* 7: 7.

Goidanich, S., Lazzari, L., Ormellese, M. (2010). AC corrosion. Part 2: Parameters Influencing Corrosion Rate. *Corrosion Science.* 52: 916-922.

Gupta S. K. And Gupta B. K. (1979). The Critical Soil Moisture Content in the Underground Corrosion of Mild Steel. *Corrosion Science*. 19: 171-178.

Ibrahim, M. A. M., El-Rahim, S. S. A., Khalid, K. F., (2001). The inhibition of 4-(2'amino-5'-methylphenylazo) antipyrine on Corrosion of Mild Steel in HCl Solution. *Materials Chemistry and Physics.* 70: 268-273.

Ismail, A. I. and El-Shamy, A. M. (2009). Engineering Behaviour of Soil Materials on the Corrosion of Mild Steel. *Journal of Applied Clay Science*. 42: 356-362.

Iverson, W. P. (1981). An Overview of the anaerobic Corrosion of Underground Metallic Structures, Evidence for New Mechanism. *Underground Corrosion, ASTM STP 741,* Edward Escalante, Ed., American Society for Testing and Materials, 1981. 33-52.

Jeremy, G. (2004). Irrigation Farm Resources. Water Wise on the Farm. NSW Department of Primary Industries.

Kadry, S. (2008). Corrosion Analysis of Stainless Steel. *Journal of Scientific Research.* 22: 508-516.

Khadom, A. A., Yaro, A. S., Kadum, A. A. H., Al-Taie, A. S., Musa, A. Y. (2009). The Effect of Temperature and Acid Concentration on Corrosion of Low Carbon Steel in Hydrochloric Acid Media. *American Journal of Applied Science.* 6 (7): 1403-1409.

Khadom, A. A., Yaro, A. S., Wael, R. K. (2010). Reaction Kinetics of Corrosion of Mild Steel in Phosphoric Acid. *Journal of the University of Chemical Technology and Metallurgy.* 45(4): 443-448.

Khaled, K. F., Benabdellah, M., Hammouti, B. (2010). Kinetic Investigation of C38 Steel Corrosion in Concentrated Perchloric Acid Solutions. *Materials Chemistry and Physics.*120: 61-64.

Kucera, V. (1988). *The Effect of acidification on Corrosion of Structures and Cultural Property.* (1st edition). Swedish: John Wiley & Sons Ltd.

Lagrenee, M., Bentiss, F., Lebrini, M. (2005).Thermodynamic Characterization of Metal Dissolution and Inhibitor Adsorption Processes in Mild Steel/ 2,5-bis(n-thienyl)-1,3,4-thiadiazoles/Hydrochloric Acid System. *Corrosion Science.* 47: 2913-2915.

Landolt, D. (2006). *Corrosion and Surface Chemistry of Metals.* (2nd edition). Switzerland: EPFL Press.

Leon, D. D. and Macias, O. F. (2005). Effect of Spatial Correlation on the Failure Probability of Pipelines under Corrosion. *International Journal of Pressure Vessels and Piping.* 82: 123-128.

Li, S. Y., Jung, S., Park, K. (2007). Kinetic Study on Corrosion of Steel in Soil Environments using Electrical Resistance Sensor Technique. *Materials Chemistry and Physics.* 103: 9-13.

Licht, S., Light, T. S., Bevilacqua, A. C., Morash, K. R. (2005). The Fundamental Conductivity and Resistivity of Water. *Journal of Electrochemical and Solid-State Letters.* 8 (1): 16-19.

Little, B., Wagner, P., Mansfeld, F. (1992). An Overview of Microbiologically Influenced Corrosion. *Journal of Electrochimica Acta.* 37(12): 2185-2194.

Lopez, E., Osella, A., Martino, L., (2006). Controlled Experiments to Study Corrosion Effects due to External Varying Fields in Embedded Pipelines. *Corrosion Science.* 48: 389-403.

Macdonald, K. A., Cosham, A., Hopkins, P. (2007). Best Practice for the Assessment of Detects in Pipelines-Corrosion. *Journal of Engineering Failure Analysis.* 14: 1245-1265.

Mansfeld, F. (2005). Tafel Slopes and Corrosion Rates obtained in the pre-Tafel Region of polarization Curves. *Corrosion Science.* 47: 3178-3186.

Mansfeld, F. and Bertocci, U. (1979). *Electrochemical Corrosion Testing, ASTM STP 727,* Philadelphia: American Society for Testing and Materials.

Maslehuddin, M., Al-Zahrani M. M., Ibrahim M., Al-Methel M. H., Al-Idi S. H. (2007). Effect of Chloride Concentration in Soil on Reinforcement Corrosion. *Journal of Construction and Building Material.* 21: 1825-1832.

McCafferty, E. (2010). *Introduction to Corrosion Science.* (1^{st} edition). New York: Springer Science+Business Media.

Mirgane, S. R and Bhagure, G. R. (2009). Investigation of Soil Corrosivity in Thane Region of Maharashtra, India. *Journal of Agriculture and Biological Sciences.*5(5): 680-688.

Moncmanova, A. (2007). *Environmental Deterioration of Material.* (2^{nd} edition). U.S.A.: WIT press.

Mughabghab, S. F., and Sullivan, T. M. (1989). Evaluation of the Pitting Corrosion of Carbon Steels and Other Ferrous Metals in Soil System. *Journal of Waste Management.* 9: 239-251.

Noor, E. A. and Al-Moubaraki, A. H., (2008). Thermodynamic Study of Metal Corrosion and Inhibitor Adsorption Processes in Mild Steel/1-methyl-4[4′(-X)-styryl pyridinium iodides/Hydrochloric Acid Systems. *Materials Chemistry and Physics.* 110: 145-154.

Obot, I. B.,and Obi-Egbedi, N. O. (2011). Inhibitive Properties, Thermodynamic and Quantum Chemical Studies of alloxazine on Mild Steel Corrosion in H_2SO_4. *Corrosion Science*. 53: 263-275.

Perez, N. (2004). *Electrochemistry and Corrosion Science.* (1^{st} edition). U.S.A.: Kluwer Academic Publishers.

Peverill, K. I., Sparrow L. A., Reuter, D. J. (2001). *Soil Analysis: an Interpretation Manual*. (3^{rd} edition). Australia. Australian Soil and Plant Analysis Council Inc.

Philip, A. S. (2003). *Metallic Material–Physical, Mechanical, and Corrosion Properties.* (3^{rd} edition). New York: Marcel Dekker, Inc.