

**EFFECTS OF SOIL PROPERTIES ON CORROSION OF
OIL PIPELINE AT NORTH OF IRAQ**

**A THESIS SUBMITTED TO THE GRADUATE
SCHOOL OF APPLIED SCIENCES
OF
NEAR EAST UNIVERSITY**

**BY
HAWKAR JALAL MUHAMMED**

**In Partial Fulfillment of the Requirements for
the Degree of Master of Science
in
Mechanical Engineering**

NICOSIA, 2016

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Hawkar J. Muhammed

Signature:

Date: 15-1-2016

ACKNOWLEDGEMENTS

This thesis would not have been possible without the help, support and patience of my supervisor Prof. Dr. Mahmut A. Savaş and co-supervisor Assist. Prof. Dr. Ali Evcil without their constant encouragement and guidance. They have helped me through all stages of the writing of my thesis. Without their consistent and illuminating instructions, this thesis could not have reached its present form.

Above all, my unlimited thanks and heartfelt love would be dedicated to my dearest family for their great confidence in me. I'm greatly indebted to my mother who was indeed my inspiration and she led me to the treasures of knowledge. I would like to thank her for giving me support, encouragement and her endless love have sustained me throughout my life. I want to thank my dear father who has been the source of all the inspiration in the adventures of my life.

Eventually, there is a long list of friends that I would like to thank. I can't mention them all; nevertheless, I would like to thank them for their valuable help and support.

To my parents...

ABSTRACT

An investigation was carried out on the effects of some soil properties on the corrosion reaction of API X70 pipeline steel that is used in buried oil pipelines from Iraq to Turkey. Experiments were performed on eight samples of soil collected from the actual site of the underground crude oil pipeline along 80 km between Taq-Taq and Khurmala region of North of Iraq. Coupons of API X70 steel were buried in each soil sample to inspect at the effects of the content of moisture (ASTM D4643-08), clay-content (ASTM D422-63) and pH (BS 1377-3:1990) on the corrosivity of API X70 steel.

The results showed that the content of moisture of the soil had the largest effect on corrosivity followed by clay content and pH.

Statistical analyses using ANOVA (Analysis of Variance) and MLR (Multiple Linear Regression) were consistent with the observation.

Keywords: ANOVA; corrosion; linear regression; moisture; pH; pipeline; statistical analysis; soil texture

ÖZET

Bu çalışmada Irak – Türkiye petrol boru hattında kullanılan çelik boruların paslanmasında bazı zemin etkileri incelenmiştir. Kuzey Irak’ da Taq-Taq ve Khurmala bölgeleri arasında toprağa gömülü yaklaşık 80 km uzunluktaki petrol boru hattı boyunca zemin numuneleri toplanmıştır. Sekiz farklı alandan (ASTMD D 4220-95) standardına göre alınan ve muhafaza edilen zemin numunelerinin petrol boru hattı çeliklerinden API X70 çeliği üzerindeki korozyon etkileri araştırılmıştır. Zemin su içeriği (ASTM D 4643-08), kil yüzdesi (ASTM D 42263) ve pH (BS-1377-3: 1990) değerlerinin korozyonu ne derecede etkiledikleri tespit edilmiştir.

Bu testler sonunda, çelik numunelerin paslanmasını en fazla sırası ile zemin su içeriği, kil yüzdesi ve pH değerinin etkilediği görülmüştür.

ANOVA (Analysis of Variance) ve MLR (Multiple Linear Regression) yöntemleri ile yapılan istatistiksel analizler test bulguları ile uyumlu sonuçlar vermiştir.

Anahtar kelimeler: ANOVA; boru hattı; istatistiksel analiz; lineer regrasyon; paslanma; pH değeri; zemin dolgusu; zemin su içeriği

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	i
ABSTRACT	iii
ÖZET	iv
TABLE OF CONTENTS	v
LIST OF TABLES	viii
LIST OF FIGURES	ix
LIST OF EQUATIONS	x
LIST OF SYMBOLS	xi
LIST OF APPREVIATIONS	xii

CHAPTER 1 INTRODUCTION

1.1 Statement of the Problem	1
1.2 The Aim of the Thesis	2
1.3 Limitations of the Study	2
1.4 Overview of the Thesis	2

CHAPTER 2 PREVIOUS WORK

2.1 Soil Characteristics and Pipeline Corrosion	4
2.2 Corrosion Modeling and Statistical Analysis	6

CHAPTER 3 LITERATURE REVIEW

3.1 Corrosion	8
3.1.1 Anode	8
3.1.2 Cathode	8
3.1.3 Electrolyte	8
3.1.4 Metallic Path	8
3.2 Corrosion Damage Forms	9
3.2.1 General corrosion	10
3.2.2 Pitting	10
3.2.3 Selective leaching	10
3.2.4 Intergranular corrosion	11

3.2.5 Crevice corrosion	11
3.2.6 Selective attack on inclusions.....	11
3.2.7 Galvanic cell.....	11
3.2.8 Concentration cell	12
3.2.9 Differential temperature cell	12
3.3 Sorts of Corrosion Cell.....	12
3.3.1 Dissimilar electrode cells	13
3.3.2 Concentration cells.....	13
3.3.3 Differential temperature cells.....	14
3.4 Corrosion of Steel	14
3.5 Pipeline and Pipeline Corrosion.....	16
3.6 Corrosion in Soil	17
3.6.1 Factors affecting the corrosivity of soils	19
3.7 Corrosion Measurement (Weight Loss Method).....	23
3.8 Statistical Analysis and Corrosion Prediction	23
3.9 Importance and Cost of Corrosion	24

CHAPTER 4 METHODOLOGY

4.1 Materials	28
4.1.1 Soil samples.....	28
4.1.2 Pipe samples.....	29
4.2 pH Testing.....	31
4.2.1 Sample preparation.....	31
4.2.2 pH.....	31
4.2.3 Test procedure	32
4.3 Moisture Content Testing.....	34
4.3.1 Sample preparation.....	34
4.3.2 Moisture content.....	34
4.3.3 Procedure.....	35
4.4 Particle Size Analysis.....	36
4.4.1 Sample preparation.....	36
4.4.2 Soil texture	37
4.4.3 Procedure.....	37
4.5 Statistical Analysis	41

CHAPTER 5 RESULTS AND DISSCUSION

5.1 pH Test	43
5.2 Moisture Test	44
5.3 Particle Size Analysis.....	46
5.4 Corrosion Rate	47
5.5 Statistical Analysis	48

CHAPTER 6 CONCLUSIONS AND FUTURE WORK

6.1 Conclusions	51
6.2 Future Work	52

REFERENCES 53

APPENDIES 57

Appendix 1: (BS 1377-3:1990) British standard.....	58
Appendix 2: (ASTM D4643-08) American Society for Testing and Material	60
Appendix 3: (ASTM D422-63) American Society for Testing and Material	61
Appendix 4: (ASTM D4220-95) American Society for Testing Material	62
Appendix 5: (ASTM G1-90) American Society for Testing Material	63
Appendix 6: (ASTM G16-13) American Society for Testing Material	64
Appendix 7: (ASTM G31-72) American Society for Testing and Material	65
Appendix 8: (ASTM G162-99) American Society for Testing and Material	66
Appendix 9: (API 5L American Petroleum Institute)	67
Appendix 10: Composite Correction.....	69

LIST OF TABLES

Table 4.1: Mechanical and chemical properties of API 5L X70.	31
Table 4.2: Relative acidity pH of soil and corrosivity of soil.....	32
Table 4.3: Test specimen masses.....	34
Table 4.4: Maximum particles size with the amount of soil portion	36
Table 4.5: Particle size in a soil texture.....	37
Table 5.1: pH test results	43
Table 5.2: Mass of samples before and after drying.....	44
Table 5.3: Soil samples and their moisture contents	45
Table 5.4: Texture data for soil samples.....	46
Table 5.5: Corrosion rate calculation.....	47
Table 5.6: Model summary.....	48
Table 5.7: Analysis of variance ANOVA.....	48
Table 5.8: Coefficient of regression	48

LIST OF FIGURES

Figure 3.1: Corrosion phenomenon in action	9
Figure 3.2: Corrosion cell phenomenon in action	12
Figure 3.3: Dry cell.....	13
Figure 3.4: Concentration cell	14
Figure 3.5: Concentration cell formation in an underground pipeline	15
Figure 3.6: Formation of rust in seawater	16
Figure 3.7: Corrosion mechanism of soil for buried pipe	19
Figure 3.8: Corrosion produce in disturbed soil vs. undisturbed soil, the direction of positive current represented by arrow	20
Figure 3.9: Different moisture capacities as function of sand content	21
Figure 4.1: Soil samples	28
Figure 4.2: Oil and gas pipeline map in North of Iraq	29
Figure 4.3: Coupon samples dimensions.....	30
Figure 4.4: Sample preparation	31
Figure 4.5: A&B GR 120 analytical balance.....	33
Figure 4.6: (100 mL) beaker with 30g soil and 70mL distilled water.....	33
Figure 4.7: Calibration of pH meter with standard buffer solution.....	33
Figure 4.8: H30140E laboratory bench oven, digital series, HUMBOLDT	35
Figure 4.9: Composite correction slurry.....	38
Figure 4.10: Dispersing soil mixer machine	39
Figure 4.11: Sedimentation 1000 mL cylinder with distilled water and soil slurry	40
Figure 4.12: Hydrometer forms include time interval and recording (temperature, hydrometer, and composite correction) with stop watch	40
Figure 5.1: pH test	43
Figure 5.2: Effect of moisture content on soil corrosivity.....	46

LIST OF EQUATIONS

Equation 3.1: White green precipitate.....	15
Equation 3.2: Hydrogen Ion expressed as pH.....	22
Equation 3.3: Half-cell reaction of hydrogen	22
Equation 3.4: pH of pure water	22
Equation 4.1: Corrosion rate equation	30
Equation 4.2: Moisture contents in Soil.....	36
Equation 4.3: Hygroscopic moisture.....	39
Equation 4.4: Rate of soil in suspension	41
Equation 4.5: Diameter of particle	41
Equation 4.6: Effective depth.....	41
Equation 4.7: Multiple regression equation	42

LIST OF SYMBOLS

a:	Correction faction to be applied to the reading of hydrometer 152H
A:	Cross-sectional area of sedimentation cylinder
b1,b2,bn:	Coefficient of the variables
C:	Hygroscopic moisture
CR	Corrosion rate
D:	Diameter of particle
K:	Constant depending on the temperature of the suspension and the specific gravity of the soil particles
L:	Effective depth
L₁:	Distance along the stem of the hydrometer from the top of the bulb to the mark for a hydrometer reading
L₂:	Overall length of the hydrometer bulb
M₁:	Mass of container and moist specimen
M₂:	Mass of container and oven dried specimen
M_{Air-Dry}:	Mass of air dry
M_C:	Mass of container
M_{Oven-Dry}:	Mass of oven dry
M_S:	Mass of solid particles
M_W:	Mass of water
P:	Percentage of soil remaining in suspension at the level at which the hydrometer measures the density of the suspension
R:	Hydrometer reading with composite correction applied
T:	Interval of time from beginning of sedimentation to the taking of the reading
V_B:	Volume of hydrometer bulb
W:	Oven-dry mass of soil in a total test sample represented by mass of soil dispersed
X1,X2,Xn:	Independent variables
Y:	Dependent variable

LIST OF APPREVIATIONS

API:	American Petroleum Institute
ANOVA:	Analysis of Variance
ASTM:	American Standard for Testing and Material
BS:	British Standard
MLR:	Multiple Linear Regression

CHAPTER 1

INTRODUCTION

The corrosion defined as surface degradation of metals, or its properties on account of their response with its environment. The principle of corrosion must be comprehended so as to adequately select materials and to design, create, and use metal structures for the ideal financial existence of facilities and security in operation. The serious outcomes of the corrosion procedure have turned into a reasons of shutdown of plants, misuse of worthy resources, misfortune or defilement of item, decrease in proficiency, immoderate support, and costly over layout. Corrosion control is accomplished by using so as to perceive and understanding erosion components, consumption safe materials and design, and by utilizing defensive frameworks, device and treatments.

Corrosion is a slow process. Hence it requires time to see its negative results. Actually, corrosion is the main consideration in deciding the investment and production costs in the industry. Some estimation revealed, the expense of corrosion to a country compasses to (3.5-5) % of the gross national product. With respect to Turkey, there are estimations guaranteeing this value is not less than 4.5 %. Oil and gas pipelines in the North of Iraq are a modern phenomenon, and currently there is no study on the evaluation of the cost for the maintenance and protection against corrosion. The estimation of cost against corrosion in the future may ranges between (0.5-1.5) % of gross domestic product.

Graphite-containing oil is extremely normal grease on the grounds that graphite is promptly accessible from steel industries, with a content of molybdenum disulphide more costly, and the graphite grease which is well known to be the cause of galvanically induced-corrosion in bimetallic couples. This case creates problems in (F16) aircraft fighter (Roberge, 1999).

1.1 Statement of the Problem

The corrosion of underground pipeline cause degradation of the pipe, with time the degradation will cause a failure to the pipes, means loss of economic, causing a catastrophe in the humanity. To avoid this, the parameters that affect the loss of pipe metals among

these parameters the influence of soil properties has been chosen as case study to treat the underground pipeline.

1.2 The Aim of the Thesis

The point of this research is based after knowing the natural condition that encompass covered or incompletely covered pipeline or structures, I have taken the soil properties that have an enormous impact on the corrosion rate of the pipeline or structures, as a sample to develop the security framework with thought to these properties in North of Iraq.

1.3 Limitations of the Study

The absence of the following:

- Non-use periods of time to retrieve the steel coupons to know the corrosion rate against time.
- Non-use of the original site for the best results.
- The absence of test in the various seasons of the year to see the effect of climate change on corrosion rate.

1.4 Overview of the Thesis

The thesis consists of an investigation of soil properties between Taq-Taq and Khurmala far away from Kirkuk city about 60 km, 85 km of the southeast city of Erbil and 120 km of the northwest city of Sulaymaniyah in North of Iraq to analyze the corrosivity of soil towards the concealed pipeline through six chapters. Chapter one consists of an introduction of the thesis with the aim, importance, and the limitation of the study. Chapter two is a brief summary of the studies those done on the parameters that affect the corrosion rate of buried pipelines or structure which were based on the experimental analysis. Chapter three summarizes the theory of the study. In chapter four described the materials and the methodology that have used in the investigation. Chapter five represented the results that were obtained from inspection of the soil samples and statistical analysis.

Chapter six in this chapter concluded the influence by far of soil properties on the buried pipeline steel coupon.

CHAPTER 2

PREVIOUS WORK

2.1 Soil Characteristics and Pipeline Corrosion

Bhattarai, (2013) investigated the soil parameters such as moisture content, pH, resistivity, oxidation-reduction potential, chloride and sulfate contents those have an influence on the corrosive nature of soils toward the buried galvanized steel and cast iron pipelines used to supply the drinking water in Kathmandu Valley. He discovered that the twenty three soil samples taken from the study area were mildly corrosive to non corrosive nature toward the buried pipeline.

Ikechukwu et al. (2014) examined the relationship of soil properties towards metal loss of API 5L X42 carbon steel coupons. An aggregate of four specimen of X42 coupons were set in four distinctive soil tests taken from four unique states inside of the Niger Delta district for 2352 hours, to consider the impact of soil properties towards metal loss by means of weight loss method. The soil coupons were covered in the soil samples put in a plastic bag, permitted to corrode normally and afterwards recovered at regular intervals. The impact of soil pH and resistivity were assessed utilizing the weight loss method to assess the consumption rate on coupons in the diverse soil tests. Results demonstrated that both parameters had an impact on covered steel yet soil resistivity had a commanding impact contrasted with soil pH.

Kleiner et al. (2010) portrays research that tries to pick up an intensive comprehension of the geometry of outer corrosion pits and the elements (e.g., soil properties, appurtenances, service associations, and so forth) that impact this geometry. This comprehension would prompt a definitive goal of accomplishing a superior capacity to survey the remaining existence of ductile iron pipe for a given set of circumstances. Fluctuating lengths of ductile iron pipes were unearthed by a few North American and Australian water utilities. The uncovered pipes were cut into segments, sandblasted and labeled. Soil samples separated along the unearthed pipes were additionally given. Funnel portions were checked, utilizing a uniquely created laser scanner examined information was prepared utilizing extraordinarily created programming. Measurable investigations were performed on three geometrical properties, to be specific pit profundity, pit region and pit volume.

Different soil qualities were explored for their effect on the geometric properties of the corrosion pits. Preparatory discoveries showed that the information does not generally supports customary traditions.

Yahaya et al. (2011) outlined a technique of the outside development demonstrating of corrosion on covered gas pipelines under different exposures to soil conditions. The method can be utilized to produce field information to demonstrate observationally the corrosion dynamic in soil or for check of consumption information from research center testing. The potential model taking into account the proposed system is exceedingly potential to foresee the probability of consumption development rate experienced by covered lines presented to destructive environment. As a result, it can significantly help administrator to secure the trustworthiness of their pipelines until the structure achieves its outlined lifetime.

Lim et al. (2011) evaluated the soil engineering parameters which are moisture and clay contents on corrosion rate of X70 pipeline type. Total number of test specimen of X70 carbon steel pipe coupon were set underground in five different sites in Peninsular Malaysia for 12 months were retrieved every three months to determine the weight loss and corrosion rate as a function of time. They discovered that the highly corrosion growth approximately relate with high moisture content of soil while a slow corrosion growth begin with clayey soil content. The moisture content was more effective to cause X70 carbon steel pipe corrode than clay content.

Sulaiman et al. (2014) examined the corrosion parameters utilizing the Potentiodynamic polarization bends. So as to focus corrosion parameters of potential and current thickness of the intriguing metal, carbon steel and ecological states of outside consumption of covered carbon steel pipeline in Iraqi soil were readied in the research facility utilizing reenacted arranged conditions. Arrangements of sodium chloride at diverse focuses (300, 1100, 1900, 2700, and 3500 ppm) were utilized. pH of arrangement were acidic at pH =5, and alkaline at pH = 9. Lab conditions were like those of Iraqi soil where the pipelines were covered. Temperature was consistent at 20 °C. Potentiodynamic polarization bends, of potential versus log current thickness, were acquired utilizing M Lab Multi-Channel Potentiostat Galvanostat. The carbon steel coupon (ASTM A179-84A) was utilized as the considered metal. The after effects of this work uncover the conduct of carbon steel in

outside erosion conditions under Iraqi soil. The rate of corrosion of carbon steel increments with the increment in chloride fixation in arrangement as pH changes from acidic to alkaline medium the rate of corrosion reductions.

Pritchard et al. (2013) surveyed the UK soil towards infrastructure, has basically evaluated the soil variables that are considered to influence soil corrosivity of which are extremely complex, don't act in segregation are inherently connected and interrelated. The survey also illustrated that the gas, oil, and water processes sector are most influenced by corrosion processes with compare to the other sectors.

Saupi et al. (2015) have focused on corrosion properties that open to soil environment. In this review, the corrosion forms as for outward appearance and changed physical properties are uniform assault, galvanic corrosion, erosion corrosion, stress corrosion, pitting corrosion, and between granular corrosion. Outer corrosion is corrosion assault upon the outside of the pipe soil medium and the most failure mechanism experienced by covered steel pipelines.

Chuka et al. (2014) conducted an experimental study on the effect of environment on corrosion of mild steel, for a period of five weeks, the different media were supplying for this study are: 0.1M of Hydrochloric acid, underground (soil), atmosphere, salt water, fresh water. It was spotted that mild steel corrode in the different circumference with decreasing concentration in the order of 0.1M of hydrochloric acid, underground (soil), atmosphere, salt water, fresh water.

2.2 Corrosion Modeling and Statistical Analysis

Ossai, (2013) applied the Monte Carlo Simulation with degradation models in order to estimate the corrosion growth and the reliability of oil and gas pipeline. The outcome of the study demonstrates that the corruption models and Monte Carlo simulation can forecast the corrosion rate of the pipelines to a precision of between 83.3-98.6% and 85.2-97% respectively.

Norhazilan et al. (2012) investigated the relationship between three engineering soil properties which are: moisture content, clay content, and plasticity index. Statistical

analysis was conveyed out to evaluate the relationship between soil properties and corrosion rate. The investigation comprised of simple bar graph, linear regression, multiple regression method, and Analysis of Variances (ANOVA). The site testing results demonstrated that the moisture content as the most administration impact on corrosion rate in light of the correlation coefficient.

Anyanwu et al. (2014) found from the ANOVA that soil resistivity had a noteworthy commitment to corrosion response in soil. A mathematical model was created utilizing multiple regression analysis. The outcome demonstrated that the model created was suitable for forecast of corrosion development rate with soil pH and resistivity as the two independent variables; since the coefficient of determination $R^2=0.8129$ was significantly high.

CHAPTER 3

LITERATURE REVIEW

3.1 Corrosion

Corrosion in general form is the destructive chemical or electrochemical reaction or loss in material properties when the materials are to be in contact with their environment. For corrosion to happen, the development of a corrosion cell is crucial. A corrosion cell is basically embodied the accompanying four segments:

- Anode
- Cathode
- Electrolyte
- Metallic path

3.1.1 Anode

One of the two dissimilar metal terminals in an electrolytic cell represented as the negative terminal of the cell. Electrons are discharged at the anode, which is the more responsive metal. Electrons are insoluble in fluid arrangements and they just move through the wire association into the cathode. Corrosion terminology is the inverse of electroplating classification, where an anode is positive, the cathode is negative.

3.1.2 Cathode

One of the two terminals in an electrolytic cell represented as a positive terminal of a cell. Decrease happens at the cathode also, electrons are expended.

3.1.3 Electrolyte

It is the electrically conductive arrangement (e.g. salt solution) that must be available for corrosion to happen.

3.1.4 Metallic path

The two terminals are joined remotely by a metallic conduit. In the metallic conduit, 'routine " current streams from (+) to (–) which is truly electrons spilling out of (–) to (+).

Metals give a way for the stream of ordinary current which is really section of electrons in the inverse head. Figure 3.1 shows an corrosion phenomenon in action (Ahmad, 2006).

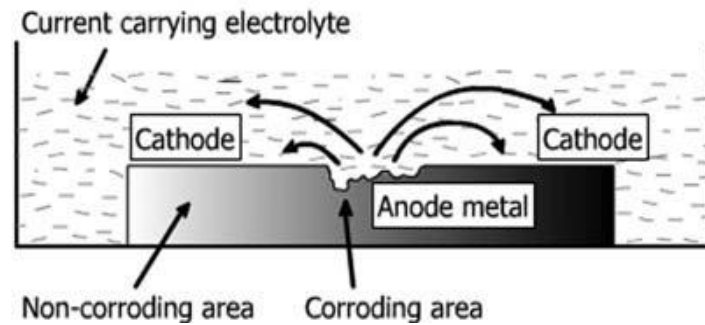


Figure 3.1: Corrosion phenomenon in action (Ahmad, 2006)

3.2 Corrosion Damage Forms

A wide spectrum of corrosion problems are encountered in industry as a result of combination of materials, environments and service conditions. Corrosion may not have a deleterious effect on a material immediately but it affects the strength, mechanical operations, physical appearance and it may lead to serious operational problems. Corrosion may manifest itself as a cosmetic problem only, but it can be very serious if deterioration of critical components is involved. Serious corrosion problems, such as the pitting of condenser tubes in heat exchangers, degradation of electronic components in aircrafts and corrosion fatigue of propellers can lead to catastrophic failures. When catastrophic failures occur, the cost in terms of lives, equipment, and time is very high. While evaluating the long range performance of materials, it is essential for an engineer to consider the effects of corrosion along with other characteristics, such as strength and formability. Environment plays a very important part in corrosion. The severity of corrosion varies considerably from one place to another.

The most corrosion sorts classified regarding outer appearance and physical features as follows:

3.2.1 General corrosion

This is the most common form of corrosion and the most popular type, general corrosion occurs in atmosphere, liquid and soil under normal service condition. This sort of corrosion can appear as rusting of iron, tarnishing of silver and fogging of nickel (Revie & Uhlig, 2008). This type of corrosion will produce a rough surface and will cause loss amount of metal which react with environment and produce adherent film coating of corrosion product.

3.2.2 Pitting

Pitting is extremely localized corrosion, this type of corrosion is by visual examination, its characteristic of interior walls at the point when subject into high speed fluid. The pitting begins when one area of metal surface become anodic with respect to surrounding surface, the combination of small anodic area and large cathodic area cause pit to form. The outcome pits are portrayed as deep. In the event that the territory of assault is moderately bigger and not all that deep, the pits are named shallow, iron covered in the soil consumes with arrangement of shallow pits, while stainless steels drenched in seawater distinctively corrode with development of deep pits.

3.2.3 Selective leaching

Also called parting, dealloying corrosion, its consist of removal of an element from alloy by corrosion. The most common example of selective leaching is dezincification, it occurs with zinc alloys, consist of removed of zinc from brass which is an alloy from zinc and copper. Comparative procedures happen in other compound systems in which aluminum; iron; cobalt; chromium and different components are removed, selective leaching is the general concept to portray these procedures, and its utilization blocks the production of terms, for example, dealuminumification, decobaltification, and so forth. Parting is a metallurgical concept that is applied.

3.2.4 Intergranular corrosion

Its corrosion along the grain boundaries often where precipitates particles form. Intergranular corrosion usually related to thermal processing such as welding. Certain austenitic steel are susceptible to inter granular corrosion. The susceptibility is called sensation, sensation it takes place when austenitic stainless steels are heated the chromium and carbon precipitate in grain boundaries as chromium carbide.

3.2.5 Crevice corrosion

This is a localized form of corrosion, caused by the deposition of dirt, dust, mud and deposits on a metallic surface or by the existence of voids, gaps and cavities between adjoining surfaces. An important condition is the formation of a differential aeration cell for crevice corrosion to occur. This phenomenon limits the use, particularly of steels, in marine environment, chemical and petrochemical industries.

3.2.6 Selective attack on inclusions

It is a special case of selective leaching, in this type of attack the body of metal is resisting to the environmental and only small amount of material corroded away, inclusion in the metal provide a small anodic area surrounded by a large cathodic area.

3.2.7 Galvanic cell

Dissimilar metals are physically joined in the presence of an electrolyte. The more anodic metal corrodes. The galvanic cell may have an anode or cathode of unique metals in an electrolyte or the same metal in unique conditions in a typical electrolyte. For instance, steel and copper anodes drenched in an electrolyte Figure 3.2, represents to a galvanic cell. The more honorable metal copper acts as the cathode and the more dynamic iron go about as an anode. Current stream pass from iron anode to copper cathode in the electrolyte.

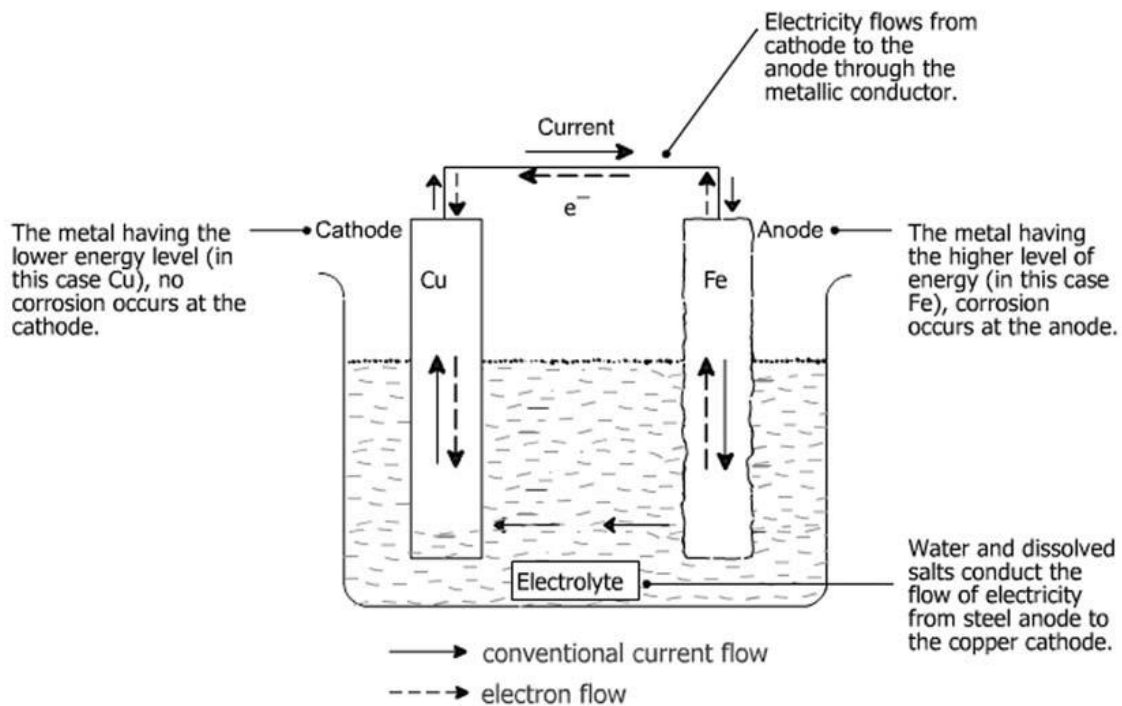


Figure 3.1: Corrosion cell phenomenon in action (Ahmad, 2006)

3.2.8 Concentration cell

Commonly occurs in the metal buried under the ground. Metals corrode because they are in contact with soils that vary in chemical composition, water content, or decrease of aeration.

3.2.9 Differential temperature cell

Corrosion can be formed by a differential in temperature, this happened particularly when the temperature differ sufficient to alter the level of dissolved oxygen from one location to another. The anode and cathode consist of the same metal and differ only in temperature.

3.3 Sorts of Corrosion Cell

In general there are three basic type of corrosion cell which are covering most of corrosion cells and consider as a segment of corrosion reaction.

3.3.1 Dissimilar electrode cells

A metal contain an electrical directing defect at first glance as a different stage, a copper pipe associated with an iron pipe, and a bronze propeller in contact with the steel frame of a boat. Unique cathode cells likewise incorporate chilly - worked metal in contact with the same metal tempered, grain - limit metal in contact with grains, and a solitary metal precious stone of definite introduction in contact with another crystal of diverse introduction, dry cell as an example of this type of cell as shown in Figure 3.3 (Revie & Uhlig, 2008).

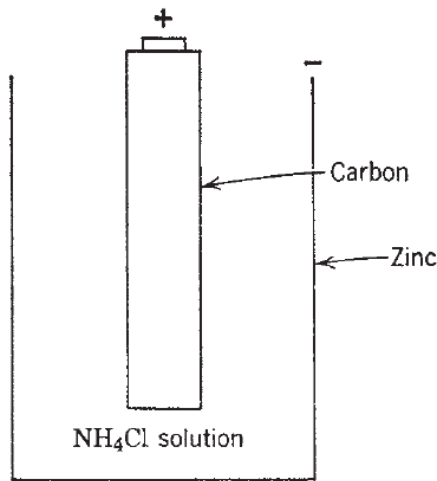


Figure 3.2: Dry cell (Revie and Uhlig, 2008)

3.3.2 Concentration cells

These are cells with two indistinguishable electrodes, each in contact with a solution of distinctive arrangement. There are two sorts of concentration cells. The principal is known as a salt concentration cell. The second sort of concentration cell, which by and by is the more vital, is known as a differential air circulation cell Figure 3.4 (Revie & Uhlig, 2008).

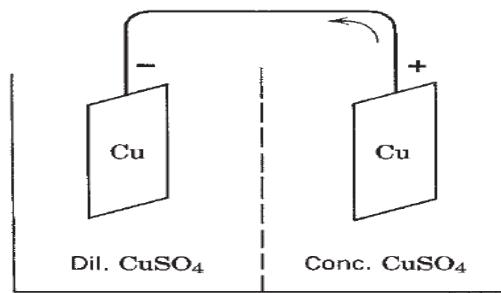


Figure 3.4: Concentration cell (Revie and Uhlig, 2008)

3.3.3 Differential temperature cells

Segments of these cells are electrodes of the same metal, each of which is at an alternate temperature, inundated in an electrolyte of the same beginning composition. These cells are found in heat exchangers, boilers, drenching radiators, and comparable equipment.

3.4 Corrosion of Steel

On the planet today, steel is utilized as a part of different designing applications for the creation of some vehicles segments, auxiliary shapes; I beam and angle iron and sheets that are utilized as a part of pipelines, structures, plants, extensions and tin cans.(Callister, 1997). Corrosion is a characteristic process that lessens the coupling vitality in metals with the deciding result including a metal being oxidized as the mass metal looses one or more electrons. The lost electrons are led through the mass metal to another site where they are decreased (Chuka et al. 2014).

The main impetus that makes metals corrode is a characteristic outcome of their impermanent presence in metallic structure. With a specific end goal to create metals beginning from actually happening minerals and ores, it is important to give a sure measure of vitality. It is accordingly just normal that when these metals are presented to their surroundings they would return back to the first state in which they were found in nature (Roberge, 2008).

An average cycle is shown by iron. The essential consumption result of iron, for instance, is Fe(OH)_2 (or more probable $\text{FeO} \cdot n\text{H}_2\text{O}$), however the activity of oxygen and water can yield different items having distinctive colors (Roberge, 2008):

- $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$ or hydrous ferrous oxide, sometimes written as Fe(OH)_3 , is the principal component of red-brown rust. It can form a mineral called hematite, the most common iron ore.
- $\text{Fe}_3\text{O}_4 \cdot \text{H}_2\text{O}$ or hydrated magnetite, also called ferrous ferrite ($\text{Fe}_2\text{O}_3 \cdot \text{FeO}$), is most often green but can be deep blue in the presence of organic complexants.
- Fe_3O_4 or magnetite is black.

Consider a bit of iron presented to muggy air which goes about as an electrolyte. Fe^{2+} ions are discharged from the anode by oxidation and OH^- particles from the cathode by decrease on the metal surface. The negative and positive ions combine.



Fe(OH)_2 is insoluble in water and separates from the electrolyte. A more familiar name of Fe(OH)_2 is rust (Ahmad, 2006).

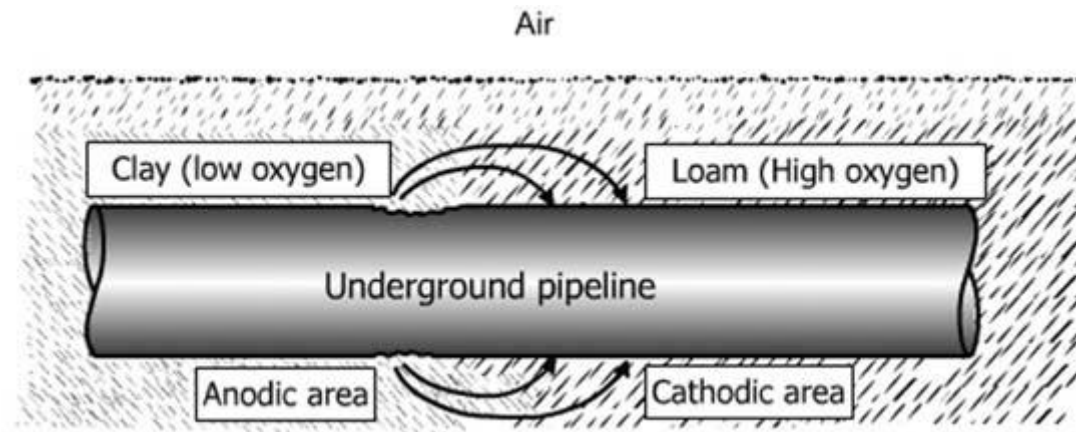


Figure 3.5: Concentration cell formation in an underground pipeline (Ahmad, 2006)

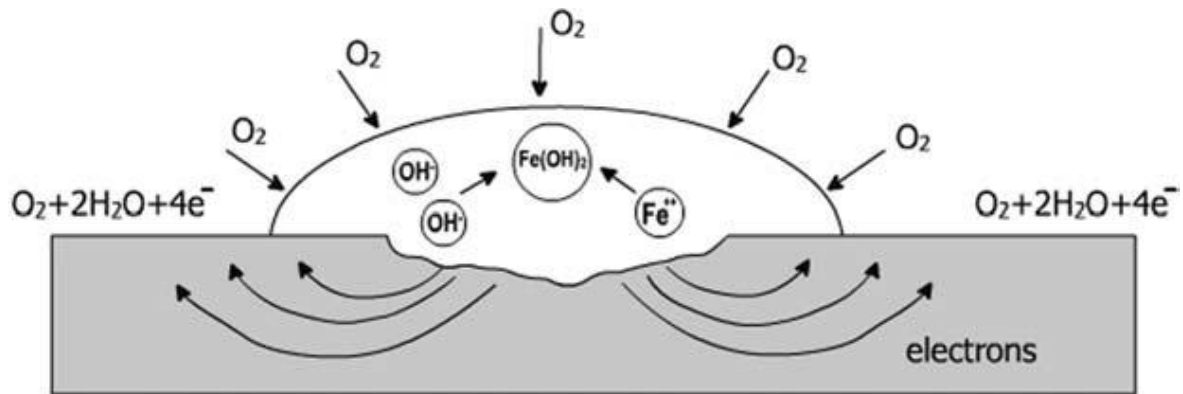


Figure 3.6: Formation of rust in seawater (Ahmad, 2006)

In most consumption issues, the critical contrasts in response potential are not those between unique metals, but rather are those that exist between independent regions blended over all the surface of a solitary metal. These potential contrasts result from neighborhood concoction or physical contrasts inside or on the metal, for example, varieties in grain structure, hassles, and scale considerations in the metal, grain limits, and scratches or other surface condition. Steel is a combination of immaculate iron with little measures of carbon present as Fe_3C and follow measures of other components. Iron carbide (Fe_3C) is cathodic as for iron. In light of the fact that in run of the mill consumption of steel the anodic and cathodic regions untruth next to each other on the metal surface, basically it is secured with both positive and negative destinations. Amid erosion, the anodes and cathodes of metals may trade much of the time (Chilingar et al., 2008).

3.5 Pipeline and Pipeline Corrosion

The concept of pipe is characterized as a rule of round cross area. It can be made of any suitable material, for example, steel. The pipeline concept alludes to a long line of associated fragments of pipe, with pumps, valves, control tools, and other tool/offices required for working the system. It is proposed for transporting a fluid (liquid or gas), mixture of fluids or solids and fluid solid mixture (Liu, 2003).

The metal in the pipe line is steel, fundamentally involved iron with one to two percent alloy for quality and strength. With respect to outer corrosion, the circumstance would be seawater for offshore pipelines and groundwater or clammy soil for onshore pipelines. The

decay would be disintegration of the iron into the environment, which decreases the quality of the pipeline (Baker, 2008).

Regularly, corrosion in pipelines shows as pitting as opposed to as a uniform decrease in wall thickness. This is on account of nature at an anodic range has a tendency to wind up more acidic. In such cases the pits will be detached from one another and, different times, they will be so near one another that they overlap and create a general yet unpredictable diminishing in the pipe wall.

Seamless pipes have been utilized as a part of a few frameworks. Most linepipe contains a longitudinal weld, or seam. The long seam, as it is called, most much of the time is made by submerged-arc segment welding or upset butt welding. A submerged-arc weld contains a filler metal that has a creation somewhat, not the same as that of the body of the pipe and the heat influenced zone beside the weld metal has a microstructure not quite the same as that of whatever is left of the pipe. Upset butt welds, which can be either electric-resistance welds or flash welds, don't contain filler metal; they likewise have a heat influenced zone that has an alternate microstructure. Since these distinctive microstructures can be more powerless to corrosion than the encompassing metal, particular corrosion at the seam can here and there happen with minimal contiguous corrosion related collapse.

MIC (Microbiologically affected corrosion) is brought about by microorganisms whose activities start the corrosion cycle. There are a few sorts of organisms that, while creating distinctive impacts, have been found to advance either outside or inside corrosion. The principle sorts are sulfate-reducing microscopic bacteria (SRB) and corrosive producing bacteria (APB). Microscopic organisms can advance outside corrosion by depolarizing the pipe through the utilization of hydrogen gas shaped at the pipe surface by the cathodic assurance streams. When the pipe is depolarized, corrosion can happen (Baker, 2008).

3.6 Corrosion in Soil

There are more than 3.7 million kilometers (2.3 million miles) of pipelines crossing the United States, transporting natural gas and hazardous liquids from sources such as wells, refineries, and ports to customers. Underground corrosion is of major importance and

results in a significant portion of pipeline failures. Because of corrosion, these pipelines must be regularly inspected, maintained, and sometimes replaced (Ricker, 2010).

Soil corrosivity, when contrasted with that of the air or seawater corrosivity is regularly harder to classify with respect to both pipe particular parameters and encompassing soil properties (Ferreira, 2006). This is because of the soil's to a great degree confined many-sided quality and heterogeneity.

In soils, water and gas occupy the spaces between solid particles, and these spaces can constitute as much as half the volume of dry soil. Some of this water is bound to mineral surfaces, whereas bulk water can flow through porous soil. Fluid flow through soil is controlled by the permeability of the soil, which, in turn, depends on the size distribution of the solid particles in the soil. Coarse – grained sand, for example, allows good drainage and access of atmospheric oxygen to a depth greater than, for example, fine - grained soils high in clay. Capillary action in fine - grained soil can draw water up, keeping the soil water - saturated, preventing drainage, retarding evaporation, and restricting oxygen access from the atmosphere to a buried structure, such as a pipeline (Wilmott and Jack, 2000).

The electrochemical corrosion processes that take place on metal surfaces in soils occur in the groundwater that is in contact with the corroding structure. Both the soil and the climate influence the groundwater composition. For example, some clay soils buffer the groundwater pH. Groundwater in desert regions can be high in chloride and very corrosive. On the other hand, groundwater in tropical climates tends to be very acidic.

The corrosion behavior of iron and steel buried in the soil approximates, in some respects, the behavior on total immersion in water. Minor composition changes and structure of steel, for example, are not important to corrosion resistance. Hence, a copper - bearing steel, low alloy steel, mild steel, and wrought iron are found to corrode at approximately the same rate in any given soil. In addition, cold working or heat treatment does not affect the rate. Gray cast iron in soils, as well as in water, is subject to graphitic corrosion. Galvanic effects of coupling iron or steel of one composition to iron or steel of a different composition are important, because they are under conditions of total immersion (Revie and Uhlig, 2008).

In other respects, corrosion in soils resembles atmospheric corrosion in that observed rates, although usually higher than in the atmosphere, vary to a marked degree with the type of soil. A metal may perform satisfactorily in some parts of the country, but not elsewhere,

because of specific differences in soil composition, pH, moisture content, and so on. For example, a cast iron water pipe may last 50 years in New England soil, but only 20 years in the more corrosive soil of southern California. Corrosion rates of underground pipeline have been measured using the Stern – Geary linear polarization method, as well as weight loss. The former method has been useful, for example, in assessing the corrosion rates of footings of galvanized - steel towers used to support power lines Figure 3.7 shows the mechanism of corrosion of buried pipe.

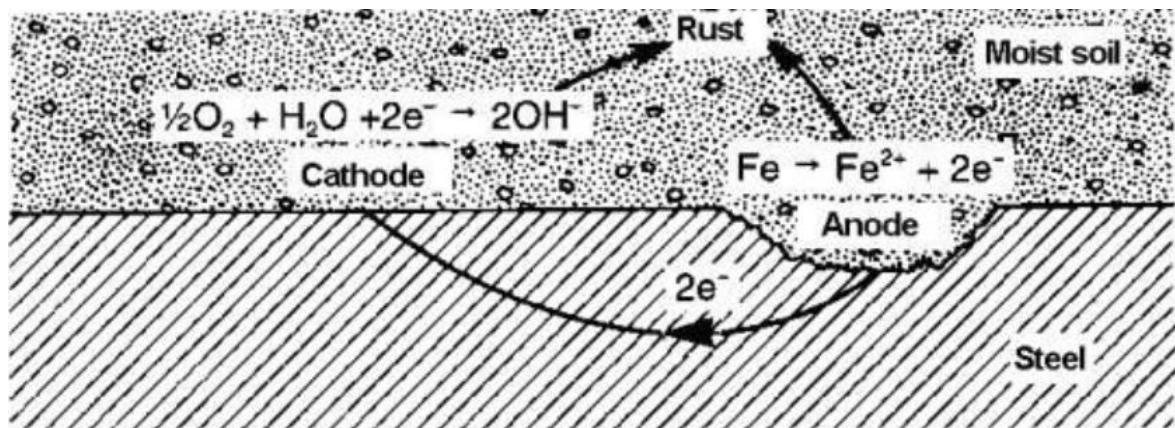


Figure 3.7: Corrosion mechanism of soil for buried pipe (Camitz, 1998)

3.6.1 Factors affecting the corrosivity of soils

One of the primary variables that impact the rate of outer corrosion is the distinctions in the attributes of the soil from spot to spot along a pipeline, and from top to bottom. Contrasts in air circulation, moisture content, and soil arrangement in these regions can create solid main impetuses for corrosion (Baker, 2008).

Among the factors that affect corrosivity of a given soil are:

- Porosity (aeration).
- Electrical conductivity or resistivity
- Dissolved salts, including depolarizers or inhibitors
- Moisture
- pH
- Soil texture

The variety of concoction and physical properties in the soil, even over a solitary site, can change how an item corrodes contrasted with another indistinguishable object. At the point

when underground pipes are initially introduced a refill is comprised of accessible (regularly irritated) soil from close-by, frequently this soil will contain transported material and building waste, either from the close-by surface or, in the event that it is brought into the site from somewhere else, it is the thing that geotechnical architects portray as “made ground” (Waltham, 2002). The Figure 3.8 shows the different and direction of current.

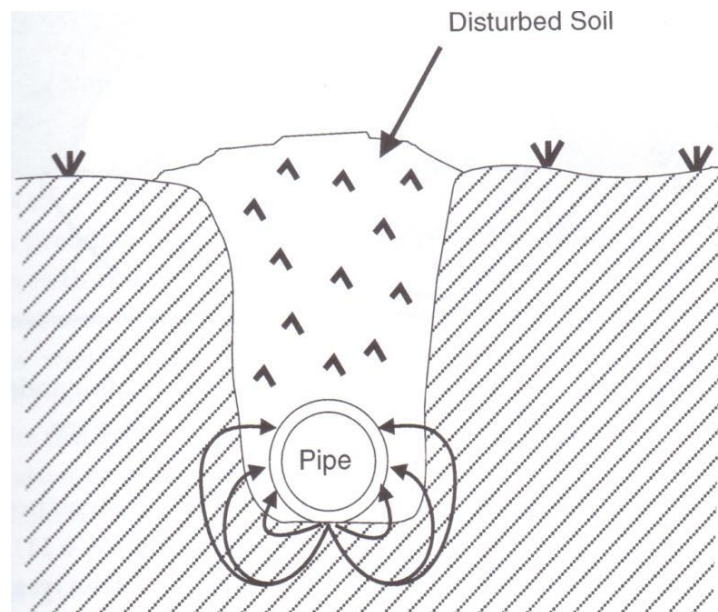


Figure 3.8: Corrosion produces in disturbed soil vs. undisturbed soil, the direction of positive current represented by arrow (Bradford, 2001)

Each of these variables may affect the anodic and cathodic polarization characteristics of a metal in a soil. A porous soil may retain moisture over a longer period of time or may allow optimum aeration, and both factors tend to increase the initial corrosion rate. The situation is more complex, however, because corrosion products formed in an aerated soil may be more protective than those formed in non aerated soil. In most soils, particularly if not well - aerated, observed corrosion takes the form of deep pitting. Localized corrosion of this kind is obviously more damaging to a pipeline than a higher overall corrosion rate occurring more uniformly. Another factor to be considered is that, in poorly aerated soils containing sulfates, sulfate – reducing bacteria may be active; these organisms often produce the highest corrosion rates normally experienced in any soil.

Aeration of soils may affect corrosion not only by the direct action of oxygen in forming protective films, but also indirectly through the influence of oxygen reacting with and

decreasing the concentration of the organic complexing agents or depolarizers naturally present in some soils. In this regard, the beneficial effect of aeration extends to soils that harbor sulfate - reducing bacteria because these bacteria become dormant in the presence of dissolved oxygen. Soil composition is an essential variable, clay soil because of its inborn sub-atomic structure, can hold dampness more promptly than a sandy soil. This implies water in clay is all the more effortlessly held thus, has a more prominent presentation to any covered metal surfaces, encouraging the corrosion activity of the soil (Jones, 1992) the different field moisture capacity as a function of different sand contents shown in Figure 3.9.

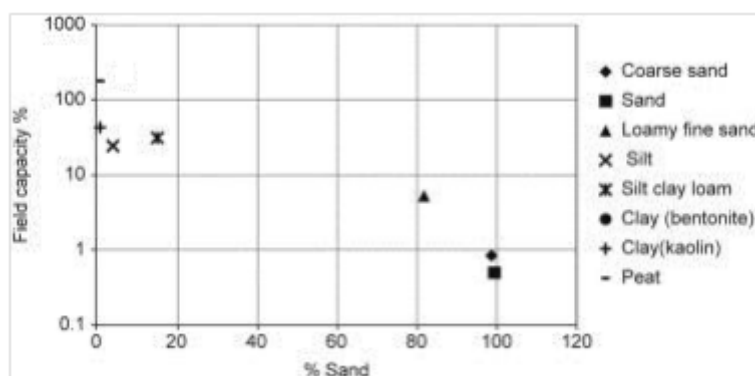


Figure 3.9: Different moisture capacities as function of sand content

A soil containing organic acids derived from humus is relatively corrosive to steel, zinc, lead, and copper. The measured total acidity of such a soil appears to be a better index of its corrosivity than pH alone. High concentrations of sodium chloride and sodium sulfate in poorly drained soils, such as are found in parts of southern California, make the soil very corrosive.

Macro galvanic cells or “ long - line ” currents established by oxygen concentration differences, by soils of differing composition, or by dissimilar surfaces on the metal become more important when electrical conductivity of the soil is high. Anodes and cathodes may be thousands of feet, or even miles, apart. A poorly conducting soil, whether from lack of moisture or lack of dissolved salts or both, is, in general, less corrosive than a highly conducting soil. But conductivity alone is not a sufficient index of Corrosivity.

While the ionic substance of a watery medium, the question frequently emerges in respect to how acid, or alkaline, is the arrangement. Very essentially, this alludes to whether there

is an abundance of H^+ (hydrogen) or OH^- (hydroxyl) particles present. The H^+ particle is acid while the OH^- particle is alkaline or essential (Roberege, 2008).

Hydrogen ion activity is commonly expressed, for convenience, in terms of pH, defined as

$$pH = -\log(H^+) \quad (3.2)$$

Hence, for the half - cell reaction $2H^+ + 2e^- \rightarrow H_2$, with the pressure of hydrogen equal to 1 atm, we have

$$\phi_{H_2} = -0.0592 \quad (3.3)$$

Since pure water contains equal concentrations of H^+ and OH^- in equilibrium with undissociated water, $H_2O \rightarrow H^+ + OH^-$, it is possible to calculate the activity of either the hydrogen ion or the hydroxyl ion from the ionization constant, the value of which at $25^\circ C$ is 1.01×10^{-14} . Therefore, the pH of pure water at $25^\circ C$ is

$$-\log \sqrt{1.01 \times 10^{-14}} = 7.0 \quad (3.4)$$

If (H^+) exceeds (OH^-), as in acids, the pH is less than 7. If the pH is greater than 7, the solution is alkaline. The pH of strong acids can be negative, and the pH of strong alkalies can be greater than 14. At temperatures above $25^\circ C$, the ionization constant of H_2O is greater than at $25^\circ C$; therefore, above $25^\circ C$, the pH of pure water is less than 7 (Revie and Uhlig, 2008).

Higher pH implies there are less free hydrogen ions, and that a change of one pH unit mirrors a tenfold change in the concentrations of the hydrogen ion. For instance, there are 10 times the same numbers of hydrogen ions accessible at pH 7 than at pH 8. Substances with a pH less than 7 are thought to be acidic, and substances with a pH equivalent to or

more prominent than 7 are thought to be basic. Subsequently, a pH of 2 is extremely acidic and a pH of 12 exceptionally basic (Roberge, 1999).

3.7 Corrosion Measurement (Weight Loss Method)

Electrochemical procedures give a distinct option for conventional methods used to decide the rate of corrosion quantitative determination of corrosion rates and Immediate. The determination of the corrosion rate will be as a time function.

Weight reduction tests are the most widely recognized of all rate estimation tests. A little metal coupon (generally low-carbon steel) is uncovered in the liquid or soil or exposed to any corrosive environments framework where corrosion may be dynamic. The coupon is left for a limited time frame and after that evacuated, cleaned, and weighed to decide the measure of metal loss. Weight reduction, surface area of coupon, and presentation time are utilized to compute corrosion rate (Chilingar et al. 2008) described in section 4.1.2 chapter four.

The weight of the specimen former and in the wake of being presented to soil environment was recorded to decide the metal loss and therefore the corrosion rate equation 4.1 in chapter four.

3.8 Statistical Analysis and Corrosion Prediction

Predictive displaying and statistical procedure control have gotten to be indispensable parts of the present day science and building of complex frameworks. The massive presentation of computers in the working environment has additionally definitely changed the significance of these machines in every day operations. Models of materials corruption procedures have been created for a huge number of circumstances utilizing an awesome assortment of strategies. For researchers and specialists who are creating materials, models have turned into a fundamental benchmarking component for the choice and life forecast connected with the presentation of new materials or procedures.

Models are in this setting an acknowledged technique for representing to current understandings of reality. For frameworks chiefs, the corrosion execution or under performance of materials has an altogether different significance. In the setting of life-cycle administration, corrosion is stand out component of the entire picture, and the principle trouble with corrosion information is to convey it to the framework administration level.

Statistical appraisal of time to disappointment is an essential theme in dependability building for which numerous numerical apparatuses have been produced. Evans, who pioneered the mixed-potential theory to explain basic corrosion kinetics, propelled the idea of corrosion likelihood in connection to limited corrosion. As indicated by Evans, a precise learning of the corrosion rate was less critical than discovering the statistical danger of its introduction. Petting is, obviously, one and only of the numerous types of limited corrosion, and the same contention can be reached out to any type of corrosion in which the instruments controlling the start stage vary from those controlling the spread stage (Roberge, 1999).

Statistics is the section of scientific method which manages the data acquired by counting or measuring the properties of natural phenomena, a natural phenomenon incorporates everything of the happenings of the external world, whether human or not.

The “Statistical Package for the Social Sciences” (SPSS) is a package of programs for manipulating, analyzing, and presenting data. the package is widely used in the social and behavioral sciences. There are several forms of SPSS. The core program is called SPSS Base and there are a number of add-on modules that extend the range of data entry, statistical, or reporting capabilities (Landau and Everitt, 2004).

3.9 Importance and Cost of Corrosion

The three principle purposes behind the significance of corrosion are: financial aspects, wellbeing, what's more, protection. To lessen the monetary effect of corrosion, corrosion engineers, with the backing of corrosion researchers, mean to lessen material misfortunes, as well as the going with financial misfortunes, that outcome from the corrosion of channeling, tanks, metal parts of machines, boats, spans, marine structures, etc. Corrosion

can trade off the security of working gear by bringing on disappointment (with disastrous results) of, for instance, weight vessels, boilers, metallic compartments for poisonous chemicals, turbine sharp edges and rotors, spans, plane segments, and car directing components. Wellbeing is a basic thought in the outline of hardware for atomic force plants and for transfer of atomic squanders. Loss of metal by corrosion is a waste not just of the metal, additionally of the vitality, the water, and the human exertion that was utilized to create and manufacture the metal structures in the first place. Furthermore, revamping eroded hardware requires further venture of every one of these assets metal, vitality, water, and human.

Financial misfortunes are partitioned into direct misfortunes and circuitous misfortunes. Direct misfortunes incorporate the expenses of corrosion structures and hardware on the other hand their segments, for example, condenser tubes, suppressors, pipelines, and metal material, including fundamental work. Different illustrations are (a) repainting structures where anticipation of rusting is the prime target and (b) the capital expenses in addition to upkeep of cathodic insurance frameworks for underground pipelines.

Sizable direct misfortunes are represented by the need to a few million residential hot - water tanks every year in view of disappointment by consumption and the requirement for substitution of a great many consumed vehicles mufflers. Direct misfortunes incorporate the additional expense of utilizing consumption - safe metals and combinations rather than carbon steel where the last has sufficient mechanical properties however not sufficient erosion resistance. There are additionally the expenses of arousing or nickel plating of steel, of adding erosion inhibitors to water, and of dehumidifying storage spaces for metal gear (Revie and Uhlig, 2008).

The financial component is also a vital for a significant part of the current research in corrosion. Misfortunes supported by industry and by governments sum to numerous billions of dollars every year, pretty nearly \$ 276 billion in the United States, or 3.1% of the Gross Domestic Product (GDP), as indicated by a later study. It has been assessed that around 25 – 30% of this aggregate could be stayed away from on the off chance that at present accessible consumption innovation were adequately connected. Investigations of the expense of consumption to Australia, Great Britain, Japan, and other nations have likewise been done. In every nation examined, the expense of corrosion is more or less 3 –

4 % of the Gross National Product. Backhanded misfortunes are more difficult to evaluate, however a brief overview of average misfortunes of this kind urges the conclusion that they add a few billion dollars to the direct misfortunes effectively outlined (Koch et al., 2002).

Some examples of indirect losses are as follows:

- Shutdown

The substitution of a consumed tube in an oil refinery may cost a couple of hundred dollars; however shutdown of the unit while repairs are in progress may cost \$ 50,000 or more every hour in lost creation. Thus, substitution of consumed heater or condenser tubes in an expensive force plant may require \$ 1,000,000 or more every day for force acquired from interconnected electric frameworks to supply clients while the evaporator is down. Misfortunes of this kind cost the electrical utilities in the United States large amount of money every year.

- Loss of Product

Misfortunes of oil, gas, or water happen through a corroded channel framework until repairs are made. Radiator fluid may be lost through a corroded auto radiator; or gas spilling from a corroded pipe may enter the storm cellar of a building, bringing on a blast.

- Loss of Efficiency

Loss of efficiency may happen as a result of decreased warmth exchange through gathered corrosion items, or due to the obstructing of channels with rust requiring expanded pumping limit. It has been assessed that, in the United States, expanded pumping limit made vital by fractional obstructing of water mains with rust, costs large amount of money every year. A further sample is given by inner - ignition motors of vehicles where cylinder rings and chamber dividers are consistently consumed by ignition gasses and condensates. Loss of discriminating measurements prompting overabundance gas and oil utilization can be brought about by consumption to a degree equivalent to or more noteworthy than that created by wear. Corrosion procedures can force limits on the efficiencies of vitality transformation frameworks, speaking to misfortunes that may add up to billions of dollars.

- Contamination of Product

A little measure of copper grabbed by slight corrosion of copper channeling or of metal gear that is generally strong may harm a whole clump of cleanser. Copper salts quicken rancidity of cleansers and abbreviate the time that they can be put away before utilization. Hints of metals might likewise adjust the shade of colors.

- Overdesign

Over design is normal in the design of response vessels, boilers, condenser tubes, oil - well sucker poles, pipelines transporting oil also, gas at high weight, water tanks, and marine structures. Gear is frequently planned ordinarily heavier than typical working weights or connected anxieties would require so as guaranteeing sensible life. With sufficient information of consumption, more solid appraisals of gear life can be made, and configuration can be simplified regarding materials and work. For instance, oil - well sucker poles are typically overdesigned to expansion administration life before disappointment happens by corrosion weakness. On the off chance that the consumption components were disposed of, misfortunes would be sliced at any rate down the middle. There would be further investment funds in the light of the fact that less power would be obliged to work a lightweight bar, and the cost of recuperating a lightweight pole after breakage would be lower.

Indirect misfortunes are a significant piece of the monetary expense forced by corrosion, despite the fact that it is hard to land at a sensible appraisal of aggregate misfortunes. In the occasion of loss of wellbeing or life through blast, unusual disappointment of compound hardware, or destruction of planes, or autos through sudden disappointment by consumption of basic parts, the circuitous misfortunes are still harder to survey and are past translation as far as dollars (Revie and Uhlig, 2008).

CHAPTER 4

METHODOLOGY

4.1 Materials

4.1.1 Soil samples

The properties of soil are considered as one of the most important parameter that influences the corrosion rate of pipelines. Through this point the investigation of soil characteristics in this research comes out. The soil properties of underground pipelines that transport the crude oil of oil wells located in North of Iraq to Turkey.

The eight samples were collected along the pipe line; the pipeline route in area consists of complex terrain and valleys, interspersed with agricultural land of Zagros basin. The samples were labeled as 'SS-1, SS-2, SS-3, SS-4, SS-5, SS-6, SS-7, and SS-8'. The samples were taken from the depth of about one meter from the ground level for the real location of the pipelines in (June/2015), the soil samples were taken in an air tight polyvinyl container less than 24 hours after collection from actual site (Bhattarai, 2013) as shown in Figure 4.1 (a) and (b) and preserved with the desired inherent conditions in accordance with ASTM D 4220-95 Reapproved, 2000 (Standard Practices for Preserving and Transporting Soil Samples. Appendix 4) the procedure presented in this standard were primarily developed for soil samples that are to be tested for engineering properties. The area is located at latitude of (45° - 46°) north and within longitude of (34° - 36°) east as shown in Figure 4.2.

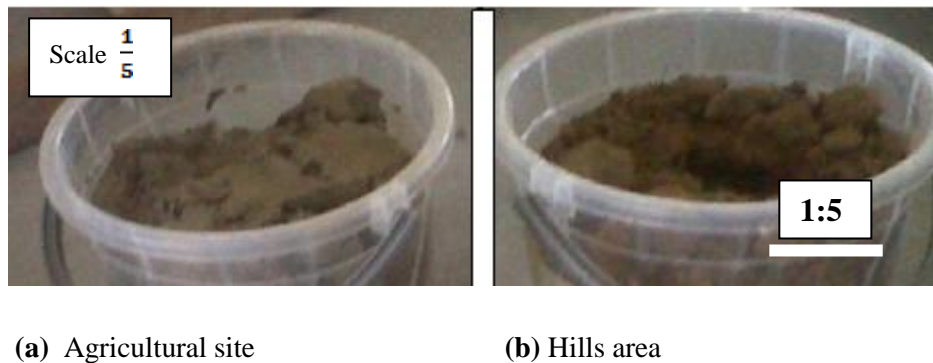


Figure 4.1: Soil samples

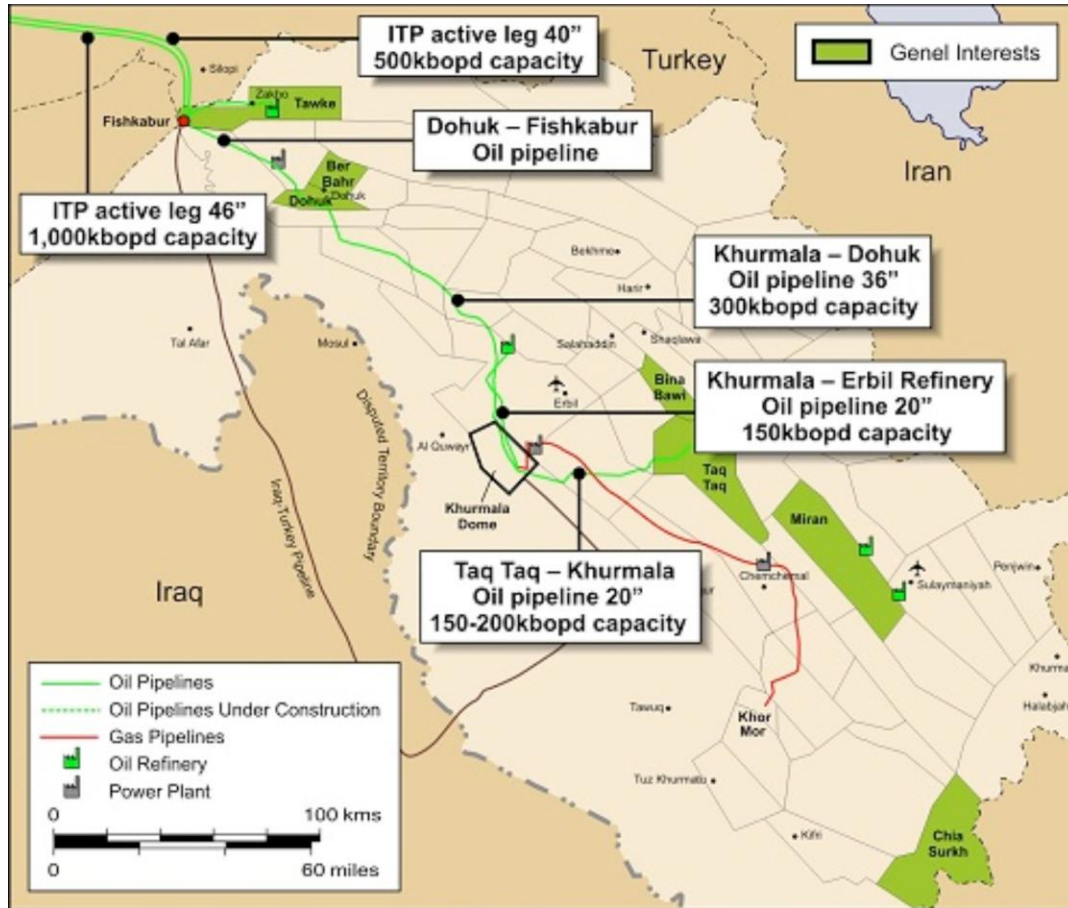


Figure 4.2: Oil and gas pipeline map in north of Iraq¹

4.1.2 Pipe samples

The API 5L X70 steel pipe was used as a case study for this research to examine the influence of soil parameters on the corrosion rate of the pipe. The eight test specimens 'steel coupon' were cut from the pipe, the flat coupon have a dimension of (60 mm * 40 mm * 10 mm) (Noor et al, 2012) the coupon geometry is shown in Figure 4.3. Utilizing hot cut process, cold cut technique was at that point used to uproot heat influenced area on the coupon which may bring about changes in properties of the material. The coatings of those specimens were removed. The procedures, preparation and cleaning process were done following the ASTM G01-03 Reapproved, 1999 (Standard Practice for Preparing, Cleaning and Evaluating Corrosion Test Specimen) (American Society for Testing and Material/ Appendix 5).

¹ <http://www.GenelEnergy.com>

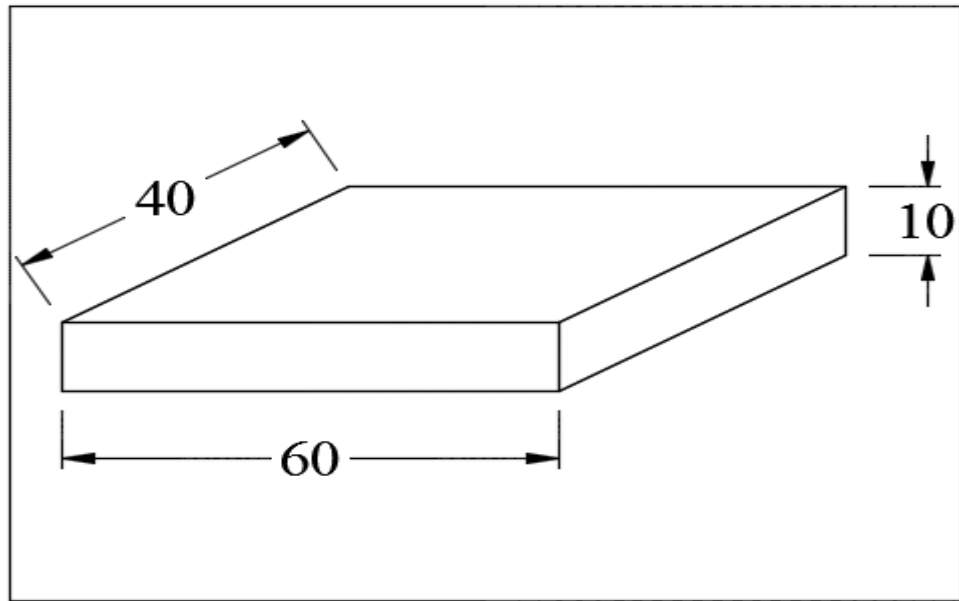


Figure 4.3: Coupon samples dimensions in mm

To evaluate the corrosion rate of the pipe, the coupons were installed in polyvinyl container containing the soil samples to simulate the actual site to corrode naturally (Anyanwu et al, 2014) for a period of three months (2160 hours) the process of installation, preparation of soil medium are referred to ASTM 162-99 (2004) (Standard Practice for Conducting and Evaluating Laboratory Corrosions Tests in Soils. Appendix 8), then the coupons were retrieved to measuring the metal loss of the samples, the coupon cleaning procedure were referred to ASTM G01- 03 (Reapproved 1999) (Standard Practice for Laboratory Immersion Corrosion Testing and Metals/ Appendix 5).

The corrosion rate was calculated by using Equation 4.1

$$CR = \frac{K*W}{A*D*T} \quad (4.1)$$

The results are given in Table 5.5 of chapter five.

The chemical and mechanical properties of API 5L X70 are shown in Table 4.1 as specified in API 5L specifications.

Table 4.1: Mechanical and chemical properties of API 5L X70 steel pipe (Appendix 9)

Chemical Properties					Mechanical Properties	
C %	Mn %	P %	S %	Ti %	Yield strength, Psi (MPa)	Tensile Strength, psi (MPa)
0.28	1.40	0.030	0.030	0.06	70000 (483)	82000 (565)

4.2 pH Testing

4.2.1 Sample preparation

A bulk sample was air dried at room temperature it was obtained after splitting and prepared over #10 (2.00mm) mesh sieve. Particles more than #10 sieve are ground with a mortar and pestle to separate aggregations of soil particles in to individual grains and sieved again Portion of material less than #10 sieve is again split down to obtain a 30 to 35 gram specimen in accordance with BS 1377-3:1999 (Methods of test for Soils for civil Engineering purposes Part 3: Chemical and electro-chemical tests. Appendix I/A1) as shown in Figure 4.4 (a and b).



(a) Agricultural site

(b) Hills area

Figure 4.1: Sample preparation

4.2.2 pH - test

pH is the measure of the acidity or basicity of a solution. The pH of a material plays a significant role in how aggressive corrosion can be. The acidity of soil comes from mineral leaching, decay of acidic plants like (coniferous tree needles), industrial wastes, acid rain, and certain forms of microbiological activity. Alkaline soils tend to have high sodium,

potassium, magnesium, and calcium contents; these elements produce calcareous deposits on buried structures that have protective behavior against corrosion. The pH level has an influence on the solubility of corrosion products and also the nature of microbiological activity (Roberge, 1999). Table 4.2 shows the relation between pH level and soil corrosivity.

Table 4.2: Relative acidity pH of soil and corrosivity of soil (Roberge, 1999)

Corrosivity of Soil	Relative Acidity (pH) of Soil Extract
Low	>12
Moderate	7.5 - 12
High	4 – 7.5
Very high	<4

4.2.3 Test procedure

Using analytical balance for determining (30 ± 0.1) g from the soil samples required for the test Figure 4.5, and placed in 100 mL beaker 75 mL of distilled water was added to the beaker with stirring for a few minutes and leaving the solution for 8 hours with covering the breaker by glass cover and stirred again before the test Figure 4.6.

Calibration of pH meter required by using standard buffer solution provide from the manufacturer Figure 4.7, taking two to three reading with washing the electrode by distilled water again with stirring the solution between each reading in accordance with BS 1377-1:1990 Methods of test for Soils for civil Engineering purposes Part 3: Chemical and electro-chemical tests/ Appendix 1).



Figure 4.5: A&B GR 120 analytical balance



(a) Hills area

(b) Agricultural site

Figure 4.6: (100 mL) beaker with 30g soil and 70mL distilled water

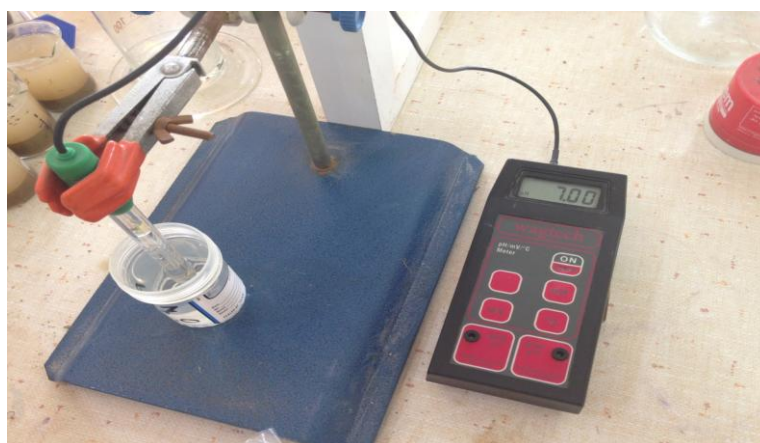


Figure 4.7: Calibration of pH meter with standard buffer solution

4.3 Moisture Content Testing

4.3.1 Sample preparation

After the fragmentation of the soil to smaller parts by hammers prepared for test, saving the samples in a non-corrosive container and preventing air to contact with the soils, at a temperature between (3-30) °C, in a place far away from exposure to direct sunlight. Taking samples of the soil after mixing and mass selection was done in accordance with ASTM D4643-08 (Standard Test Method for Determination of Water (Moisture) Content of Soil by Microwave Oven Heating/ Appendix 2). Table 4.3 shows the relation between sieve number and recommended mass of moist specimen.

Table 4.3: Test specimen masses (ASTM D 4643-08)

Sieve retaining not more than about 10% of sample	Recommended mass of moist specimen, g
2.0 mm (No. 10)	100 to 200
4.75 mm (No. 4)	300 to 500
19 mm (¾ in.)	500 to 1000

4.3.2 Moisture content

The test measure the water present in a soil as percentage between the amounts of absorbed water through soil mass to the same amount of soil mass without water ASTM D 4643-08 (Standard Test Method for Determination of Water (Moisture) Content of Soil by Microwave Oven Heating/ Appendix 2).

The water plays a critical role as fundamental electrolyte in the electrochemical corrosion action (Roberge, 2008).

Shrier *et al.*, (2000) identified three types of soil moisture:

- Free ground water: Basically this represent to the water table of the substrate, beneath which water is constantly present. The profundity to free ground water can fluctuate, subordinate upon topographical and climatic elements.

- Gravitational water: Whereby water, ordinarily as an after effect of precipitation, enters the soil surface and permeates downwards. In the long run this water achieves the free ground water table, regularly quickly, particularly in coarser grained soils (sand and gravel as an example).
- Capillary water: Water that is held inside of the "capillary" spaces between clay and silt particles, this asset is the thing that plants and creatures living inside of the soil mass depend on for their water utilization. The large sandy soils have a little measure of fine water accessible.

Water substance and water movement in soils can be seen as a variable of (Cole and Marney, 2012):

- Water flow patterns.
- Ground topography, soil profiles and the position of the water table.
- Soil type and water saturation limits.

4.3.3 Procedure

Identified soil samples were used in clean, dry container were weighed using GR 120 analytical balance shown in Figure 4.5, After determination the amount of soil sample to be tested according to Table 4.2, place an amount of 200g into the container and then recording the mass of container and the sample together, the sample placed inside the an oven dryer Figure 4.8, 700 W oven dryer accordance with ASTM 4643-08 (Standard Test Method for Determination of Water (Moisture) Content of Soil by Microwave Oven Heating/ Appendix 2) and dried for 3 minutes at a temperature of 110 °C.



Figure 4.8: H30140E laboratory bench oven, digital series, HUMBOLDT

To calculate the soil moisture contents was used Equation 4.2

$$W = [(M_1 - M_2)/(M_2 - M_c)] * 100 = (M_w/M_s) * 100 \quad (4.2)$$

The result are tabulated in the chapter five Table 5.3.

4.4 Particle Size Analysis

4.4.1 Sample preparation

The amount of soil sample used for particle analysis was air dried, the size of the sample that were used for analyzing the soil compositions were separated into two parts, one part include those particles retained on No. 10 (2 mm) sieve, the other one includes those passing No.10 (2 mm) sieve.

The amount of portion that was retained on No. 10 (2 mm) sieve depended on the maximum size of particles according to the Table 4.3.

Table 4.4: Maximum particles size with the amount of soil portion

Nominal diameter of largest particles in. (mm)	Approximate minimum mass of portion, g
$\frac{3}{8}$ (9.5)	500
$\frac{3}{4}$ (19)	1000
1 (25.4)	2000
1½ (38.1)	3000
2 (50.8)	4000
3 (76.2)	5000

The amount of portion passing No. 10 sieve and then used for hydrometer should be around 115g for sandy soils and approximately 65g for silt and clay soil according to ASTM D 422-63 (Standard Test Method for Particle-Size Analysis of Soils/ Appendix 3).

4.4.2 Soil texture

The soil texture is an indication to the size of mineral spread or include in a soil, the sand, silt and clay are refer to the soil texture Table 4.4 illustrate the different particle size with the soil texture.

Table 4.5: Particle Size in a Soil Texture (Roberge, 1999)

Category	Diameter (mm)
Sand (very coarse)	1 – 2
Sand (coarse)	0.5 – 1
Sand (medium)	0.25 – 0.5
Sand (fine)	0.10 – 0.25
Sand (very fine)	0.05 – 0.10
Silt	0.002 – 0.05
Clay	< 0.002

4.4.3 Procedure

The analysis classifies the soil particles in to two groups according to ASTM D 442 – 63 (Standard Test Method for Particle-Size Analysis of Soils. Appendix I/A3) as follow:

- Sieve analysis of soil portion that retained on number 10 (2 mm) sieve. The portion retained on No. 10 sieve will be again sieving into a series of fraction using 3-in. (76.2 mm), 2-in. (50.8 mm), 1½-in. (38.1 mm), 1-in. (25.4 mm), ¾-in. (19.05 mm), ½-in. (12.7 mm), ⅜-in. (9.552 mm), No. 4 (4.75 mm), No. 10 (2 mm). And making further sieving analysis and weighting and recording the amount that retained on each sieve, to specify the total percentage passing for each sieve dividing the total mass passing by the total mass of sample and multiplying the result by 100.
- Hydrometer and sieve analysis of portion passing the No. 10 (2 mm) sieve. Weigh out the soil sample that passed No.10 sieve about 50g that was used for hydrometer testing. The analysis consists of the following steps:

Composite Correction Factor and Calibration:

The first step in the hydrometer analysis is the calibration of the hydrometer that used in the test because the manufacturers calibrate the hydrometer at a standard temperature 20 °C. Hydrometers are graduated by the producer to be perused at the

base of the meniscus framed by the fluid on the stem. Since it is impractical to secure readings of soil suspensions at the base of the meniscus, readings must be taken at the top and a correction used connected. In our texture test a H152 hydrometer type was used. For convenience, a chart or table of composite revisions for a progression of 1° temperature contrasts Figure 4.6 for the scope of expected test temperatures may be arranged and utilized as required. This is in (Appendix 10).



Figure 4.9: Composite correction slurry

Determination of Hygroscopic Moisture:

The moisture differences between air dried and oven dried samples were found using Equation 4.3, weigh out about (10 to 15) g in a small container, and then drying the sample in an oven at $(110 \pm 5) ^\circ\text{C}$ and weigh out the mass of oven dried sample.

$$C = \frac{M_{\text{Oven-Dry}}}{M_{\text{Air-Dry}}} \leq 1 \quad (4.3)$$

Soaking the Soil Sample:

Since the soil sample mostly clay/silt, weighing out about (50) g of soil and then pour it in a glass beaker with (40) g of sodium hexametaphosphate that act as dispersion agglomeration within the sample and allow to soak for at least 16 hours after that it will be disperse further on a soil dispersion mixer machine as shown in Figure 4.10.



Figure 4.10: Dispersing Soil mixer machine (ASTM D 422)

Hydrometer Test:

The procedure is as follows:

Prepare the glass sedimentation cylinder with dispersed soil slurry from the dispersion mixer machine and add distilled water until the total volume reach 1000 ml Figure 4.11. Utilizing the palm of the hand over the open end of the cylinder (or an elastic plug in the open end), turn the cylinder upside down and back for a time of 1 min to finish the unsetting of the slurry. Toward the end of 1 min set the cylinder in a suitable area and take hydrometer readings at the accompanying interims of time (0.5, 1, 2, 5, 15, 45, 90, 180, 240, 1440) minutes Figure 4.12.



Figure 4.11: Sedimentation 1000 mL cylinder with distilled water and soil slurry

A hydrometer test form is shown with a digital stop watch resting on it. The form contains fields for STR No., Pan No., Cylinder No., and Hyd. No. (handwritten as 1945.2.3). It also includes a table for recording hydrometer readings at various time intervals (0.5, 1, 2, 5, 15, 45, 90, 180, 240, 1440 minutes) and temperature. The table has columns for Time (min), Hydr. read for soil (Ra), Temp °C, and Hydr. Read For water. Handwritten data is present in the first five rows of the table. The form also has fields for Tested by, Checked by, and Engineer.

Time (min)	Hydr. read for soil (Ra)	Temp °C	Hydr. Read For water
0.5	47	21	-2
1	46	21	-2
2	46	21	-2
5	45	21	-2
15	44	21	-2
45			
90			
180			
240			
1440			

Figure 4.12: Hydrometer forms include time interval and recording (temperature, hydrometer, and composite correction) with stop watch

Calculation of soil percentage in suspension

The mass of a total sample represented by the mass of soil used in the hydrometer test by dividing the oven-dry mass used by the percentage passing No. 10 (2 mm) sieve, and multiplying the result by 100. This value is the weight W in the equation for percentage remaining in suspension.

The rate of soil staying in suspension at the level at which the hydrometer is measuring the density of the suspension computed by using Equation 4.4:

$$P = \left(\frac{R_a}{W} \right) (ml) P_5 * 100 \quad (4.4)$$

Diameter of Soil Particles:

The diameters of particles corresponding to the percentage indicated by a given hydrometer reading were calculated according to Stokes' law Equation 4.5:

$$D = K\sqrt{L/T} \quad (4.5)$$

The values of effective depth (L) are calculated from Equation 4.6:

$$L = L_1 + \frac{1}{2}[L_2 - (V_B/A)] \quad (4.6)$$

The procedure followed the following route:

Sieve analysis for portion finer than No. 10 (2 mm), wash and dry the amount of soil were used in the hydrometer test and then sieve under set (No. 40, No. 100, No. 200), weighing the amount that retained on each sieve, to specify the total percentage passing for each sieve dividing the total mass passing by the total mass of sample and multiplying the result by 100.

4.5 Statistical Analysis

The statistical analysis was performed using IBM SPSS Statistics 20 software, the multiple linear regressions (MLR) and analysis of variance methods were employed to estimate the corrosion rate through (MLR) Equation 4.7 and compare the predicted corrosion rate with the corrosion rate obtained experimentally from weight loss method Equation 4.1 in

chapter 4. Also to determine the relationship between soils parameters that play a role in the corrosion of buried pipeline the statistical process was performed according to ASTM G 16-13 (Standard Guide for Applying Statistics to Analysis of Corrosion Data/ Appendix 6).

The multiple regression analysis consists of a tool of statistical that examines the multiple independent variables those are related to dependent variable means modeling a data set with more than one independent variables and one dependent variable. The outcomes of independent variables can be used to make much more powerful and accurate predictions.

The a , b_1 , b_2 , and b_n in equation 4.7 called regression coefficient the b_1 is indicate the expected change in Y the dependent variable per unit change in X_1 when X_2 (dependent variables) is held constant, similarly for b_2 . The linear word is used from the equation 4.7 it is a linear function of the unknown parameters a , b_1 , b_2 , b_n .

Compares means between the independent groups. It's more likely to identify analysis of variance ANOVA in terms of factors with levels.) a factor is an independent variable (i.e., some property, characteristic, or quality that can be manipulated) that is being used as a predictor or "explainer of variance" in the data analysis. In most cases, each specific value of the independent variable defines a level within the factor. The Equation 4.7 was shown below are (MLE) to estimate the corrosion of the pipeline.

$$y = a + b_1X_1 + b_2X_2 + b_3X_3 \dots b_nX_n \quad (4.7)$$

CHAPTER 5

RESULTS AND DISSCUSION

5.1 pH Test

pH examination were performed in the Sulaymaniyah Constructional Laboratories according to the procedure outlined in (BS 1377-3:1990/ Appendix 2). The device used in the study was G038-B028 hanna portable pH meter. The sample prepared as mentioned, 30 g of soil and 70 g from soil sample in beaker as shown in Figure 5.1 (a and b), read the pH (2 – 3) reading until the difference will be close to 0.05 pH units before being adopted. The test outcomes of the samples are shown in Table (5.1).



(a) Agricultural site soil sample

(b) Hills area soil sample

Figure 5.1: pH test

Table 5.1: pH test results

Samples	pH meter reading
SS-1	8.66
SS-2	8.57
SS-3	8.89
SS-4	9.00
SS-5	9.10
SS-6	8.40
SS-7	8.80
SS-8	8.70

Sulaiman. et, al. (2014) found that in Iraqi soil when the pH adjusts from acidic to alkaline then the corrosion will be decreased. Oguzie Et al. (2004) recommend that an underground structure becomes sensitive to corrosion at any level of pH. Mostly it is concerned to take note(s) of the inside of that pH scope of the range of (4 - 8.5) that iron may be free from.

The pH results of the soil samples in this investigation, the highest value of pH is 9.1 and the lowest value of pH is 8.4. The result revealed that the soil were slightly corrosive to non corrosive, the results of pH also shown that the soil samples are alkaline.

5.2 Moisture Test

Moisture test were performed in the Sulaymaniyah Constructional Laboratories according to the procedure outlined in (ASTM D4643 – 08/ Appendix 2). The device used in this test was A&B GR 120 analytical balance, H-30140E laboratory bench oven, digital series, HUMBOLDT. Weighed out the sample was 200 g for each sample, the container was 100 g. the data obtained shown in Table 5.2.

Table 5.2: Mass of Samples before and after drying

Soil Sample	Mass before drying, g	Mass after drying, g	Mass of container, g
SS-1	200	193	100
SS-2	200	134	100
SS-3	200	142	100
SS-4	200	148	100
SS-5	200	152	100
SS-6	200	143	100
SS-7	200	168	100
SS-8	200	162	100

The moisture content in the soil samples were calculated according to Equation 4.1, the result of moisture content shown in Table 5.3. It seems that the moisture content was

varied between 3.62% and 49.25% in the eight samples. Hence the regional area, climate and year seasons has a key role to play in the determination of the water content in soil.

Table 5.3: Soil samples and their moisture contents

Soil Samples	Moisture content, %
SS-1	3.62
SS-2	49.25
SS-3	40.84
SS-4	35.13
SS-5	31.57
SS-6	39.86
SS-7	19.04
SS-8	23.45

Gupta, (1979) evaluated the significant content of the moisture of the soils on the corrosion of mild steel when it is more than (50%) holding limit, the other research were done on the study of influence of soil properties on the buried pipelines and structure, (Ismail and El-Shamy, 2009) discovered that the sensitive moisture content in a soil for corrosion are between (50-60) % where shown in Figure 5.2 (Yahaya et, al. 2001) shows that the high moisture content cause a quick growth of corrosion on X70 carbon steel coupons. The results of moisture content of the soil samples in this region revealed that the high moisture content cause corrosion rate in the pipe coupons increases and decreases in low level of moisture content.

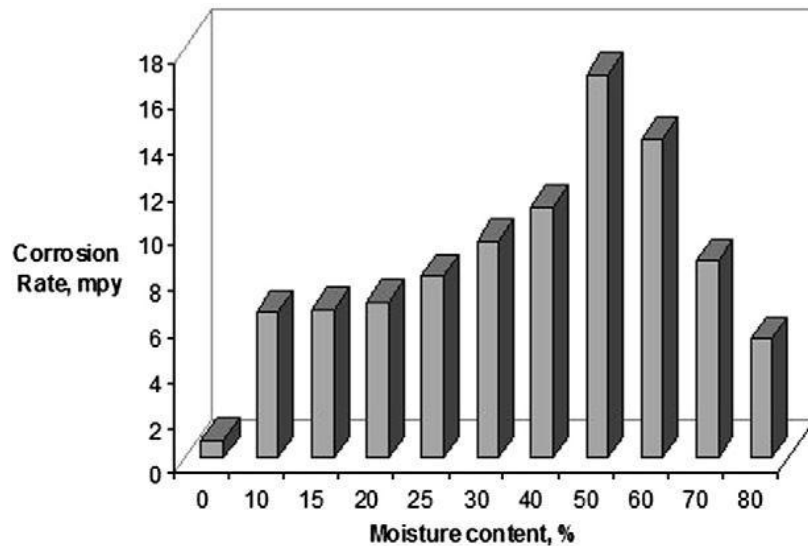


Figure 5.2: Effect of moisture content on soil corrosivity (Ismail and El-Shamy, 2009)

5.3 Particle Size Analysis

Soil texture test were performed in the Sulaymaniyah Constructional Laboratories according to the procedure outlined in (ASTM D422 – 63/ Appendix 3). The test was done by using hydrometer method as discussed previously. The data obtained shown in Table 5.4.

Table 5.4: Texture test results of soil samples

Samples	Gravel, %	Sand, %	Silt, %	Clay, %
SS-1	11.65	23.45	45.9	19
SS-2	4.20	41.20	36.60	18
SS-3	3.2	33.1	37.2	20
SS-4	2.1	34.8	35	19
SS-5	5.4	38.2	34.9	21
SS-6	4.3	29.7	39.2	16
SS-7	4.6	30.2	38.42	17
SS-8	3.92	25.1	37.25	22

Soil texture is one of the most impact factor that influence on the corrosiveness of soil towards buried pipelines and structure. Oguzie, et al. (2004) concluded that the influence of soil components on the deterioration of the buried steel coupon from the corrosiveness is

clay > loam > sand, Yahya, et al. (2011) discovered that the corrosion rate can be initiated at a low level of clay content. The texture test shown that most of the soil samples were (sandy) to (sand - silt) depends on previous research these kinds of soil are slightly corrosive to non corrosive.

5.4 Corrosion Rate

The coupon initial weight and the final weight after test are presented in Table 5.5 to decide the metal loss and hence, the corrosion rate.

The normal rate of corrosion will figured utilizing the accompanying mathematical Equation 4.1; the data are tabulated in Table 5.5.

Table 5.5: Corrosion rate calculation

Soil Samples	Initial Weight, g	Final Weight, g	Density D (g/cm ³)	Factor K for mm/year	Surface Area cm ²	Time Exposure T, hours	Corrosion Rate mm/year
SS-1	188.40	188.32	7.85	8.76×10^4	68	2160	0.0061
SS-2	188.40	186.50	7.85	8.76×10^4	68	2160	0.1444
SS-3	188.40	186.81	7.85	8.76×10^4	68	2160	0.1208
SS-4	188.40	187.00	7.85	8.76×10^4	68	2160	0.1064
SS-5	188.40	187.16	7.85	8.76×10^4	68	2160	0.0942
SS-6	188.40	186.85	7.85	8.76×10^4	68	2160	0.1178
SS-7	188.40	187.66	7.85	8.76×10^4	68	2160	0.0562
SS-8	188.40	187.49	7.85	8.76×10^4	68	2160	0.0691

When Table 5.5 is examined with Table 5.3 and Table 5.4, it can be seen that sample SS-2 which contained the highest moisture content (49.25%) is the most corrosive soil sample toward pipe steel coupon.

5.5 Statistical Analysis

The statistical analyses were carried out by using multiple linear regression (MLR) and analysis of Variances (ANOVA) of the IBM SPSS 20 software. The data are shown in Table 5.6, 5.7 and 5.8.

Table 5.6: Model summary

Model	R	R ²	Adjusted R ²	Standard Error of the Estimate
1	1.000 ^a	0.999	0.999	0.0016496

^a Predictors: (Constant), pH, Moisture and Clay

Table 5.7: Analysis of variance (ANOVA)^a

Model	Sum of Squares	df	Mean Square	F	Sig.
1 Regression	0.014	3	0.005	1662.53	0.000 ^b
Residual	0.000	4	0.000	2	
Total	0.014	7			

^a Dependent Variable: Corrosion

^b Predictors: (Constant), pH, Moisture and Clay

Table 5.8: Coefficient of regression ^a

Model		Un standardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
	(Constant)	-0.049	0.025		-1.907	0.129
X ₁	Moisture	0.003	0.000	1.000	69.679	0.000
X ₂	Clay	0.000	0.000	-0.008	-0.464	0.667
X ₃	pH	0.006	0.003	0.029	1.707	0.163

^a Dependent Variable: Corrosion

To estimate the corrosion rate using multiple independent variables related to soil parameters. The equation 4.6 in the previous chapter for the (MLR) can be written:

$$y = a + b_1(\text{moisture}) + b_2(\text{clay}) + b_3(\text{pH})$$

The table 5.6 which is a summary of the multiple regression analysis, the R^2 (R square) which is a measure of the extent of the degree of participation and effectiveness independent variables (moisture, clay and pH) (predictors) in the rate of corrosion (dependent variable) of the coupon, multiplying the R^2 value by (100) means 99% of the predictors have responsibility of corrosion in the coupon.

The table 5.7 represent the (ANOVA) is utilized for recognizing the elements essentially influencing the rate of corrosion of the coupons. This analysis was conducted for significance level of $\alpha=0.05$, for a confidence level of 95%. P-value (sig.) under 0.05 is considered the independent variables to have a statistical contribution in corrosion conduct of coupons. The significance (sig.) in table 5.7 is less than 0.05 so the variables have significance affect the corrosion rate of the coupons.

Table 5.8 which represents the constant and the coefficient of the variables values in the regression equation, and the P- value (sig.) of each predictors (moisture, clay and pH). The P- value of the moisture content is less than 0.05 the sig. value of the moisture is (0.000), for clay is (0.667) much greater than 0.05 and for the pH is (0.163) greater than 0.05 but when it compare with the sig. value of clay content it have more effects on the soil corrosivity toward buried pipe coupons, so the moisture content in the soil samples considered having greater effect. This is in agreement with corrosion rate estimations given in Table 5.5.

The coefficients of regression equation are represented in Table 5.8 which was used in the typical linear regression equation 4.6 the final form of the regression equation (statistical modeled corrosion rate) was shown in Equation 4.6

$$\text{Estimated CR} = (-0.049) + (0.003)(\text{Moisture}) + (0.000)(\text{clay}) + (0.006)(\text{pH})$$

The estimated corrosion rate from statistical modeling was shown in Table 5.9 with experimental corrosion rate of pipe coupons.

Table 5.9: Experimental corrosion rate and estimated corrosion rate

Soil samples	Experimental Corrosion rate (mm/year)	Estimated Corrosion Rate (mm/year)	Absolute Error
SS-1	0.0061	0.01382	-126.5 %
SS-2	0.1444	0.15017	-4.0 %
SS-3	0.1208	0.12686	-5.0 %
SS-4	0.1064	0.11039	-3.7 %
SS-5	0.0942	0.10031	-6.5 %
SS-6	0.1178	0.12098	-2.7 %
SS-7	0.0562	0.06092	-8.4 %
SS-8	0.0691	0.07355	-6.4 %

In summary, the most corrosive soil sample was the one (SS-2) with highest moisture content (49.25%).

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

In this investigation some of soil properties were investigated to study the effect of these properties towards the corrosion of buried API 5L X70 pipeline steel.

The results of some soil properties and steel pipe coupons can be summarized as follows:

The pH value for eight soil samples shows the lowest value at 8.4 and the highest value at 9.1, these results revealed that the soils are non corrosive. The highest moisture content is 49.25%, the lowest is 3.62% and when the moisture content is high then, the corrosion will increase. The clay content in the soil samples was varied between 16 % and 22 %. The clay content in the soil is related with the aeration and the amount of holding water. This means the high clay content may cause a high corrosion in the buried pipeline.

The experimental corrosion rate of buried steel coupon revealed the highest corrosion rate of 0.1444 mm/year when moisture content was 49.25 %, pH 8.57 and clay content was 18 %. The lowest rate was 0.0061 mm/year with the moisture content was 3.62 %, pH 8.66 and clay content 19 %; therefore, the amount of moisture content has the highest effect on rate of corrosion in steel coupons.

The estimated rate of corrosion on steel coupons revealed a closer result with the experimental corrosion rate. The lowest value was 0.01382 mm/year and the highest value was at 0.15017 mm/year, depending on the amount of moisture content and pH value.

It is concluded through the outcome of the tests for soil properties toward steel coupons that both the experimental and also the estimated corrosion rates showed that the moisture content ratio has the primary role in causing corrosion of steel coupons, and this was followed by a lesser extent with pH and very small percentage with the clay content.

6.2 Future Work

In the future the other parameters of soil such as chloride and sulfite contents, resistivity of the soil, redox potential and the mineral and organic contents in the soil should be studied in different seasons of the year using different steel pipeline grades especially, those listed under API 5L SPL 2 (Specific Product Level) which related with the chemical composition and mechanical properties of a pipeline steel.

Also, a survey can be made on the effect of crude oil composition, velocity in the corrosion of the inner surface of the pipeline, settlement of mud and residue inside the pipe during maintenance, oil embargo, etc. The inspection should be made at directly the actual site.

REFERENCES

- Ahmad, Z. (2006). Principles of Corrosion Engineering and Corrosion Control. Oxford: Butterworth-Heinemann/ICChemE Series.
- Anyanwu, I. S., Eseonu, O., and Nwosu, H. U. (2014). Experimental investigations and mathematical modelling of corrosion growth rate on carbon steel under the influence of soil pH and resistivity. *International organization of Scientific Research Journal of Engineering*, 4(10), 7-18.
- Baker, M. (2008). Pipeline Corrosion. Phoenix: U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration Office of Pipeline Safety.
- Bhattarai, J. (2013). Study on the corrosive nature of soil towards the buried-structures. *Scientific World*, 11(11) 43-47.
- Bradford, S. A. (2001). Practical Handbook of Corrosion Control in Soils: Pipelines, Tanks, Casings, Cables. Edmonton: Casti Publishing Ltd.
- Callister, W. D. (1997). Material Science and Engineering: an Introduction. New York: John Willy & Sons.
- Camitz, G. (1998). Corrosion and Protection of Steel Piles and Sheet Piles in Soil and Water. Stockholm: Swedish Commission on Pile Research.
- Chilingar, G., Mourhatch, R., and Al-Qahtani, G. (2008). The Fundamentals of Corrosion and Scaling for Petroleum and Environmental Engineers. Houston, Texas: Gulf Publishing Company.
- Cole, I., and Marney, D. (2012). The science of pipe corrosion: A review of the literature on the corrosion of ferrous metals in soils. *Corrosion Science*, 56(14), 5-16.
- Emmanuel, C., Odio, O., Chukwuneke, J., and Sinebe., E. (2014). Investigation of the effect of corrosion on mild steel in five different environments. *International Journal of Scientific & Technology Research Volume*, 3(7), 306-310.
- Ferreira, C., and Ponciano, J. (2006). Determination of the soil corrosivity of samples from southeastern Brazilian region. *Eurocorr*, 5(1), 38-70.

- Gupta SK. (1979). The critical soil moisture content in the underground corrosion of mild steel. *Corrosion Science*, 19(3), 171-178.
- Ikechukwu, A. S., Ugochukwu, N. H., Ejimofor, R. A., and Obioma, E. (2014). Correlation between soil properties and external corrosion growth rate of carbon steel. *The International Journal of Engineering and Science*, 3(10) 38-47.
- Ismail, A., and El-Shamy, A. (2009). Engineering behavior of soil materials on the corrosion of mild steel. *Applied Clay Science*, 42(3-4), 356-362.
- Jones, D. A. (1992). Principles and Prevention of Corrosion. New York: MacMillan Publishing Company.
- Kleiner, Y., Rajani, B., and Kryszewski, D. (2012). Impact of soil properties on pipe corrosion: Re-examination of traditional conventions. 12th Annual International Conference on Water Distribution Systems Analysis. (pp. 968-982). Tucson, AZ.
- Koch, G. H., Brongers, M. P., Thompson, N. G., Virmani, Y. P., and Payer, J. H. (2002). Corrosion Costs and Preventive Strategies in the United States. McLean, Virginia: Federal Highway Administration, U.S. Department of Transportation.
- Landau, S., and Everitt, B. S. (2004). A Handbook of Statistical Analyses Using SPSS. London: Chapman & Hall/CRC Press LLC.
- Liu, H. (2003). Pipeline Engineering. Florida: Lewis Publishers.
- Norhazilan, M., Nordin, Y., K.S. Lim, R. S., Safuan, A., and Norhamimi, M. (2012). Relationship between soil properties and corrosion of carbon steel. *Journal of Applied Sciences Research*, 8(3), 1739-1747.
- Oguzie, E., Agochukwu, I., and Onuchukwu, A. (2004). Monitoring the corrosion susceptibility of mild steel in varied soil textures by corrosion product count technique. *Materials Chemistry and Physics*, 84(1), 1-6.
- OSSAI, C. I. (2013). Pipeline corrosion prediction and reliability analysis: A systematic approach with Monte Carlo simulation and degradation models. *International Journal of Scientific and Technology Research*, 2(3), 58 - 69.

- Parker, M., and Peattie, E. (1999). Pipe Line Corrosion and Cathodic Protection. Houston: Gulf Professional Publishing.
- Pritchard, O., Hallett, S. H., and Farewell, T. S. (2013). Soil Corrosivity in the UK - Impact on Critical Infrastructure. Infrastructure Transitions Research Consortium. Cranfield University.
- Revie, R., and Uhlig, H. (2008). Corrosion and Corrosion Control an Introduction to Corrosion Science and Engineering. Hoboken, New Jersey: A John Wiley & Sons.
- Ricker, R. E. (2010). Analysis of pipeline steel corrosion data from NBS (NIST) studies conducted between 1922-1940 and relevance to pipeline management. *Journal of Research of the National Institute of Standards and Technology*, 115(10), 373-392.
- Roberge, P. (1999). Handbook of Corrosion Engineering. New York: McGraw-Hill Companies.
- Roberge, R. (2008). Corrosion Engineering Principles and Practice. New York: McGraw-Hill Companies.
- Saupi, S., Sulaiman, M., and Masri, M. (2015). Effects of soil properties to corrosion of underground pipelines: A review. *Journal of Tropical Resources and Sustainable Science*, 3(2), 14-18.
- Shreir, L., Jarman, R., and Burstein, G. (2000). Corrosion Volume 1: Metal/Environment Reactions. Oxford: Butterworth-Heinemann.
- Sulaiman, Q., Taie, A., and Hassan, M. (2014). Evaluation of sodium chloride and acidity effect on corrosion of buried carbon steel pipeline in Iraqi soil. *Iraqi Journal of Chemical and Petroleum Engineering*, 29(9), 1-8.
- Velázquez, J., Caleyó, F., Valor, A., and Hallen, J. (2009). Predictive model for pitting corrosion in buried oil and gas pipelines. *NACE International Corrosion Engineering Section*, 65(5), 332-342.
- Waltham, T. (2002). Foundations of Engineering Geology. London: Spon Press.
- Wilmott, M., and Jack, T. (2000). Corrosion by Soils. London: John Wiley and Sons.

Yahaya, N., Lim, K., Noor, N., Othman, S., and Abdullah, A. (2011). Effects of clay and moisture content on soil-corrosion dynamic. *Malaysian Journal of Civil Engineering*, 8(3), 24-32.

APPENDICES

APPENDIX 1
(BS 1377-3:1990) BRITISH STANDARD

BRITISH STANDARD

**BS 1377-3:
1990**
*Incorporating
Amendment No. 1*

Methods of test for

**Soils for civil
engineering
purposes —**

**Part 3: Chemical and electro-chemical
tests**

Licensed Copy: Puan Ms. Northayati, Petroliaam Nasional Berhad, 12 March 2003, Uncontrolled Copy, (c) BSI

NO COPYING WITHOUT BSI PERMISSION EXCEPT AS PERMITTED BY COPYRIGHT LAW



9 Determination of the pH value

The requirements of Part 1 of this standard, where appropriate, shall apply to this test method.

9.1 General

This clause describes the procedure for determining the pH value, by the electrometric method, which gives a direct reading of the pH value of a soil suspension in water. This method can also be used for determining the pH value of a sample of ground water.

NOTE Good practice in chemical testing requires that duplicate specimens should be tested. In each of the test methods the measurement of only one value of the overall result is described. It is recognized that it is necessary in many practical applications to make a number of tests in order to obtain a mean value and an indication of the reliability of the results. Guidance on the number of measurements required and the treatment of the results obtained is beyond the scope of this Part of this standard.

9.2 Apparatus

9.2.1 Apparatus for preparation of test specimens

9.2.1.1 Balance, readable to 0.001 g.

9.2.1.2 Pestle and mortar, or a suitable mechanical crusher.

9.2.1.3 Test sieve, of 2 mm aperture size, with receiver.

9.2.1.4 Non-corrodible tray.

9.2.2 Apparatus for electrometric method of pH determination

9.2.2.1 pH meter, fitted with a glass electrode and a calomel reference electrode (which may be incorporated in one probe) covering the range pH 3.0 to pH 10.0. The scale shall be readable and accurate to 0.05 pH units.

9.2.2.2 Three 100 mL glass or plastics beakers with cover glasses and stirring rods.

9.2.2.3 Two 500 mL volumetric flasks.

9.2.2.4 Wash bottle, preferably made of plastics, containing distilled water.

9.3 Reagents

9.3.1 General. All reagents shall be of recognized analytical reagent quality.

9.3.2 Buffer solution, pH 4.0. Dissolve 5.106 g of potassium hydrogen phthalate in distilled water and dilute to 500 mL with distilled water.

Alternatively, a proprietary buffer solution of pH 4.0 may be used.

9.3.3 Buffer solution, pH 9.2. Dissolve 9.54 g of sodium tetraborate (borax) in distilled water and dilute to 500 mL. Alternatively, a proprietary buffer solution of pH 9.2 may be used.

9.3.4 Potassium chloride. Saturated solution (for maintenance of the calomel electrode).

9.4 Preparation of test specimen

9.4.1 Obtain an initial sample as described in 7.3, and of the appropriate size specified in 7.5 of BS 1377-1:1990.

9.4.2 Allow the sample to air-dry by spreading out on a tray exposed to air at room temperature.

9.4.3 Sieve the sample on a 2 mm test sieve (if appropriate, guarded by a sieve of larger aperture) and crush retained particles other than stones to pass through the 2 mm test sieve.

9.4.4 Reject the stones, ensuring that no fine material adheres to them, e.g. by brushing. Record the mass m_2 (in g) of the sample passing the 2 mm test sieve to the nearest 0.1 %. Throughout these and subsequent operations ensure that there is no loss of fines.

9.4.5 Divide the material passing the 2 mm test sieve by successive riffing through the 15 mm divider to produce a representative test sample of 30 g to 35 g.

9.5 Electrometric method of pH determination

9.5.1 From the sample obtained as described in 9.4, weigh out 30 ± 0.1 g of soil and place in a 100 mL beaker.

9.5.2 Add 75 mL of distilled water to the beaker, stir the suspension for a few minutes, cover with a cover glass and allow to stand for at least 8 h.

NOTE The pH value of a soil suspension varies with the ratio of soil to water, an increase in dilution bringing the pH closer to 7.

9.5.3 Stir the suspension again immediately before testing.

9.5.4 Calibrate the pH meter by using the standard buffer solutions, following the procedure recommended by the manufacturer.

9.5.5 Wash the electrode with distilled water and immerse in the soil suspension. Take two or three readings of the pH of the suspension with brief stirrings between each reading. These readings shall agree to within 0.05 pH units before being accepted.

NOTE The pH readings of the soil suspension should reach a constant value in about 1 min. No readings should be taken until the pH meter has reached equilibrium.

9.5.6 Remove the electrodes from the suspension and wash them with distilled water. Re-check the calibration of the pH meter against one of the standard buffer solutions.

9.5.7 If the instrument is out of adjustment by more than 0.05 pH units, set it to the correct adjustment and repeat steps 9.5.5 and 9.5.6 until consistent readings are obtained.

9.5.8 When not in use, leave the electrode standing in a beaker of distilled water.

9.6 Test Report

The test report shall state that the test was carried out in accordance with 9.5 of BS 1377-3:1990 and shall contain the following information:

- the method of test used;
- the pH value of the soil suspension to the nearest 0.1 pH unit;
- the information required by 9.1 of BS 1377-1:1990.

APPENDIX 2

(ASTM D4643-08) AMERICAN SOCIETY FOR TESTING AND MATERIALS



Designation: D 4643 – 08

Standard Test Method for Determination of Water (Moisture) Content of Soil by Microwave Oven Heating¹

This standard is issued under the fixed designation D 4643; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.
This standard has been approved for use by agencies of the Department of Defense.

1. Scope*

1.1 This test method outlines procedures for determining the water (moisture) content of soils by incrementally drying soil in a microwave oven.

1.2 This test method can be used as a substitute for Test Method D 2216 when more rapid results are desired to expedite other phases of testing and slightly less accurate results are acceptable.

1.3 When questions of accuracy between this test method and Test Method D 2216 arise, Test Method D 2216 shall be the referee method.

1.4 This test method is applicable for most soil types. For some soils, such as those containing significant amounts of halloysite, mica, montmorillonite, gypsum or other hydrated materials, highly organic soils, or soils in which the pore water contains dissolved solids (such as salt in the case of marine deposits), this test method may not yield reliable water content values.

1.5 The values stated in SI units are to be regarded as the standard. No other units of measurement are included in this test method.

1.6 Refer to Practice D 6026 for guidance concerning the use of significant figures. This is especially important if the water content will be used to calculate other relationships such as moist mass to dry mass or vice versa, wet unit weight to dry unit weight or vice versa, and total density to dry density or vice versa. For example, if four significant digits are required

in any of the above calculations, then the water content has to be recorded to the nearest 0.1 %. This occurs since 1 plus the water content (not in percent) will have four significant digits regardless of what the value of the water content is; that is, 1 plus 0.1/100 = 1.001, a value with four significant digits. While, if three significant digits are acceptable, then the water content can be recorded to the nearest 1 %.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the*

responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use. See Section 7.

2. Referenced Documents

2.1 *ASTM Standards:* ²

D 653 Terminology Relating to Soil, Rock, and Contained Fluids

D 2216 Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass

D 3740 Practice for Minimum Requirements for Agencies Engaged in the Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D 4753 Guide for Evaluating, Selecting, and Specifying Balances and Standard Masses for Use in Soil, Rock, and Construction Materials Testing

D 6026 Practice for Using Significant Digits in Geotechnical Data

3. Terminology

3.1 *Definitions:*

3.1.1 All definitions are in accordance with Terminology D 653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *microwave heating*—a process by which heat is induced within a material due to the interaction between dipolar molecules of the material and an alternating, high frequency electric field. Microwaves are electromagnetic waves with 1 mm to 1 m wavelengths.

3.2.2 *water (moisture) content*—the ratio, expressed as a percentage, of the mass of “pore” or “free” water in a given mass of soil to the mass of the solid particles.

APPENDIX 3

(ASTM D422-63) AMERICAN SOCIETY FOR TESTING AND MATERIAL



Designation: D 422 – 63 (Reapproved 1998)

Standard Test Method for Particle-Size Analysis of Soils¹

This standard is issued under the fixed designation D 422; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the quantitative determination of the distribution of particle sizes in soils. The distribution of particle sizes larger than 75 μm (retained on the No. 200 sieve) is determined by sieving, while the distribution of particle sizes smaller than 75 μm is determined by a sedimentation process, using a hydrometer to secure the necessary data (Note 1 and Note 2).

NOTE 1—Separation may be made on the No. 4 (4.75-mm), No. 40 (425- μm), or No. 200 (75- μm) sieve instead of the No. 10. For whatever sieve used, the size shall be indicated in the report.

NOTE 2—Two types of dispersion devices are provided: (1) a highspeed mechanical stirrer, and (2) air dispersion. Extensive investigations indicate that air-dispersion devices produce a more positive dispersion of plastic soils below the 20- μm size and appreciably less degradation on all sizes when used with sandy soils. Because of the definite advantages favoring air dispersion, its use is recommended. The results from the two types of devices differ in magnitude, depending upon soil type, leading to marked differences in particle size distribution, especially for sizes finer than 20 μm .

2. Referenced Documents

2.1 ASTM Standards:

D 421 Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants²
E 11 Specification for Wire-Cloth Sieves for Testing Purposes³
E 100 Specification for ASTM Hydrometers⁴

3. Apparatus

3.1 *Balances*—A balance sensitive to 0.01 g for weighing the material passing a No. 10 (2.00-mm) sieve, and a balance sensitive to 0.1 % of the mass of the sample to be weighed for weighing the material retained on a No. 10 sieve.

3.2 *Stirring Apparatus*—Either apparatus A or B may be used.

3.2.1 Apparatus A shall consist of a mechanically operated

stirring device in which a suitably mounted electric motor turns a vertical shaft at a speed of not less than 10 000 rpm without

load. The shaft shall be equipped with a replaceable stirring paddle made of metal, plastic, or hard rubber, as shown in Fig. 1. The shaft shall be of such length that the stirring paddle will operate not less than $\frac{3}{4}$ in. (19.0 mm) nor more than $1\frac{1}{2}$ in. (38.1 mm) above the bottom of the dispersion cup. A special dispersion cup conforming to either of the designs shown in Fig. 2 shall be provided to hold the sample while it is being dispersed.

3.2.2 Apparatus B shall consist of an air-jet dispersion cups (Note 3) conforming to the general details shown in Fig. 3 (Note 4 and Note 5).

NOTE 3—The amount of air required by an air-jet dispersion cup is of the order of 2 ft³/min; some small air compressors are not capable of supplying sufficient air to operate a cup.

NOTE 4—Another air-type dispersion device, known as a dispersion tube, developed by Chu and Davidson at Iowa State College, has been shown to give results equivalent to those secured by the air-jet dispersion cups. When it is used, soaking of the sample can be done in the sedimentation cylinder, thus eliminating the need for transferring the slurry. When the air-dispersion tube is used, it shall be so indicated in the report.

NOTE 5—Water may condense in air lines when not in use. This water must be removed, either by using a water trap on the air line, or by blowing the water out of the line before using any of the air for dispersion purposes.

3.3 *Hydrometer*—An ASTM hydrometer, graduated to read in either specific gravity of the suspension or grams per litre of suspension, and conforming to the requirements for hydrometers 151H or 152H in Specifications E 100. Dimensions of both hydrometers are the same, the scale being the only item of difference.

3.4 *Sedimentation Cylinder*—A glass cylinder essentially 18 in. (457 mm) in height and $2\frac{1}{2}$ in. (63.5 mm) in diameter, and marked for a volume of 1000 mL. The inside diameter shall be such that the 1000-mL mark is 36.62 cm from the bottom on the inside.

3.5 *Thermometer*—A thermometer accurate to 1°F (0.5°C).

3.6 *Sieves*—A series of sieves, of square-mesh woven-wire cloth, conforming to the requirements of Specification E 11. A full set of sieves includes the following (Note 6):

APPENDIX 4

(ASTM D4220-95) AMERICAN SOCIETY FOR TESTING MATERIAL



Designation: D 4220 – 95 (Reapproved 2000)

Standard Practices for Preserving and Transporting Soil Samples¹

This standard is issued under the fixed designation D 4220; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope *

1.1 These practices cover procedures for preserving soil samples immediately after they are obtained in the field and accompanying procedures for transporting and handling the samples.

1.2 *Limitations*—These practices are not intended to address requirements applicable to transporting of soil samples known or suspected to contain hazardous materials.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* See Section 7.

2. Referenced Documents

2.1 ASTM Standards:

D 420 Guide to Site Characterization for Engineering, Design, and Construction Purposes²

D 653 Terminology Relating to Soil, Rock, and Contained Fluids²

D 1452 Practice for Soil Investigation and Sampling by Auger Borings²

D 1586 Test Method for Penetration Test and Split-Barrel Sampling of Soils²

D 1587 Practice for Thin-Walled Tube Sampling of Soils²

D 2488 Practice for Description and Identification of Soils (Visual-Manual Procedure)²

D 3550 Practice for Ring-Lined Barrel Sampling of Soils²

D 4564 Test Method for Density of Soil in Place by the Sleeve Method² D 4700 Guide for Soil Sampling from the Vadose Zone²

3. Terminology

3.1 Terminology in these practices is in accordance with Terminology D 653.

4. Summary of Practices

4.1 The various procedures are given under four groupings as follows:

4.1.1 *Group A*—Samples for which only general visual identification is necessary.

4.1.2 *Group B*—Samples for which only water content and classification tests, proctor and relative density, or profile logging is required, and bulk samples that will be remolded or compacted into specimens for swell pressure, percent swell, consolidation, permeability, shear testing, CBR, stabilimeter, etc.

4.1.3 *Group C*—Intact, naturally formed or field fabricated, samples for density determinations; or for swell pressure, percent swell, consolidation, permeability testing and shear testing with or without stress-strain and volume change measurements, to include dynamic and cyclic testing.

4.1.4 *Group D*—Samples that are fragile or highly sensitive for which tests in Group C are required.

4.2 The procedure(s) to be used should be included in the project specifications or defined by the designated responsible person.

5. Significance and Use

5.1 Use of the various procedures recommended in these practices is dependent on the type of samples obtained (Practice D 420), the type of testing and engineering properties required, the fragility and sensitivity of the soil, and the climatic conditions. In all cases, the primary purpose is to preserve the desired inherent conditions.

5.2 The procedures presented in these practices were primarily developed for soil samples that are to be tested for engineering properties, however, they may be applicable for samples of soil and other materials obtained for other purposes.

6. Apparatus

6.1 The type of materials and containers needed depend upon the conditions and requirements listed under the four groupings A to D in Section 4, and also on the climate and transporting mode and distance.

6.1.1 *Sealing Wax*, includes microcrystalline wax, paraffin, beeswax, ceresine, carnaubawax, or combinations thereof.

6.1.2 *Metal Disks*, about $\frac{1}{16}$ in. (about 2 mm) thick and having a diameter slightly less than the inside diameter of the tube, liner, or ring and to be used in union with wax or caps and tape, or both.

6.1.3 *Wood Disks*, prewaxed, 1 in. (25 mm) thick and having a diameter slightly less than the inside diameter of the liner or tube.

APPENDIX 5

(ASTM G1-90) AMERICAN SOCIETY FOR TESTING MATERIAL



Designation: G 1 — 90 (Reapproved 1999)^{€1}

Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens¹

This standard is issued under the fixed designation G 1; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (€) indicates an editorial change since the last revision or reapproval.

€¹ NOTE—Editorial corrections were made throughout in January 1999.

1. Scope

1.1 This practice covers suggested procedures for preparing bare, solid metal specimens for tests, for removing corrosion products after the test has been completed, and for evaluating the corrosion damage that has occurred. Emphasis is placed on procedures related to the evaluation of corrosion by mass loss and pitting measurements.

NOTE 1—**Caution:** In many cases the corrosion product on the reactive metals titanium and zirconium is a hard and tightly bonded oxide that defies removal by chemical or ordinary mechanical means. In many such cases, corrosion rates are established by mass gain rather than mass loss.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* For specific precautionary statements, see Note 1 and Note 6.

2. Referenced Documents

2.1 ASTM Standards:

- A 262 Practices for Detecting Susceptibility to Intergranular Attack in Austenitic Stainless Steels²
- D 1193 Specification for Reagent Water³
- D 1384 Test Method for Corrosion Test for Engine Coolants in Glassware⁴
- D 2776 Test Methods for Corrosivity of Water in the Absence of Heat Transfer (Electrical Methods)⁵
- G 15 Terminology Relating to Corrosion and Corrosion Testing⁶
- G 16 Guide for Applying Statistics to Analysis of Corrosion Data⁶

¹ This practice is under the jurisdiction of ASTM Committee G-1 on Corrosion of Metals and is the direct responsibility of Subcommittee G01.05 on Laboratory Corrosion Tests.

Current edition approved March 30, 1990. Published May 1990. Originally published as G 1 — 67. Last previous edition G 1 — 88.

² *Annual Book of ASTM Standards*, Vol 01.03.

³ *Annual Book of ASTM Standards*, Vol 11.01.

⁴ *Annual Book of ASTM Standards*, Vol 15.05.

⁵ *Discontinued*—Replaced by Guide G 96. See 1990 *Annual Book of ASTM Standards*, Vol 03.02.

⁶ *Annual Book of ASTM Standards*, Vol 03.02.

G 31 Practice for Laboratory Immersion Corrosion Testing of Metals⁶

G 33 Practice for Recording Data from Atmospheric Corrosion Tests of Metallic-Coated Steel Specimens⁶

G 46 Guide for Examination and Evaluation of Pitting Corrosion⁶

G 50 Practice for Conducting Atmospheric Corrosion Tests on Metals⁶

G 78 Guide for Crevice Corrosion Testing of Iron Base and Nickel Base Stainless Alloys in Seawater and Other Chloride-Containing Aqueous Environments⁶

3. Terminology

3.1 See Terminology G 15 for terms used in this practice.

4. Significance and Use

4.1 The procedures given are designed to remove corrosion products without significant removal of base metal. This allows an accurate determination of the mass loss of the metal or alloy that occurred during exposure to the corrosive environment.

4.2 These procedures, in some cases, may apply to metal coatings. However, possible effects from the substrate must be considered.

5. Reagents and Materials

5.1 *Purity of Reagents*—Reagent grade chemicals shall be used in all tests. Unless otherwise indicated, it is intended that all reagents conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society where such specifications are available.⁷ Other grades may be used, provided it is first ascertained that the reagent is of sufficiently high purity to permit its use without lessening the accuracy of the determination.

5.2 *Purity of Water*—Unless otherwise indicated, references to water shall be understood to mean reagent water as defined by Type IV of Specification D 1193.

⁷ *Reagent Chemicals, American Chemical Society Specifications*, American Chemical Society, Washington, DC. For suggestions on the testing of reagents not listed by the American Chemical Society, see *Anal. Standards for Laboratory Chemicals*, BDH Ltd., Poole, Dorset, U.K., and the *United States Pharmacopeia and National Formulary*, U.S. Pharmacopeial Convention, Inc. (USPC), Rockville, MD.

APPENDIX 6

(ASTM G16-13) AMERICAN SOCIETY FOR TESTING MATERIAL



Designation: G16 – 13

Standard Guide for

Applying Statistics to Analysis of Corrosion Data¹

This standard is issued under the fixed designation G16; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (°) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers and presents briefly some generally accepted methods of statistical analyses which are useful in the interpretation of corrosion test results.

1.2 This guide does not cover detailed calculations and methods, but rather covers a range of approaches which have found application in corrosion testing.

1.3 Only those statistical methods that have found wide acceptance in corrosion testing have been considered in this guide.

1.4 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

2. Referenced Documents

2.1 *ASTM Standards*:²

[E178 Practice for Dealing With Outlying Observations](#)

[E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method](#)

[G46 Guide for Examination and Evaluation of Pitting Corrosion](#)

[IEEE/ASTM SI 10 American National Standard for Use of the International System of Units \(SI\): The Modern Metric System](#)

3. Significance and Use

3.1 Corrosion test results often show more scatter than many other types of tests because of a variety of factors, including the fact that minor impurities often play a decisive role in controlling corrosion rates. Statistical analysis can be very helpful in allowing investigators to interpret such results, especially in determining when test results differ from one another significantly. This can be a difficult task when a variety of materials are under test, but statistical methods provide a rational approach to this problem.

3.2 Modern data reduction programs in combination with computers have allowed sophisticated statistical analyses on data sets with relative ease. This capability permits investigators to determine if associations exist between many variables and, if so, to develop quantitative expressions relating the variables.

3.3 Statistical evaluation is a necessary step in the analysis of results from any procedure which provides quantitative information. This analysis allows confidence intervals to be estimated from the measured results.

4. Errors

4.1 *Distributions*—In the measurement of values associated with the corrosion of metals, a variety of factors act to produce measured values that deviate from expected values for the conditions that are present. Usually the factors which contribute to the error of measured values act in a more or less random way so that the average of several values approximates the expected value better than a single measurement. The pattern in which data are scattered is called its distribution, and a variety of distributions are seen in corrosion work.

4.2 *Histograms*—A bar graph called a histogram may be used to display the scatter of the data. A histogram is constructed by dividing the range of data values into equal intervals on the abscissa axis and then placing a bar over each interval of a height equal to the number of data points within that interval. The number of intervals should be few enough so that almost all intervals contain at least three points; however, there should be a sufficient number of intervals to facilitate visualization of the shape and symmetry of the bar heights. Twenty intervals are usually recommended for a histogram. Because so many points are required to construct a histogram, it is unusual to find data sets in corrosion work that lend themselves to this type of analysis.

4.3 *Normal Distribution*—Many statistical techniques are based on the normal distribution. This distribution is bellshaped and symmetrical. Use of analysis techniques developed for the normal distribution on data distributed in another manner can lead to grossly erroneous conclusions. Thus, before attempting data analysis, the data should either be verified as being scattered like a normal distribution, or a transformation

APPENDIX 7

(ASTM G31-72) AMERICAN SOCIETY FOR TESTING AND MATERIAL



Designation: G 31 – 72 (Reapproved 2004)

Standard Practice for

Laboratory Immersion Corrosion Testing of Metals¹

This standard is issued under the fixed designation G 31; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice² describes accepted procedures for and factors that influence laboratory immersion corrosion tests, particularly mass loss tests. These factors include specimen preparation, apparatus, test conditions, methods of cleaning specimens, evaluation of results, and calculation and reporting of corrosion rates. This practice also emphasizes the importance of recording all pertinent data and provides a checklist for reporting test data. Other ASTM procedures for laboratory corrosion tests are tabulated in the Appendix. (**Warning**—In many cases the corrosion product on the reactive metals titanium and zirconium is a hard and tightly bonded oxide that defies removal by chemical or ordinary mechanical means. In many such cases, corrosion rates are established by mass gain rather than mass loss.)

1.2 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 ASTM Standards:³

A 262 Practices for Detecting Susceptibility to Intergranular Attack in Austenitic Stainless Steels
E 8 Test Methods for Tension Testing of Metallic Materials
G 1 Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens
G 4 Guide for Conducting Corrosion Coupon Tests in Field Applications
G 16 Guide for Applying Statistics to Analysis of Corrosion Data
G 46 Guide for Examination and Evaluation of Pitting Corrosion.

3. Significance and Use

3.1 Corrosion testing by its very nature precludes complete standardization. This practice, rather than a standardized procedure, is presented as a guide so that some of the pitfalls of such testing may be avoided.

3.2 Experience has shown that all metals and alloys do not respond alike to the many factors that affect corrosion and that “accelerated” corrosion tests give indicative results only, or may even be entirely misleading. It is impractical to propose an inflexible standard laboratory corrosion testing procedure for general use, except for material qualification tests where standardization is obviously required.

3.3 In designing any corrosion test, consideration must be given to the various factors discussed in this practice, because these factors have been found to affect greatly the results obtained.

4. Interferences

4.1 The methods and procedures described herein represent the best current practices for conducting laboratory corrosion tests as developed by corrosion specialists in the process industries. For proper interpretation of the results obtained, the specific influence of certain variables must be considered. These include:

4.1.1 Metal specimens immersed in a specific hot liquid may not corrode at the same rate or in the same manner as in equipment where the metal acts as a heat transfer medium in heating or cooling the liquid. If the influence of heat transfer effects is specifically of interest, specialized procedures (in which the corrosion specimen serves as a heat transfer agent) must be employed (**1**).⁴

4.1.2 In laboratory tests, the velocity of the environment relative to the specimens will normally be determined by convection currents or the effects induced by aeration or boiling or both. If the specific effects of high velocity are to be studied, special techniques must be employed to transfer the

APPENDIX 8

(ASTM G162-99) AMERICAN SOCIETY FOR TESTING AND MATERIAL



ASTM G162-99(2004)

Standard Practice for Conducting and Evaluating Laboratory Corrosions Tests in Soils

Scope

1.1 This practice covers procedures for conducting laboratory corrosion tests in soils to evaluate the corrosive attack on engineering materials.

1.2 This practice covers specimen selection and preparation, test environments, and evaluation of test results.

1.3 This practice does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

Significance and Use

This practice provides a controlled corrosive environment that has been utilized to produce relative corrosion information.

The primary application of the data from this practice is to evaluate metallic materials for use in soil environments.

This practice may not duplicate all field conditions and variables such as stray currents, microbiologically influenced corrosion, non-homogeneous conditions, and long cell corrosion. The reproducibility of results in the practice is highly dependent on the type of specimen tested and the evaluation criteria selected as well as the control of the operating variables. In any testing program, sufficient replicates should be included to establish the variability of the results.

Structures and components may be made of several different metals; therefore, the practice may be used to evaluate galvanic corrosion effects in soils (see Guide G 71).

Structures and components may be coated with sacrificial or noble metal coatings, which may be scratched or otherwise rendered discontinuous (for example, no coating on the edges of metal strips cut from a wide sheet). This test is useful to evaluate the effect of defective metallic coatings.

Structures and components may be coated or jacketed with organic materials (for example, paints and plastics), and these coatings and jackets may be rendered discontinuous. The test is useful to evaluate the effect of defective or incompletely covering coatings and jackets.

The corrosivity of soils strongly depends on soluble salt content (related parameters are soil resistivity, see Test Method G 57, and chemistry), acidity or alkalinity (measured by soil pH, see Test Method G 51), and oxygen content (loose, for example, sand, or compact, for example, clay, soils are extreme examples). The manufacturer, supplier, or user, or combination thereof, should establish the nature of the expected soil environment(s) and select the test environment(s) accordingly. Multiple types of soil can be used to determine the effect of this variable.

APPENDIX 9
(API 5L) AMERICAN PETROLEUM INSTITUTE

Specification for Line Pipe

API 5L

Upstream Segment

API SPECIFICATION 5L
FORTY-THIRD EDITION, MARCH 2004
EFFECTIVE DATE: OCTOBER 2004
ERRATA DECEMBER 2004



**Helping You
Get The Job
Done Right.™**

1 Scope

1.1 PURPOSE AND COVERAGE

The purpose of this specification is to provide standards for pipe suitable for use in conveying gas, water, and oil in both the oil and natural gas industries. This specification covers seamless and welded steel line pipe. It includes plain-end, threaded-end, and belled-end pipe, as well as through-the-flowline (TFL) pipe and pipe with ends prepared for use with special couplings. Although the plain-end line pipe meeting this specification is primarily intended for field makeup by circumferential welding, the manufacturer will not assume responsibility for field welding.

1.2 PRODUCT SPECIFICATION LEVEL (PSL)

This specification establishes requirements for two product specification levels (PSL I and PSL 2). These two PSL designations

define different levels of standard technical requirements.

PSL 2 has mandatory requirements for carbon equivalent, notch toughness, maximum yield strength, and maximum tensile strength. These and other differences are summarized in Appendix 1.

Requirements that apply to only PSL I or only PSL 2 are so designated. Requirements that are not designated to a specific PSL apply to both PSL I and PSL 2.

The purchaser may add requirements to purchase orders for either PSL I or PSL 2, as provided by the supplementary requirements (Appendix F) and other options (4.2 and 4.3).

1.3 GRADES

The grades (see the note) covered by this specification are the standard Grades A25, A, B, X42, X46, X52, X56, X60, X65, X70 and X80; and any intermediate grades (grades that are higher than X42, intermediate to two sequential standard grades, and agreed upon by the purchaser and manufacturer).

PSL I pipe can be supplied in Grades A25 through X70.

PSL 2 pipe can be supplied in Grades B through X80.

Class II (CI II) steel is rephosphorized and probably has better threading properties than Class I (CI I). Because Class II (CI II) has higher phosphorus content than Class I (CI I), it may be somewhat more difficult to bend.

Pipe manufactured as Grade X60 or higher shall not be substituted for pipe ordered as Grade X52 or lower without purchaser approval.

1.4 DIMENSIONS

The sizes used herein are dimensionless designations, which are derived from the specified outside diameter as measured in U.S. Customary units, and provide a convenient method of referencing pipe size within the text and tables (but not for order descriptions). Pipe sizes $2\frac{3}{8}$ and larger are expressed as integers and fractions; pipe sizes smaller than $2\frac{3}{8}$ are expressed to three decimal places. These sizes replace the "size designation" and the "nominal size designation" used in the previous edition of this specification. Users of this specification who are accustomed to specifying nominal sizes rather than 00 sizes are advised to familiarize themselves with these new size designations used in this specification, especially the usage in Tables 4, 5, and 6A. PSL I pipe can be supplied in sizes ranging from 0.405 through 80.

PSL 2 pipe can be supplied in sizes ranging from $4\frac{1}{2}$ through 80. Dimensional requirements on threads and thread gages, stipulations on gaging practice, gage specifications and certification, as well as instruments and methods for inspection of threads are given in API Standard 5B and are applicable to threaded products covered by this specification.

1.5 UNITS

U.S. Customary units are used in this specification; SI (metric) units are shown in parentheses in the text and in many tables. The values stated in either U.S. Customary units or SI units are to be regarded separately as standard. The values stated are not necessarily exact equivalents; therefore, each system is to be used independently of the other, without combining values for any specific order item.

See Appendix M for specific information about rounding procedures and conversion factors.

APPENDIX 10 **COMPOSITE CORRECTION**

Specific Gravity(Gs):	2.57	Dry weight of Specimen(g):	50.00
Temperature (C):	29.8	Hydrometer type:	152 - H
Meniscus Correction:	1	Zero Correction:	3
		Gs correction factor:	1.02
K-Factor	0.0128	Temp correction factor:	2.60

Adjust %finer for hydrometer PA=(P*F200)/100

Test Data: F200=%finer sieve 200

Time (min)	Hyd. Reading Ra	Temp. Average	Composite Correction	Corr. Hyd. Reading Rc	Effective Depth, L (cm)	Percent Finer P %	D (mm)	Adjust finer PA %
0.5	49	31	2.7	46.3	8.3	94.47	0.0520	61.31
1	48	31	2.7	45.3	8.4	92.43	0.0371	58.99
2	46	31	2.7	43.3	8.7	88.35	0.0268	57.34
5	43	31	2.7	40.3	9.2	82.24	0.0174	53.37
15	39	31	2.7	36.3	9.9	74.08	0.0104	48.08
45	33	30	2.9	30.1	10.9	61.27	0.0063	39.76
90	29	28	3.5	25.5	11.5	51.95	0.0046	33.72
180	27	27	3.8	23.2	11.9	47.29	0.0033	30.69
240	25	27	3.8	21.2	12.2	43.22	0.0029	28.05
1440	18	31	2.7	15.3	13.3	31.28	0.0012	20.30

Tested by:



Checked by:



Approved by: