EVALUATION OF POLYETHYLENE TAPE COATING/MILD STEEL BOND FAILURE ON THE SOIL-TO-AIR REGION OF A CRUDE OIL PIPELINE

BY

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DEDICATION

This thesis is dedicated to Almighty God for His grace and strength during the course of this program and to my wife, Stella Ufuoma and my children Danielle, Mitchelle and Reinelle. Without their patience, understanding, support, and most of all love, the completion of this work would not have been possible.

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It would be a form of unforgivable negligence if I do not mention my children.
They gave me the emotional support needed for me to carry on this work to conclusion.

ABSTRACT

In evaluating the performance of organic coating (Polyethylene Tape) in the corrosion protection of mild steel pipelines, pipelines around the shores of Escravos in the Niger Delta region of Nigeria with organic coating (Polyethylene tape) installed at the soil-to-air interface (Transition section) for 14 years was considered in the scope of this study. This was to provide performance data when considering the use of Polyethylene Tape coating on the of pipeline transition section that is susceptible to accelerated corrosion attack due to numerous environmental variables.

Corrosion damage ranging from surface rust to mild external corrosion were noted on the specimen pipeline surfaces and with no evidence of through wall perforation noted on the polyethylene tape coating, however, coagulation failure (Adhesive failure between adhesive layer and pipe surface) was observed in all specimen examined. A limitation in the effectiveness of organic coating (Polyethylene Tape) in corrosion protection of mild steel due to its none continuous spread (many joining points) over the coated pipeline surfaces thereby providing failure prone locations was established.

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

For centuries, pipelines offered the safest, most efficient, and reliable method for transporting oil and gas. The global demand for a sustainable supply of oil and gas dictates an effective pipeline system. Therefore, economical and effective techniques to minimize the deteriorating effects such as corrosion and coating failure are critical for the lifetime of pipeline systems (Alrudayni, 2015). Corrosion protection of pipeline accomplished by a combination of cathodic protection and protective coatings. The coating provides a barrier to the corrosive environment and the cathodic protection protects the damaged sites in the coating which may exist due to failure of the protective coating after interacting with the environment.

The failure of pipelines by external corrosion has caused both financial and environmental consequences, and also a safety hazard as corrosion is considered the major reason behind most pipeline failure.

Corrosion is a natural process that reduces the binding energy in metals with the end result involving a metal being oxidized as the bulk metal loses one or more electrons. The lost electrons are conducted through the bulk metal to another site where they are reduced. Thus, a variety of natural and environmental factors can have significant effect on the corrosion of metals even when no other special conditions are involved (Amadi et al 2014).

Available literatures indicates that tape coatings have been in use for more than 70 years for the reliable corrosion protection of pipelines, particularly the soil to air interface (transition section) which is very susceptible to rapid external corrosion attack. It is expected that these tape coatings should protect equipment against corrosion for the overall period of their operation and satisfy a set of contradicting and rigorous requirements, i.e., to possess high chemical and biological stability, mechanical strength, dielectric properties, integrity, and low water permeability; to provide resistance against osmosis and electro-osmosis; to be sufficiently elastic; and to maintain their main properties at temperature change in different weather conditions ((Zaikin et al, 2010). The most common types of tapes are manufactured from Polyolefins - addition polymers which are polyethylene, polypropylene and Teflon tapes. Tapes used for corrosion protection are mostly manufactured using polyethylene because besides offering flexibility, conformability, and excellent chemical resistance, it is also environmentally friendly (Stanisława, 2014). Many studies have been done on organic coating, Polyethylene in particular, used for corrosion protection. While some are field based study, many laboratories and experiment base studies of the evaluation of organic coating as a means of corrosion protection in different environment have also been carried out.

One of the earliest was the study carried out by Wagner in 1950 using polyethylene wrap on steel surface buried in highly corrosive cinder fill. This study and another by the Yoshiyuki et al, 1990 on behalf of the Japanese Association for Steel Pipe Piles (JASPP) who also conducted a 15year Marine exposure tests on the polyethylene coating in the tropical marine environment in the Philippines all pointed to the fact that polyethylene as a material provides sufficient corrosion protection of mild steel.

A paper, Corrosion Prevention with Loose Polyethylene Encasement by Smith in 1972 reports: "After almost 20 years of experience, including research and application in the field, there has been no failure of pipe so protected." Since that time, however, there have been some reports of failures of polyethylene-wrapped pipe.

The field studies were on polyethylene as a material used in different forms other than in the form of a standard tape with adhesive surface.

A laboratory studies evaluating organic coating as a form of corrosion protection was carried out by Amadi et al, in 2014 but there is a need to carry out a field-based study of organic tape coating within our immediate environment as the data from this study will make a good reference in the oil & gas sector where organic coatings (Polyethylene tapes) are used for corrosion protection of pipelines soil to air interface (transition sections). Since the performance of the organic coating is a function of the exposed environment, an evaluation of its performance within a Nigerian oilfield of application becomes necessary.

1.2 Statement of the Problem

Pipelines are conduit made from pipes connected end-to-end for long distance transportation of liquid, gas or any chemically stable substance. The soil-to-air interface/region where pipelines transits from above to below ground is more susceptible to corrosion than either buried or raised sections. High moisture content, temperature variation, oxygen, pH, bacteria and chemical contaminants all accelerate soil line organic coated corrosion barriers between the underlying metal and the corrosive environment.

Organic coating efficiency depends on the mechanical properties of the coating system, type and concentration of suspended inhibitors, pretreatment of the metal surface, adhesion of the coating to the underlying metal base, and other additives that inhibit substrate corrosion. Failure of this organic coated steel starts when pits or holes are formed, usually from mechanical shocks or aging, in the coating. The corrosive species attacks the underlying metal through the defects, increases the exposed surface, and thereby accelerates the corrosion process. The reaction happens not only on the exposed metal surface, but also on the metal underneath the coating. The aggressive species reacts with the coating or the metal substrate, which eventually causes cathodic or anodic delamination, blisters, loss of gloss, solvent entrapment and pinhole respectively. The failure of the polyethylene tape coating/mild steel bond on the soil to air region of pipelines needs to be evaluated to understand the prevalent damage mechanisms over a period of in-service environment and also provide field data that will improve the use of polyethylene tape coating on this corrosion susceptible section of the pipeline.

1.3 Aims and Objectives of the Study

1.3.1 Aims of the Study

The main aim of this project is to carry out an evaluation of polyethylene tape coating/mild steel bond failure on the soil-to-air region of a crude oil pipeline

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1.3.2 The objectives of this project are:

i. To evaluate the chemical composition of the organic coated substrate in order to determine how they relate to corrosion prevention of a mild steel pipelines.
ii. To analyzed the predominant failure mechanism affecting organically (Polyethylene tape) coated steel using visual examination, scanning electron microscope, adhesion test.
iii. To analyze the effect of soil corrosivity on the corrosion degradation of Polyethylene Tape coated mild steel pipeline by carrying out soil resistivity test.
iv. To analyze the extent of coating degradation on the tape coated mild steel pipelines exposed to service environment for 14 years.

1.4 Scope of the Study

i. Carry out survey on equipment with installed polymer tape coating in service and identify the period of installation to establish the current service life.
ii. Examine each installed organic coating (Tape) to determine the external condition considering the period of service, using visual examination.
iii. Carry out Tests, micro and macro examination on sample organic coating (Tape) to evaluate the extent of degradation and compare with the original condition.
iv. Investigate and evaluate the failure mechanism where coating failure is evident.
v. Carry out soil test to ascertain the soil corrosivity within the area of installation.

CHAPTER TWO

LITERATURE REVIEW

2.1 Steel

Steel is essentially an alloy of iron and carbon with trace quantities of other alloying elements such as silicon, Sulphur, phosphorus, manganese etc., which are present in varying amounts. Its remarkable properties and ability to control these properties stems from the presence of carbon and the polymorphic nature of iron (Onyekpe, 2002). Carbon steel is the most common material of construction, not because of their corrosion resistance, which is usually fair to poor in most environments, but because of their excellent mechanical properties and their cost. In most cases, when steel is used in corrosive environment, it usually requires auxiliary protection, such as protective coating or cathodic protection. The carbon content, which is so important for mechanical properties, usually have very little effect on corrosion resistance. Corrosion may be defined as: “a physicochemical interaction leading to a significant deterioration of the functional properties of either a material, or the environment with which it has interacted, or both of these” (Shreir et al 1994). Generally, corrosion can occur in the different classes of materials such as metals, semiconductors, ceramics, polymers, composites. The corrosion of metallic materials is taken into consideration in this work due to its wide range of its applicability in the oil and gas industry. The corrosion of metal embraces all interaction of a metal with its environment. It can be defined as the undesirable deterioration of a metal i.e., an interaction of the metal with its environment that adversely affects those properties of the metal that are to be preserved.

2.1.1. Buried pipelines

A buried operating pipeline is rather unobtrusive and rarely makes its presence known except at valves, pumping or compressor stations, or terminals. The vast majority of underground pipelines are made of carbon steel, based on American Petroleum Institute API 5L specifications (Specifications for Line Pipe, API 2000). Typically, maximum composition limits are specified for carbon, manganese, phosphorous, and sulfur. In some cases, other alloying elements are added to improve mechanical properties. These steels have inadequate alloy additions to be considered corrosion resistant and undergo a variety of corrosion failure modes/mechanisms in underground environments, including general corrosion, localized corrosion, pitting corrosion, and stress-corrosion cracking (SCC). For a buried pipeline, corrosion involves local electrochemical processes where water acts as an electrolyte at the pipeline surface. Usually, soil characteristics enable the access of atmospheric oxygen to the pipeline surface, fostering biological activity microbial induced corrosion (MIC) which alters the chemical composition of the water phase in contact with the pipeline. Additionally, Sulfate-reducing bacterial sometimes influences corrosion whereby soluble sulfates present in the soil are reduced to sulfides (Tator, 2010 and Victor, 2000). Figure 2.1. shows a situation where the buried pipeline is protected from the soil by a protective coating. If the protective coating remains intact and is impervious, corrosion will not occur. However, if water reaches the metal surface, corrosion is initiated on the pipeline (see Figure 2.2 for an example of corroded pipeline after coating removal), and this reaction is autogenously as described below. In this particular situation and due to the corrosion processes at the pipeline surface, change in composition can alter the chemistry of the trapped water.

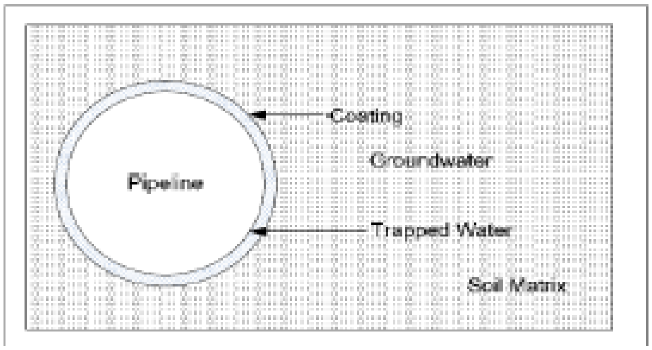


Figure 2.1: Protective coating can enable water to reach the pipeline. (Mohammed 2015)

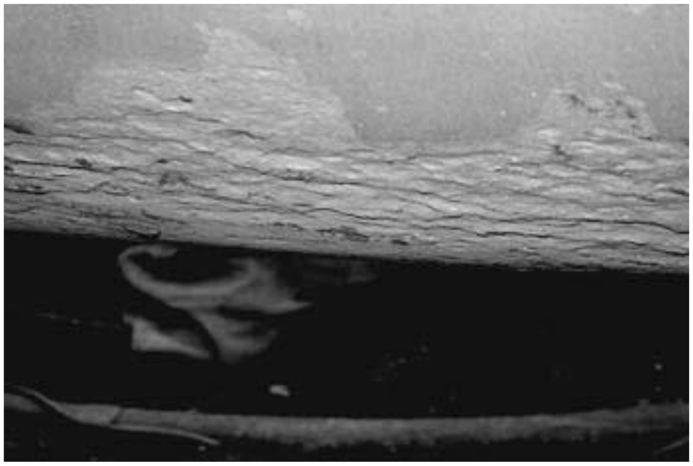


Figure 2.2: Example of external corrosion of an underground pipeline. Lower quadrant of pipeline shown after coating removal and abrasive cleaning. (Beavers et al., 2006)

2.2 Major Forms of Corrosion in Oil and Gas Industries

Corrosion is the gradual deterioration of materials due to interactions with their environments, and corrosion of most metals and many materials for that matter is inevitable. While primarily associated with metallic materials, all types of materials undergo corrosion or degradation, and this is a function of time, the circumstances and environment where the material is put to use (Onyekpe, 2002). Thus, polymeric materials, ceramics, noble metals such as platinum, gold, silver etc. all undergo corrosion processes. While some are very slow to corrosion process as a result of their inertness, some form protective covering around themselves and hinder further corrosion by a mechanism called passivation. Examples of such materials include aluminum, tungsten, titanium, etc.

Ferrous and non- ferrous structural alloys may corrode merely from exposure to moisture in the atmosphere due to their affinity for oxygen. However, the oxidation of many of these metals is extremely slow at ambient temperature but occur much more rapidly as the temperature rises. This is demonstrated by the scaling of steel at red heat (Gao et. al, 2008). Besides the presence of moisture, other factors also facilitate the process of corrosion e.g., pH (acidity/alkalinity), ionic species, fluid flow, etc. However, corrosion rates depend on a complex interaction between the material, its environment and the circumstances of exposure (Onyekpe, 2002).

The electro-chemical oxidation of iron to form iron hydroxide (rust) is an example of corrosion process since it involves loss of electron from the iron atoms (oxidation).

$Fe + \frac{1}{2}O_2 + H_2O \longrightarrow Fe(OH)_2$ …………………………………… (2.1)

At the anode

$Fe \longrightarrow Fe^{2+} + 2e^-$ …………………...………………………… (2.2)

At the cathode

$H_2O + \frac{1}{2}O_2 + 2e^- \longrightarrow 2OH^-$ ……………………………… (2.3)

Combining equations (2.2) and (2.3) and cancelling the electron from each side yields equation (2.4)

$Fe + H_2O + \frac{1}{2}O_2 \longrightarrow Fe(OH)_2$ ……………………………… (2.4)

The iron (ii) hydroxide, Fe $(OH)_2$ so formed quickly oxidized to iron (iii) hydroxide, Fe $(OH)_3$ by atmospheric oxygen. This iron (iii) hydroxide formed is the basis of reddish-brown substance called rust (Onyekpe, 2002). It is porous and soluble and can give rise to further rusting; rusting therefore is the corrosion of Fe.

$$2Fe\,(OH)_2 + H_2O + \tfrac{1}{2}O_2 \longrightarrow \underset{\text{(Hydrated iron (iii) oxide)}}{\underset{\downarrow}{2Fe\,(OH)_3}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.5)$$

Figure 2.3 below depicts this corrosion process.

The reaction (2.2) and (2.3) are called ‘half-cell’ reactions. Reaction (2.2) is the half of the process which is responsible for the damage during corrosion. The speed at which this reaction proceeds is directly related to the corrosion rate.

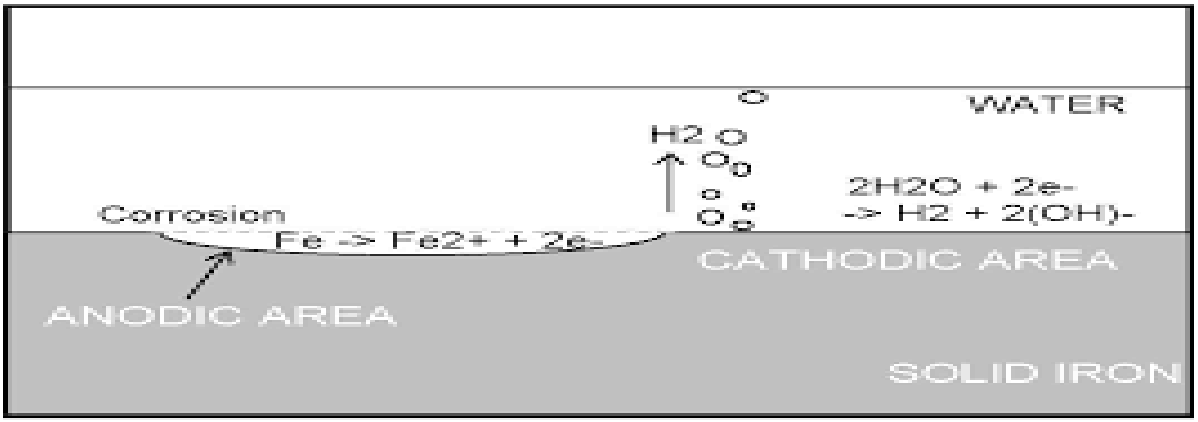


Figure 2.3: Schematic of the Corrosion Process (ASM International, 1992)

The Petroleum industry contains a wide variety of corrosive environments. Some of these are unique to this industry. However, some basic forms of corrosion in the oil and gas industry within the scope of this work are:

2.2.1. Differential Cell Corrosion

In the case of true general corrosion of a metal, the oxidation and reduction reactions occur physically at or very near the same location on a metal. At any given moment, one atom is being oxidized while the reduction reaction is occurring at an adjacent atomic site. Corrosion of a metal in an acid solution is a common example of this type of behavior. It is also possible for the oxidation and reduction reactions to be separated on a metal surface, where the metal oxidation occurs predominantly at one site while the reduction reaction occurs predominantly at another site.

This is referred to as a differential corrosion cell. Underground corrosion of pipelines and other structures is often the result of differential corrosion cells of which a variety of different types exist.

a. Surface films

Films present on a metal also can alter the corrosion potential and cause differential cell corrosion. For example, mill scale is created on line pipe steel during the manufacturing process (hot rolling) and, if not removed, the mill-scale-coated steel will act like a dissimilar metal in contact with non-mill-scale coated pipe steel. The potential of the bare pipe steel surface will be more negative (active) than the mill-scale-coated surface, resulting in severe corrosion of the bare steel surface in low-resistivity soils. A similar condition can occur when new steel pipe is intermixed with old steel pipe. The potential of bright new steel is typically more negative than that of old rusted steel, resulting in rapid corrosion of the new steel unless the new section is electrically insulated from the old section and, or cathodically protected. A similar corrosive condition can occur if, during work on an existing piping system, tools cut or scrape the pipe and expose areas of bright steel. The potential of these bright spots will be more negative than the remainder of the pipe, resulting in accelerated corrosion in low resistivity soils (Beavers et al., 2006).

b. Relative size of anodic and cathodic areas

This can have a significant effect on the severity of the differential corrosion cell. In general, the severity of corrosion of the anodic areas increases as the ratio of the anodic to the cathodic area decreases. When the anode is small and the cathode is large, the anode will be subject to a high density of current discharge per unit area, with the total amount of current flowing governed by the kinetics of the oxidation and reduction reactions and the soil resistivity. The current collected per unit area on the cathode is relatively low and may not be sufficient to result in any degree of polarization, which would tend to limit corrosion current. In a low-resistivity soil, corrosion can be rapid (Beavers et al., 2006).

Table 2.1: Practical galvanic series and redox potentials of metals and alloys in neutral soils and water

Material	Potential (CSE)(a), V
Most Noble	
Carbon, graphite, coke	+0.3
Platinum	0 to-0.1
Mill scale on steel	-0.2
High-silicon cast iron	-0.2
Copper, brass, bronze	-0.2
Low-carbon steel in concrete	-0.2
Lead	-0.5
Cast iron (not graphitized)	-0.5
Low-carbon steel(rusted)	-0.2 to-0.5
Low-carbon steel (clean and shiny)	-0.5 to-0.8
Commercially pure aluminum	-0.8
Aluminum alloy (5% Zn)	-1.05
Zinc	-1.1
Magnesium alloy (Mg-6Al-3Zn-0.15Mn)	-1.6
Commercially pure magnesium	-1.75
Most Active	

Measured with respect to copper sulfate reference electrode (CSE) (Peabody et al., 2001).

2.2.2 Differential Aeration Cell Corrosion

This is probably the most common corrosion cell found on pipelines or other underground structures. One area of the pipeline is exposed to higher concentrations of oxygen and becomes the cathode in the cell, while another part of the structure is oxygen deficient and becomes the anode. Electrical current leaves the metal surface at the anode, increasing the corrosion rate, and flows to the oxygenated cathodic area, decreasing the corrosion rate. Differential aeration cells as well as other corrosion cells can be autocatalytic in that the chemical and electrochemical reactions, as well as ion migration, tend to produce conditions that promote the continuation of the cells. At the anode, the metal ions produced by the corrosion reactions hydrolyze (react with water), reducing the local pH. Corrosive negative halide ions migrate to the anodic sites to maintain charge neutrality. Both of these processes increase the corrosivity at the anodic sites. At the cathodic sites, the reduction reactions increase the pH and improve the protective nature of the corrosion films. Differences in soil properties, variation in the moisture content of the soil, the depth from the surface or oxygen barriers such as paved roads can produce differential aeration cells. An example is illustrated in Fig 2.4, which shows a pipeline passing through two dissimilar soils. The corrosion potential of the pipeline in the clay soil which have fine texture and high water-holding capacity result in poor aeration and poor drainage, leading to an increase in the corrosion rate of the pipe in the clay soil. This is more negative than the corrosion potential in the sandy soil where there is greater circulation of air, and a decrease in the corrosion rate of the pipe (see Table 2.2 for soil types and their corrosive effect). Factors other than differences in the oxygen concentration of the soil can produce a differential corrosion cell such as the one shown in Fig 2.4. For example, differences in the pH, or the concentration of aggressive ions such as chlorides in the soil, can produce differential corrosion cells.

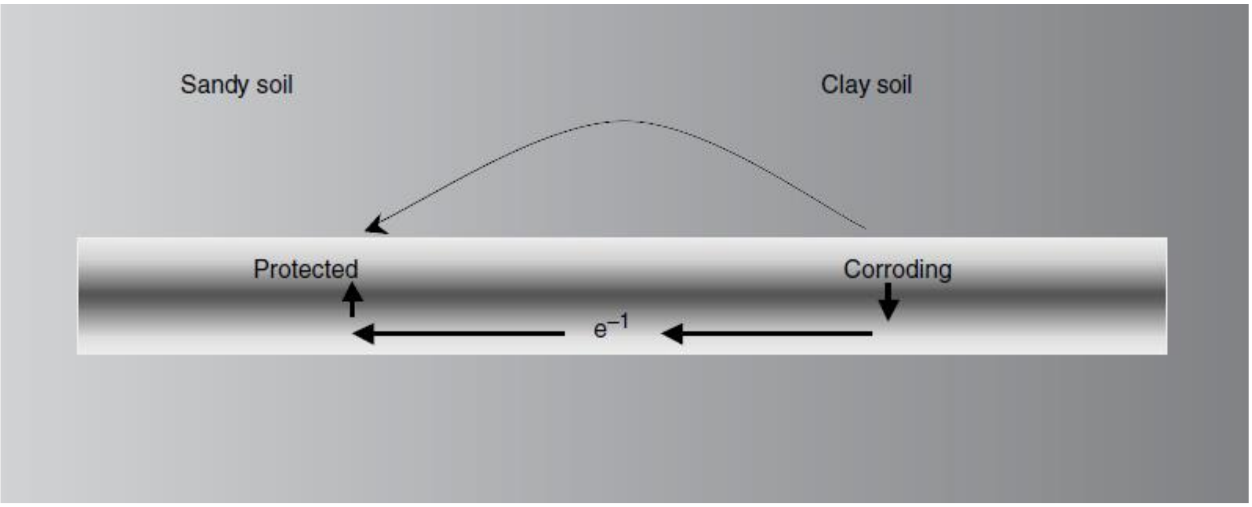


Figure 2.4: Differential corrosion cells created by differences in soils. Arrows indicate the direction of ionic and electronic current flow. (Beavers et al., 2006)

Table 2.2: Soil type, resistivity effect and corrosivity

Soil Resistivity (ohm-cm)	**Soil Type**	**Moisture**	**Corrosivity**
<500	Muskeg/sloughs/free water accumulations	Always wet	Very corrosive
500 - 2000	Loams/clays	Mainly wet	Corrosive to moderately corrosive
2000 - 10000	Gravels, sandy	Mainly dry	Mildly corrosive
>10000	Arid, sandy	Always dry	Non-corrosive

The Canadian Association of Petroleum Producers (CAPP), 2018

2.2.3 Galvanic corrosion

This is another example of a differential corrosion cell. In the case of galvanic corrosion, the potential difference is created by the presence of different metals. Different metals have a different corrosion potential in a given environment. An example is the galvanic series for metals in soils, shown in Table 2.1 (Peabody et al, 2001). When these metals are electrically coupled, the metal with the most positive corrosion potential is cathodically polarized, reducing its corrosion rate, while the more negative member of the couple is anodically polarized, increasing its corrosion rate. Galvanic corrosion can be very detrimental to an underground structure. Examples include the corrosion of iron in contact with copper or stainless-steel fittings. However, galvanic corrosion can be used as an effective means of CP (Beavers et al., 2006).

2.2.4 Microbiologically Influenced Corrosion

Microbiologically influenced corrosion (MIC) is defined as corrosion that is influenced by the presence and activities of microorganisms, including bacteria and fungi. It has been estimated that 20 to 30% of external corrosion on underground pipelines is MIC-related (Koch et al., 2002).

Microorganisms located at the metal surface do not directly attack the metal or cause a unique form of corrosion. The by-products from the organisms promote several forms of corrosion, Including pitting, crevice corrosion, and under deposit corrosion. Typically, the products of a growing microbiological colony accelerate the corrosion process by either interacting with the corrosion products to prevent natural film forming characteristics of the corrosion products that would inhibit further corrosion or providing an additional reduction reaction that accelerates the corrosion process. A variety of bacteria have been implicated in exacerbating corrosion of underground pipelines, and these fall into the broad classifications of aerobic and anaerobic bacteria (Little et al., 1997). Obligate aerobic bacteria can only survive in the presence of oxygen, while obligate anaerobic bacteria can only survive in its absence. A third classification is facultative aerobic bacteria that prefer aerobic conditions but can live under anaerobic conditions. Common obligate anaerobic bacteria implicated in corrosion include sulfate-reducing bacteria (SRB) and metal reducing bacteria. Common obligate aerobic bacteria include metal-oxidizing bacteria, while acid-producing bacteria are facultative aerobes. The most aggressive attack generally takes place in the presence of microbial communities that contain a variety of types of bacteria. In these communities, the bacteria act cooperatively to produce conditions favorable to the growth of each species. Obligate anaerobic bacteria can thrive in aerobic environments when they are present beneath bio-films/deposits in which aerobic bacteria consume the oxygen. An example is shown in Figure 2.5. In the case of underground pipelines, the most aggressive attack has been associated with acid-producing bacteria in such bacterial communities (Koch et al., 2002).

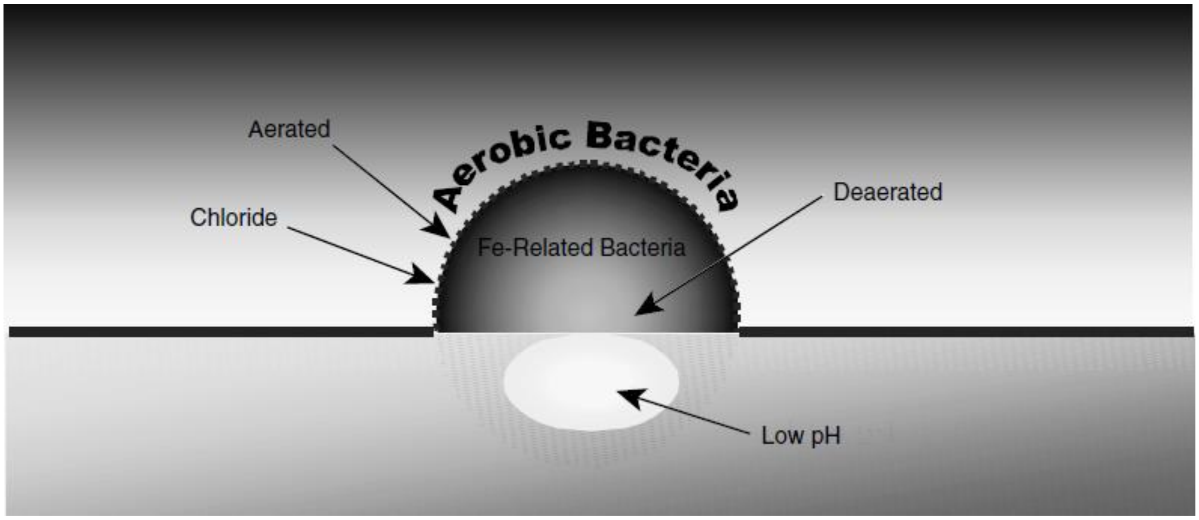


Figure 2.5: Iron-related bacteria creating a differential oxygen and pH cell on a metal surface (Beavers et al., 2006)

2.2.5 Stray Current Corrosion

Corrosion of underground pipelines can be accelerated by stray DC flowing in the soil near the pipeline. Sources of direct electrical current include foreign pipelines that are not properly bonded to the pipeline and ground currents from DC sources. Electrified railroads, mining operations, and other similar industries that utilize large amounts of DC sometimes allow a significant portion of current to use a ground path return to their power sources. These currents often utilize pipelines in close proximity as a part of the return path. This "stray" current can be picked up by the pipeline and discharged back into the soil at some distance down the pipeline close to the current return. Current pickup on the pipe is the same process as cathodic protection, which tends to mitigate corrosion. The process of discharge of a DC off the pipe and through the soil accelerates corrosion of the pipe wall at the discharge point, causing stray current corrosion. The morphology of stray current corrosion tends to be very localized at holidays (defects or holes) in the pipeline coating. Rates of attack can be very high, resulting in rapid perforation of a pipeline. In the case of stray current corrosion from a foreign pipeline, the pipeline acts as a return current path for the cathodic protection system on the foreign pipeline. Stray current corrosion occurs where the DC discharges from the pipeline and collects onto the foreign pipeline, as shown in Figure 2.6. While relatively rare, cathodic protection rectifiers are occasionally connected backwards, such that DC current is discharged from the pipeline and the impressed current "anode" actually collects rather than discharges current. This can result in severe stray current corrosion of the pipeline (Figure 2.7). Field experience and laboratory research results indicate that stray alternating current (AC) can also cause accelerated corrosion of underground pipelines (Yunovich et al., 2004). The most common sources of stray AC are induced AC from power lines and pipelines in a common right of way and ground faults from AC power transmission. It is generally agreed that AC-enhanced corrosion rates are only a small fraction (51%) of those of DC currents. Nevertheless, corrosion damage can be extensive where the ac currents are large.

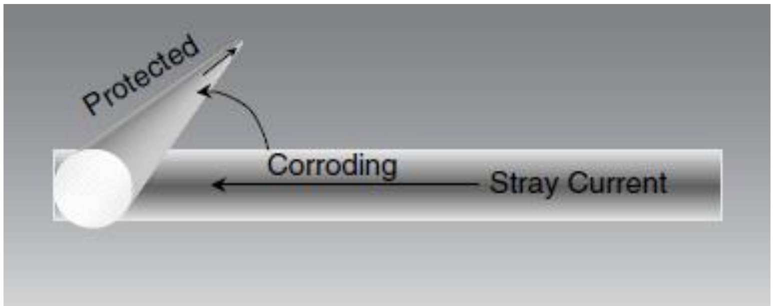


Figure 2.6: Stray current corrosion caused by foreign pipeline (Beavers et al., 2006)

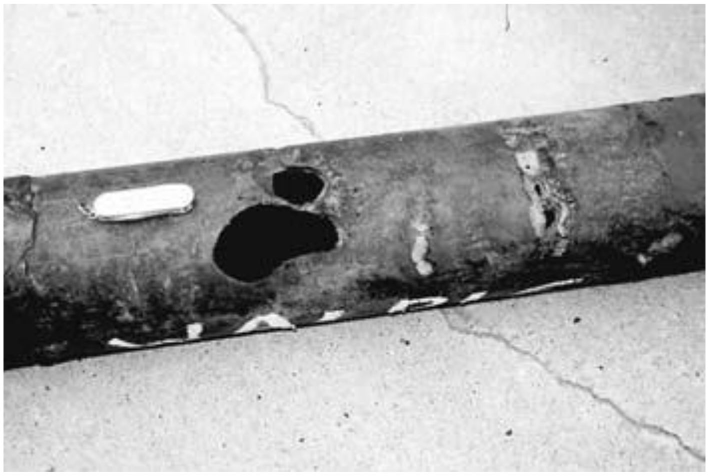


Figure 2.7: Pipeline that experienced stray current corrosion caused by inverting the electrical leads to a cathodic protection rectifier (Beavers et al., 2006)

2.2.6 Stress-Corrosion Cracking

Stress-corrosion cracking (SCC) is defined as cracking of a material produced by the combined action of corrosion and tensile stress. There are two forms of external SCC on underground pipelines: high-pH SCC (also referred to as classical SCC) and near-neutral-pH SCC (also referred to as low-pH SCC). A characteristic of both forms of SCC is the development of colonies of longitudinal surface cracks in the body of the pipe that link up to form long, shallow flaws. In some cases, growth and interlinking of the stress-corrosion cracks produce flaws that are of sufficient size to cause leaks or ruptures of pipelines. An example of an SCC colony that caused a pipeline failure is shown in Figure 2.8. The high-pH form of SCC is inter-granular (Wenk, 1974), the cracks propagate between the grains in the metal, and there is usually little evidence of general corrosion associated with the cracking (Figure 2.9). The near-neutral-pH form of SCC is trans-granular—the cracks propagate through the grains in the metal—and it is associated with corrosion of the crack faces and, in some cases, with corrosion of the external surface of the pipe as well (Figure 2.10). This form of cracking was first reported on a polyethylene-tape coated pipeline on the TransCanada Pipelines Ltd. (TCPL) system in the 1980s (Justice et al, 1988; Delanty et al., 1992).

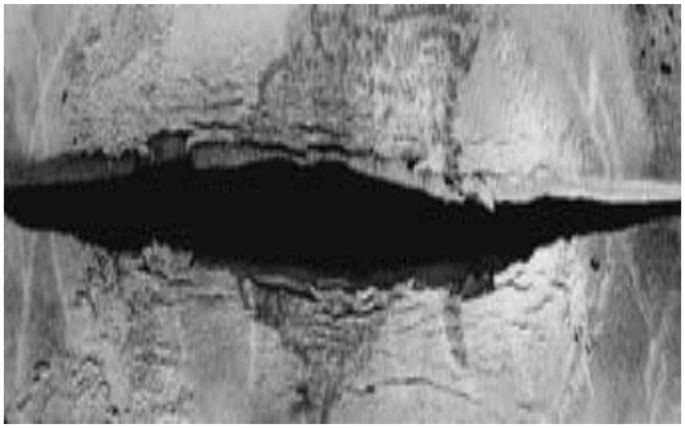
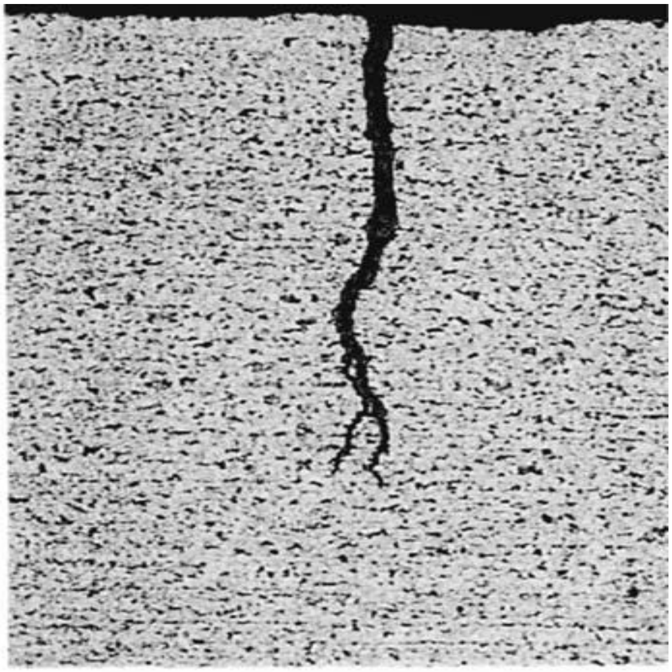


Figure 2.8: Example of colony of stress-corrosion cracks on external surface of high-pressure gas transmission pipeline. The top scale is inches and the bottom in centimeters. (Beavers et al., 2006)

20 µm

Figure 2.9: Intergranular high-pH stress-corrosion crack inline pipe steel. Nital etchant. Original magnification:400 X (Beavers et al., 2006)



100 µm

Figure 2.10: Trans-granular near-neutral-pH stress-corrosion crack in Nital etchant. Original magnification: 100 x. (Beavers et al., 2006)

2.3. Corrosion Control.

There are numerous measures available for the control of corrosion, the choice of which centers on economy, safety requirements, workability (sense) and other technical consideration. Any of the following or a combination of them serves to control corrosion.

a. **Design**: From the onset of the design of a system, corrosion could be minimized or checked by making the following consideration:
   i. Eliminating water retention
   ii. Avoiding crevices
   iii. Using dissimilar metals prudently
   iv. Avoiding areas for water and debris collection

However, as corrosion is inevitable, systems could be design to accommodate corrosion i.e., adding a corrosion allowance (Onyekpe, 2002):

i. Making inspection/ replacement easy
ii. Allowing for maintenance accessibility

b. Material selection

It makes sense to use corrosion resistant materials for our setup but it makes more sense to make a consideration of economy and specific engineering properties. Hence there must be an optimum reconciliation between the choice of material and cost and the suitability of the material for specific requirement (Onyekpe, 2002).

c. Coating

Coating is used to isolate the material from the environment and their barrier properties are of specific interest. They may also render some chemical benefits. Protective coating and lining serve to control corrosion by providing one of the followings:

i. A high resistant electrolyte path between anodic and cathodic reaction sites e.g., paints, rubber, plastic and most polymeric coatings.
ii. A reservoir of corrosion inhibitor close to the metal surface e.g., primer paint with anti-corrosive pigments
iii. Cathodic protection e.g., zinc rich paints (Onyekpe, 2002)
iv. An inert or highly corrosion resistant barrier between the metal and the environment e.g., chromium coating

Coating materials could be organic (e.g., paint, thermoplastic), inorganic (e.g., ceramic), metallic (e.g., Anodic- zinc, aluminum, cathodic- nickel, chromium) composites (e.g., cermets) duplex-aluminum-polymeric- sealer.

d. Chemical Treatment

Chemical treatment involves the addition of chemical to remove or neutralize cathodic reactants and to inhibit corrosion reactions. Thus, oxygen scavengers are removed, inhibitors are neutralized and pH is controlled by the addition of chemical. Similarly, the addition of chemical species (called inhibitors) can inhibit of hinder corrosion processes (Onyekpe, 2002).

e. Combination

In some occasions, it may be necessary to combine two corrosion control measures so as to create an effective barrier to corrosion process e.g., the use of corrosion allowance and inhibitors, cathodic protection and coating. However, care must be taken as some combinations may be dangerous while some may be considered superfluous e.g., the use of a cathodic protection on titanium is dangerous; application of coating on a corrosion resistance alloy is considered superfluous (Onyekpe, 2002).

f. Corrosion Allowance

If the rate of corrosion of a material in a given medium is known, the time for the degradation of the material of given thickness to failure can be predicted. Therefore, additional thickness (allowance) could be made to buy life for the material over an estimated period of time, and within this time little or no expenses is incurred in preventing the material against corrosion (Alexander et al, 2014)

g. Allowing Corrosion to Progress (Do Nothing)

Corrosion may be allowed to progress unabated if the cost of controlling it far outweighs the cost of not administering any control measures provided the consequences of failure is not expensive and hazardous to life and property. This may be a valid option (Onyekpe, 2002).

2.4 Organic Coating

Coatings are the first line of defense against corrosion. Coatings are known to prevent corrosion by four primary means. Firstly, by barrier resistance through which the coating film prevents the corrosive elements from coming in contact with the metallic substrate; secondly, by the electrical resistance that the coating offers, restricts electrical conductivity in the corrosion circuits; thirdly, cathodic protection where an electrical current counteracts the corrosion current and fourthly, through anodic or cathodic chemical inhibition of the corrosion process. Coatings are defined as films applied to the surfaces of structures, piping, tanks, and offshore structures. Although there are numerous types of coatings, they are similar in composition, consisting of four principal components: Vehicle or binder, solvents, pigments, and additives. Vehicle is the most important component that forms the film and provides the necessary integrity to prevent corrosion. It provides basic physical properties such as resistance to water, hydrocarbons, and other chemicals and to weather. Typical vehicles include epoxy, phenolic, alkyd, vinyl, and acrylic which are polymers. Solvents are the key to any coating's success because they provide viscosity, drying properties, and flow control. Solvents are used to dissolve the vehicle so that the coating may be uniformly applied to the surface. Pigments are solid materials that deliver atmospheric resistance, corrosion resistance, color, and toughness. Additives are small amounts of liquid or solid that control the drying and curing of the coatings, flow, and wetting (Mohammed, 2015). The required properties of pipeline coatings are as follows;

CAPP, (2009). Mitigation of External Corrosion on Buried Pipeline Systems Best Management Practice are:

1. Coating should have a high electrical resistance in order to isolate the external surface of the piping from the environment
2. Coating should be an effective moisture barrier.
3. Coating should have good ductility to resist cracking.
4. Coating should have sufficient strength and adhesion to mitigate soil stress and normal handling.
5. Coating should be compatible with cathodic protection to prevent shielding.
6. Coating should be resistant to chemical and physical damage or degradation during service.
7. The use of the coating should not impart or pose any environmental or health risks.

Pipeline coatings have been in constant development and in use for more than 80 years. Coating technology has changed over time, which has resulted in the use of different types of coating systems. Coatings are usually classified based on the resin binder, which provides protective properties and resistance to degradation. Different coating resin types exhibit different properties such as good adhesion to substrate. According to the coating's formulation, they can be used as primers or top coats. They include but not limited to:

1. Fusion Bond Epoxy (FBE)
    - Epoxy coating consisting of resins, curing agents, catalysts, accelerators, etc.
    - Excellent adhesion and resistance to soil stress, gouging and abrasion. Does not shield cathodic protection current (i.e., fails safe)

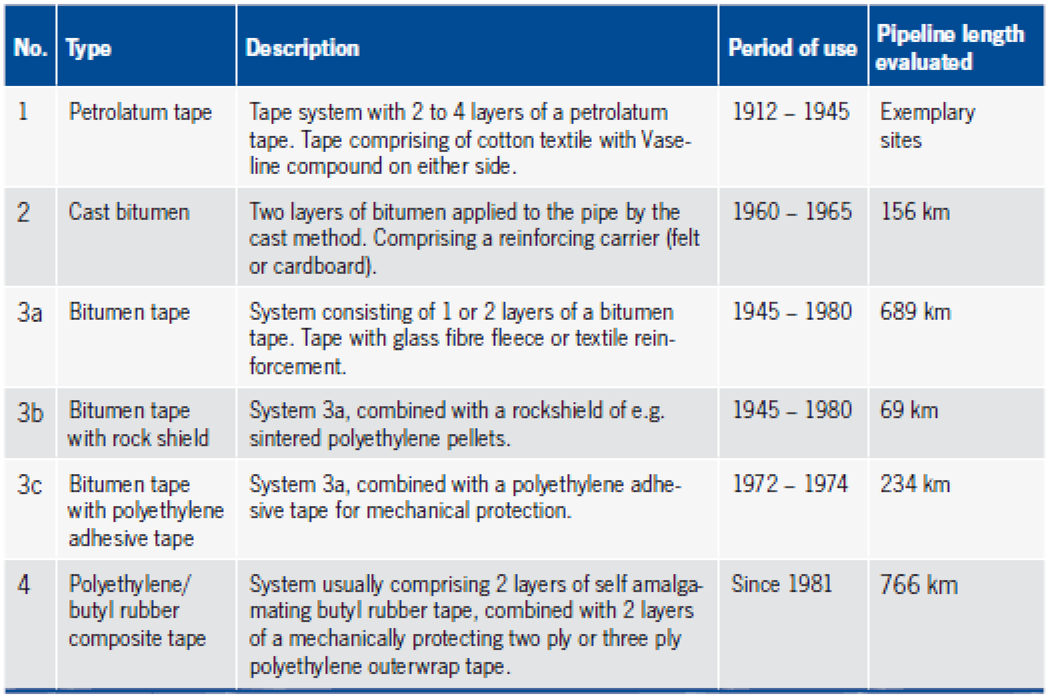
2. Abrasion Resistant Fusion Bond Epoxy (Dual Power – DPS)
    - Several layers of FBE, or FBE overcoated with a liquid epoxy, to provide improved abrasion resistance
    - Often used for horizontal bored crossing sections
3. Three (3) Layer Extruded Polyethylene (e.g., YJ2K)
    - Product consists of three layers: an FBE primer, a co-polymeric adhesive and an extruded polyethylene outer sheath

4. Two (2) Layer Extruded Polyethylene (e.g., YJ1, Yellow Jacket)
   - Rubber-modified asphalt adhesive covered by an extruded polyethylene outer sheath

5. Thermally insulated pipeline coatings such as:
   - Polyurethane foam applied direct to pipe, polyethylene tape or extruded polyethylene outer sheath currently used only in select system with built-in leak detection and monitoring systems (LDMS)
   - Primer, polyethylene tape anti-corrosion barrier, polyurethane foam, extruded polyethylene outer jacket
   - Primer, polyethylene tape anti-corrosion barrier, polyurethane foam, polyethylene tape outer jacket (no longer implemented)
   - Two-layer extruded polyethylene anti-corrosion barrier, polyurethane foam, extruded polyethylene outer jacket (no longer implemented)
   - Fusion bond epoxy anti-corrosion barrier, polyurethane foam, extruded polyethylene outer jacket
   - Three-layer extruded polyethylene anti-corrosion barrier, polyurethane foam, extruded polyethylene outer jacket
6. Polyethylene tape (solid film backing)
   - Primer, butyl rubber or similar adhesive, and polyethylene solid film backing applied in a spiral wrap
   - Poor adhesion, soil stress resistance. Low operating temperature.
7. Coal-tar enamel and asphalt mastics
   - 1950s/60s technology no longer in use. Coal tar pipe coatings can contain kraft paper layers, asbestos, or fiberglass layers to improve their performance
   - Care must be taken when working with coal tar coatings to avoid asbestos hazards.

(Mitigation of External Corrosion on Buried Carbon Steel Pipeline Systems, Canada’s Oil & Natural Gas Producers, July 2018)

Table 2.3: Field coating system overview (Rehberg et al.,2010)



No.	Type	Description	Period of use	Pipeline length evaluated
1	Petrolatum tape	Tape system with 2 to 4 layers of a petrolatum tape. Tape comprising of cotton textile with Vaseline compound on either side.	1912 – 1945	Exemplary sites
2	Cast bitumen	Two layers of bitumen applied to the pipe by the cast method. Comprising a reinforcing carrier (felt or cardboard).	1960 – 1965	156 km
3a	Bitumen tape	System consisting of 1 or 2 layers of a bitumen tape. Tape with glass fibre fleece or textile reinforcement.	1945 – 1980	689 km
3b	Bitumen tape with rock shield	System 3a, combined with a rockshield of e.g. sintered polyethylene pellets.	1945 – 1980	69 km
3c	Bitumen tape with polyethylene adhesive tape	System 3a, combined with a polyethylene adhesive tape for mechanical protection.	1972 – 1974	234 km
4	Polyethylene/ butyl rubber composite tape	System usually comprising 2 layers of self amalgamating butyl rubber tape, combined with 2 layers of a mechanically protecting two ply or three ply polyethylene outerwrap tape.	Since 1981	766 km

Since the main scope of this research is to evaluate the effectiveness of organic coating (Tape) on the corrosion prevention of mild steel, emphasis will be on the use of tape for corrosion protection.

2.5 Organic coating (Tape)

Among the many types of polymer coatings, the most widely applied are polymer adhesive tapes with a pressure sensitive adhesive layer. The substrates of these tapes are made of polyvinylchloride (PVC), polypropylene (PP), or polyethylene (PE) films with an adhesive layer on top. The tape coatings are characterized by fairly high strength and wear resistance. The main advantage of these coatings is the high maintainability of their use: the coatings can be applied directly on pipes in a field environment. The tape coatings applied under field conditions are characterized by integrity, therefore, the problem of individual protection of weld joints is eliminated (Zaikin et al, 2010). The advantages of the tape coatings are as follows: high maintainability of their application on pipes under factory and field conditions; good dielectric characteristics; low moisture and oxygen permeability, and fairly wide temperature range of operation (–40 to +40°C) (Zaikin et al, 2010). The major disadvantages of polymer tape coatings are low stability to shear at soil settlement, insufficiently high shock resistance, and low biological stability of adhesive under layer. The operating experience of the Russian gas and petroleum pipelines demonstrated, that the operation lifetime of the polymer tape coatings on pipelines with diameters of 1020 mm and higher is 7–15 years, which is two to four times lower than the calculated depreciation period (at least 33 years) of long-distance pipelines (Zaikin et al, 2010).

2.5.1 Polyethylene (PE) Tape

Polyethylene films are the most common type of plastic, and an environmentally friendly alternative to PVC. Offering flexibility, conformability, and excellent chemical resistance, these films are used in a range of applications which includes surface protection application tape. (Industrial Tape and Supply Company).

Polyethylene film is available with or without adhesive and various grades of densities. Polyethylene film is the primary material for polyethylene tape, which used as backing, and other material as adhesive or rubber used as primer. Adhesive can be used both side of the films.

i. System Composition and Function of Polyethylene Tape

The total tape system components consist of a primer applied directly to the pipe surface, an inner-wrap tape layer that provides a corrosion barrier and an outer-wrap tape layer that provides mechanical protection (Figure 13).

a. Primer

The primer is an integral part of the cold applied tape system. It is mainly composed of butyl rubber along with tackifiers, stress corrosion inhibitors and other additives that will facilitate good adhesion to the blasted pipe surface as well as maximize bonding of the inner-wrap tape layer to the pipe. These components are typically dispersed in a high evaporating solvent matrix and sprayed at controlled thickness on the blasted pipe surface, allowed to adequately dry prior to the application of the inner wrap tape layer. Due to recent state and federal regulations mandating solvent emission controls, 100% solids hot melt adhesive “primers” have been developed and introduced recently to the market as an alternate solution. They are also formulated with a butyl rubber and applied to the pipe surface using more specialized spray equipment (Mamish, 2009).

b. Backing

The inner and outer wrap layers backings are primarily composed of Polyethylene (PE). The PE backing is formulated to the demands of the coating for a specific application on pipe, or for a specific application as a coating. The PE composition of the anti- corrosion layer product is different than the mechanical layer, due to the function of the respective layers. The anti-corrosion layer generally has more medium and low-density PE composition which provide strength and conformability, while mechanical layers require the use of select high and low-density PE that provide higher mechanical strength, toughness and resistance to stress cracking. A typical formula would include low and high-density PE, antioxidants, UV inhibitor and colorant.

c. Adhesive

The adhesive in both tape layers is elastomeric based. Butyl rubber (BR) is predominantly used as opposed to other elastomers. BR's molecular structure of low un-saturation levels yields unique characteristics of chemical and moisture resistance, thermal stability, weathering and gas permeability, all essential properties required for long term in-ground performance. In addition to BR, a typical formula would include a tackifier, oil, filler, antioxidant, biocide and a colorant. Cross-linkers may also be used in applications requiring high, long term resistance to excessive soil stress and continuous heat exposure (up to 125 °C) (Mamish, 2009). The adhesive works in conjunction with the primer to form a strong bond to the steel substrate, providing the corrosion protection and long-term performance that the pipe requires as well as imparting high cathodic disbonding resistance, high shear and soil stress resistance. Different adhesive formulas are used depending on the surface to be applied to. There is the steel pipe surface and the PE backing layer of the anti-corrosion layer and the backing layer of the mechanical layer. Each layer of the PE Tape system must have a specific adhesive composition to insure achievement of a good adhesion at each interface.

ii. Factors that affect the durability of Polyethylene coating

In addition to the selection of the proper coating, other variables affect coating performance and long-term durability. These variables are as follows:

a. Environment

The environmental conditions in which a surface coating system is exposed can have a significant effect on the performance and durability of the coating.

b. Surface preparation

Surface preparation is the most important factor that can affect coating performance. Perhaps more than 70% of coating failures result from inadequate surface preparation. In most cases, surface preparation can account for as much as 40%–50% of the total cost. Usually, the quality of proper surface preparation is controlled by accessibility.

c. Application

Field-applied coatings used for coating weld joints, fittings, risers, or for making repairs to damaged coatings, are an important part of any coating system. The field application of pipeline coatings is always challenging. These coatings are applied outside in non-ideal weather conditions and difficult terrain. However, if the quality of the work is not comparable to the plant-applied coating, corrosion problems, often referred to as joint corrosion, will result. Common barriers to obtaining quality-field applied coatings are lack of worker supervision, poor training of workers applying the coatings and lack of proper coating inspection. Addressing these issues will improve the long-term performance of any coating system and help avoid disbonded and shielding joint coatings.

2.5.2 Tape Application to Pipe

The pipe coating process consists of the following steps, (Figure 14):

- Drying and cleaning using a grit or sand blasting to remove mil scale
- Phosphoric acid wash and drying, if required
- Primer spray and drying
- Inner-wrap application continuously and spirally using precision tension control
- Outer-wrap application continuously and spirally using precision tension control
- Holiday Detection
- Cut backs at both pipe ends

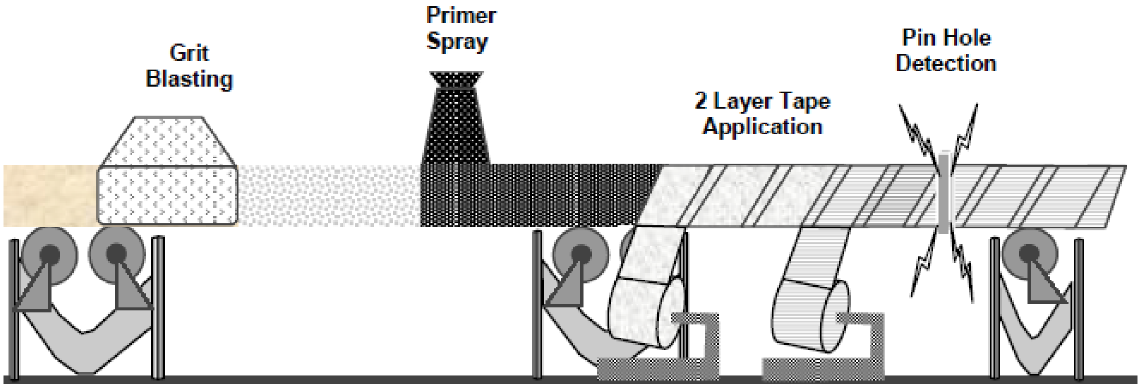


Figure 2.11: Multilayer PE Tape Application – Plant Coating (Mamish, 2009)

The above steps are carried out using detailed specifics to conform to industry and tape manufacturer application standards under the watchful eyes of a certified inspector. For example, the sand blasting step requires achieving a well-defined cleanliness and anchor pattern for the primer/inner-wrap to achieve expected adhesion, primer dryness and thickness, tape tension, temperature and overlap control are among many application conditions that are required to be practiced. Both tape layers are applied with recommended tension to ensure good application to the pipe, to ensure good conformability at the overlap and to achieve the mechanical and chemical adhesion of the coating system to the pipe. With machine application using tension, the coating experiences tension and necking down of the coatings by < 2%. This tension effect creates a "gasket effect" or flow of the adhesive at the overlap sealing the adhesive to the overlap and further creating mechanical adhesion of the coating to the substrate and to the multiple interfaces within the PE tape coating system. The tape coatings are applied to both insulate pipes and protect weld joints (Kuznetsov et al, 1992). In some cases, prior to application of adhesive tapes with curing rubber adhesive layer, the weld joints of the pipes are covered by epoxy layer (Dontsov, et al, 1979). The design of protective adhesive tapes for pipelines, materials for manufacturing them, and the technology of applications depend on the operating parameters, including the temperature of the conveyed product, pipeline diameter, the conditions of applying the coating, and the method of arranging the pipeline (underground, underwater (buried under the bottom), surface pipeline (land fill) and pipeline transition section (Soil-to-Air interface)). Since 1999, adhesive polymer tapes in the field insulation of gas pipelines have only been applied for pipe diameters of no more than 820 mm and operating temperatures of no more than +40°C. For petroleum pipelines, it is permitted to use tape coatings for field applications to insulate pipes with diameters of up to 1420 mm; however, total coating thickness should be at least 1.8 mm (Zaikin, 2010). In a system of polymer tape coatings, insulating tape and protective wrappings have different functions. The insulating tape ensures the adhesion of the coating to steel and the resistance against cathode peeling; furthermore, it acts as a protective barrier and prevents water, soil electrolyte, and oxygen, i.e., actively corrosive agents, from penetrating the surface of the pipe. The protective wrapping serves mainly to improve the mechanical and shock resistance of the coating; it protects the tape coating against damage when placing pipes into trenches and during filling operations, as well as in soil settling and the technological motion of the pipeline. Polymer tapes and protective wrappings are supplied as a set completed by factory produced adhesion primer (Zaikin, 2010).

2.6 Related Literature Review on the Effectiveness of Organic Coating (Tapes) on the Corrosion of Mild Steel.

Yoshiyuki et al, 1990 on behalf of The Japanese Association of Steel Pipe Piles (JASPP), conducted 15years marine exposure tests to investigate the durability of uncoated steels and protective organic coated steels and various steel pipe piles were selected and long-term exposure tests were conducted for these steels in the Philippines, which constitutes a standard tropical marine environment and Singapore, which is in a coastal industrial zone. The test methods for the organic coated steels involves specifications of four kinds of typical heavy- duty paint systems, Polyethylene coating and Petrolatum-saturated tape + FRP (Fiber Reinforced Plastic) cover were separately applied to steel pipe sandblasted to remove rust. The evaluation results of appearance, under-coating corrosion and pinhole revealed that comparatively, Polyethylene coating was good except for damage like scratch, impairment of the appearance was not observed in the steels coated with “Petrolatum-saturated tape + FRP cover”. “Polyethylene” and “Petrolatum-saturated tape + FRP cover” were good resistance against coating damage, and good corrosion protection.

Amadi et al 2014, researched on the performance evaluation of different types of anti-corrosion coating in an oil industry. In their work, four types of organic coatings namely, fusion bonded epoxy (FBE) scotchkote-206N, polyurethane (PU) aqualinc-600A, polyurethane-l 55 and 3- layer polyethylene (PE) were employed for the evaluation. They found out that fusion bonded epoxy (FBE) was consider more effective after the test was carried out among others.

Malik et al., 1999 researched on the corrosion protection evaluation of some organic coatings in water transmission lines. The project encompasses short- and long-term testing of three types of organic coatings, viz., polyethylene (PE), polyurethane (PU) and fusion bonded epoxy (FBE) on steel in order to determine the corrosion behavior in aqueous environment with special reference to product water. They carried various tests which includes mechanical testing, wet tests and impedance studies and the Coating materials are FBE-Scotchkote-206N, PU–Aqualine-600A, PU-Irathane-155 and 3-layer PE were used for the studies, wet tests consisting of salt fog, autoclave and close circuit corrosion loop were carried out to study the corrosion behavior of coating, water uptake or permeation and stability of coating under high temperature and pressure. The mechanical testing consisted of adhesion, bending and cathodic disbonding tests. The results of accelerated tests (salt fog tests) showed that in the scribed-coated samples, the creepage increases with increasing exposure time. FBE, 3-layer PE and Irathane-155 (PU) showed no blistering after 100 days exposure in salt spray cabinet but Aqualine-600A (PU) showed blistering on scribed and unscribed surfaces. Autoclave tests results indicated that FBE, Aqualine-600A and 3-layer PE coatings are quite resistant to waters at 40°C and 1500 psi but Irathane–155 showed decrease in thickness in liquid as well as vapor phases and also exhibits slight discoloration, swelling and texture appearance in both phases. This is an indication of degradation of Irathane-155 in water under high temperature and pressure. The results of adhesion tests on coatings showed that the binding between the metal substrate and the coating was more than the coating and the dolly. The pull off adhesion tests carried out on coated samples after autoclave tests showed that adhesive strength of all the coating is greater than 500 psi. The flexibility (bending) tests carried out on coatings showed no defect or presence of holidays at the bending site.

Alrudayni, 2015, researched on the evaluation of external coating performance on buried pipelines in the oil and gas industry. His research was designed to evaluate the coating performance of FBE and hybrid epoxy in simulated Arabian Gulf water and simulated soils conditions (Sabkha). The influence of coating damage and disbondment on corrosion resistance was also investigated. Results of his research indicated a reduction in the adhesion bond between the coatings and substrate. The corrosion current density measurements indicated that both media are corrosive. Protective coatings under investigation did not show any blistering effect or color change under test conditions, thus, reflecting their excellent corrosion resistance property.

Wagner 1950, conducted a test on polyethylene wrap in which a six-inch mechanical joint was encased in polyethylene and buried in highly corrosive cinder fill. Two years later, the test section was uncovered and he found out that the mechanical joint, the gland, nuts, bolts, and pipe inside the polyethylene wrap, were in excellent condition. The unprotected section of the pipe outside the wrap was pitted with corrosion.

CHAPTER THREE

MATERIAL AND METHODS

3.1 Material

The specimens of investigation are of the pipeline polyethylene tapes installed on the soil to air transition section for corrosion protection. The soil to air transition section was excavated and the polyethylene tape coating examined. The specimens were taken/examined from different transition point of pipelines within a field in Escravos, Delta State. The equipment used for this project are: Holiday detector (Elcometer 236), Soil Tester (MeggerDET4TCR2) SEM, EIS, Digital Camera. Table 3.1 shows the specification of the organic coated steel used for this experiment. The organic coating is a cold applied high-density polyethylene with butyl rubber adhesive (Denso Butyl 35 Tape) installed in 2005. Specimen 1a, 2a, 3a and 4a were taken from above ground at different transition points and examined and specimen 1b, 2b, 3b and 4b were taken and examined as well from below ground at different transition points.

Table 3.1 Organic Coated Steel Specifications.

Specimen	**Exposure Period**	**Organic Coating system (Tape)**	**Thickness of Coating (μm)**	**Distance from specimen 4 (m)**
Specimen 1	14 years	PE + Butyl rubber adhesive	890	27
Specimen 2	14 Years	PE + Butyl rubber adhesive	890	10
Specimen 3	14 Years	PE + Butyl rubber adhesive	890	35
Specimen 4	14 Years	PE + Butyl rubber adhesive	890	0 (Reference)

Where,

PE – Polyethylene.

Figure 3.1 shows Pipeline 1 segment from which specimen 1a & 1b were taken

Figure 3.2 shows Pipeline 2 segment from which specimen 2a & 2b were taken

Figure 3.3 shows Pipeline 3 segment from which specimen 3a & 3b were taken

Figure 3.4 shows Pipeline 4 segment from which specimen 4a & 4b were taken

3.2 Methods:

3.2.1 Close Visual Examination

The soil to air transition section was excavated and the polyethylene tape coating examined. While polyethylene tape specimens were taken from the pipelines being investigated, the appearance of the specimens were visually observed (Macro examination) to investigate the general condition of rust and coating deterioration such as blisters (Holiday), exfoliation, cracks and scratches. The examination was carried out before and after brushing the surfaces of the polyethylene tape coating samples and a handheld lens used to reveal details that were not very visible unaided.

3.2.2 Soil Resistivity Test

Equipment used: Resistance Meter (Megger DET4TCR2), Test Voltage: 50 V/128Hz, Technique: Wenner four-electrode (IEEE Std 81) method. Wenner four-electrode method was used to measure the electrical resistivity. In this method, four-electrode are driven into the earth along a straight line at equal interval. The depth of the electrode in the ground is of the order of 12cm. The earth megger is placed on a steady and approximately level base. A current is passed through two outer electrodes C_1 and C_2 and the earth. A voltage difference is observed between two inner electrodes P_1 and P_2. The current flowing into the earth produces an electric field proportional to its density and to the resistivity of the soil.

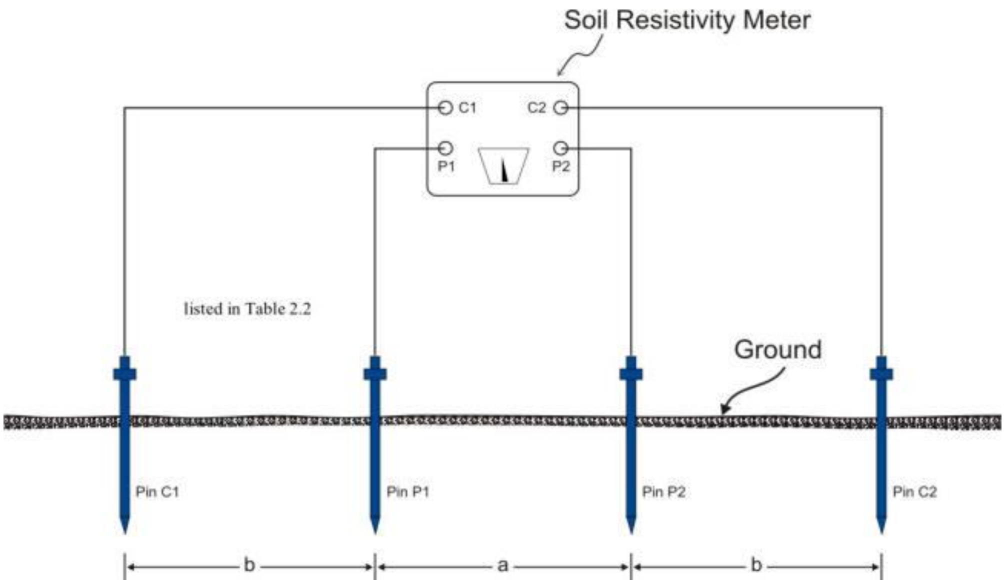


Figure 3.5. Soil Resistivity Test setup

The soil resistivity test was carried out close to the transition section of each pipeline specimen. Wenner four-electrode method and resistance meter (Megger) was used. Readings were taking both parallel and perpendicular to the pipeline direction with electrode distance of 1m, 3m and 5m for each specimen area and an average recorded. Soil Resistivity plays a vital part in determining the earthing grid, depending on the Soil Resistivity the complexity of the earthing grid can be determined, the soil will act as the return path for the fault current to the source, higher soil resistivity will lead to higher earth grid resistance value which means higher voltage rise, this will lead to an unsafe working environment and will have potential of damaging equipment (Salam et al, 2015). These points prove the importance of the soil Resistivity testing. See Table 4.6 for soil resistivity values.

3.2.3. Structural Examination

Model phenom prox scanning electron microscope was used to study the surfaces of the coated tapes and also to obtain an approximation of film thicknesses and compositions. The SEM is equipped with LaB6 electron gun and an EDAX EDS system. For EDS, the software EDAX Genesis was used. All surfaces were studied with both SE and BSE (COMPO mode) detector at one EO (15kv). Correlating simulations were made for complementary information about the information depth. Some of the samples also studied were tilted to 60˚ for better topographical view.

3.2.4 Holiday Test

The holiday test was carried out in accordance with NACE RP-0274 (National Association of Corrosion Engineers, Recommended practice) on the external surface of the coating by applying an electrode brush to the coating surface using a voltage of 600V/100µm to 900V/100µm, to determine the extent of coating failure, holidays or discontinuities. Holiday testing allows the detection of even smallest coating flaws invisible to the naked eye. The coating failure were represented in the form of a profile with the extent depicted in colour-codes for ease of interpretation.

3.2.5 Adhesion Test (Peel-off test)

Adhesion tests on coated polyethylene pipeline tape specimen were carried out under atmospheric condition to ASTM D4541 using Elcometer 106 Adhesion tester. Pull-Off adhesion test methods was employed to determine the adhesive strength of the coatings. Adhesion tester consists of a 20mm dolly, which were glued perpendicular onto the coated surface of the specimen. The dolly cutter was used to cut the coating around to the dolly diameter. After the curing of the adhesive (glue) after 24hours, the magnetic dolly clamp was attached to the dolly and then pulling the dolly by exerting a force perpendicular to the surface in an effort to remove the dolly with the coating from the surface of the specimen. The force applied to the magnetic dolly clamp is then gradually increased and monitored until plug of coating material is detached. When the coating is pulled off the surface, an indicator on the scale shows the numerical value of adhesion strength expressed in terms of the force per unit area required to remove the dolly. Inspection of the dolly face was done to determine the failure mode. These failure modes are shown in Figure 3.6 below.

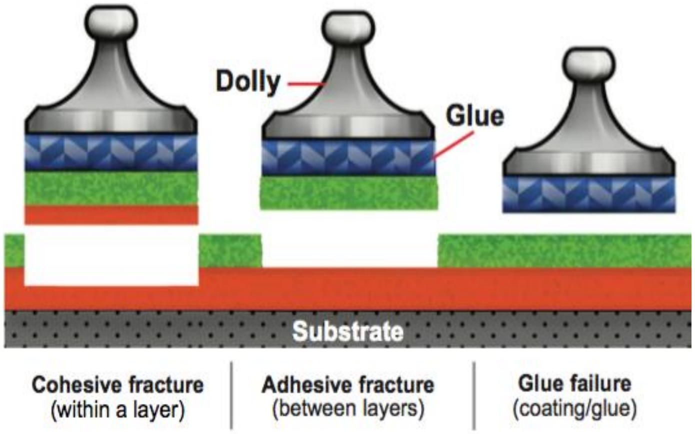


Figure 3.6. Types of coating failure

(Photo Source - Positest AT Automatic Adhesion Tester Product Manual**)**

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

4.1.1. Visual Examination

The appearance of the specimen was visually observed (Macro examination) to investigate the general condition of the external coating and metal surface for rust, undercoating corrosion and coating deterioration. The results are presented in Figure 4.1 to 4.4. A summary of the close visual inspection is found in table 4.1.

Specimen 1a (Above ground) External Tape coating surface

Specimen 1b (Below ground) External Tape coating surface

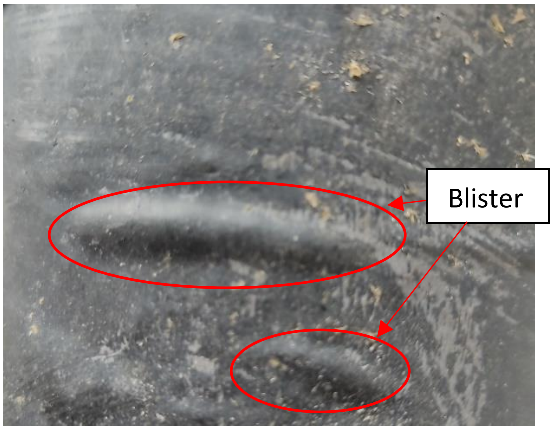
Specimen 1a (Above ground) External metal surface underneath Tape coating

Specimen 1b (Below ground) External metal surface underneath Tape coating

Figure 4.1 Presents the Close Visual Examination of Pipeline 1:

Specimen 1a external Tape coating surface shows minimal degradation (surface abrasion) and blisters while Specimen 1b external Tape coating surface shows more degradation and blisters compared to specimen 1a. Specimen 1a & 1b shows some degree of rust with negligible concerns on pipeline metal surface underneath the tape coating.

Specimen 2a (Above ground) External Tape coating surface



Specimen 2b (Below ground) External Tape coating surface

Specimen 2a (Above ground) External metal surface underneath Tape coating

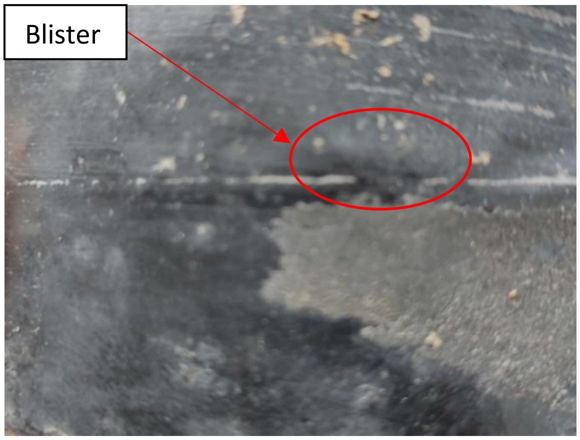
Specimen 2b (Below ground) External metal surface underneath Tape coating

Figure 4.2 Presents the Close Visual Examination of Pipeline 2:

Specimen 2a external tape coating surface was observed with more blisters and degradation while Specimen 2b external tape coating surface was observed also with more blisters and degradation when compared with specimen 2a.

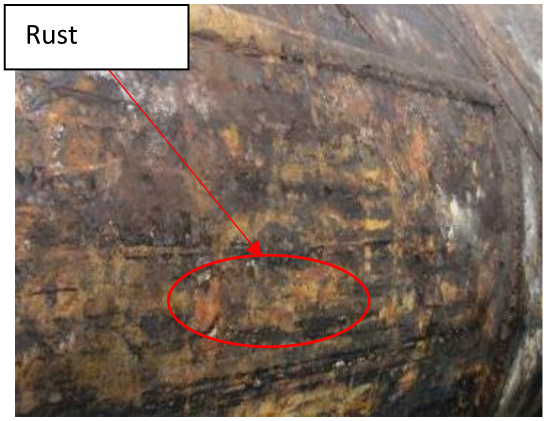
Specimen 2a pipeline metal surface underneath the tape coating shows some minimal localized rust while Specimen 2b shows more general rust on the pipeline metal surface.

Specimen 3a (Above ground) External Tape coating surface



Specimen 3b (Below ground) External Tape coating surface

Specimen 3a (Above ground) External metal surface underneath Tape coating



Specimen 3b (Below ground) External metal surface underneath Tape coating

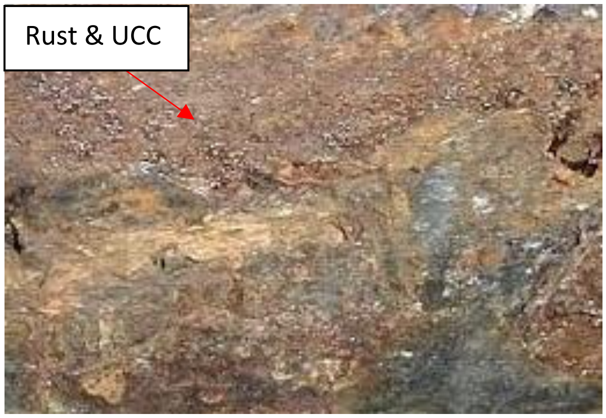
Figure 4.3 Presents the Close Visual Examination of Pipeline 3:

Specimen 3a external tape coating surface was observed with more blisters and general degradation while Specimen 3b external tape coating surface was observed with more blisters and more severe degradation when compared with specimen 3a.

Specimen 3a pipeline metal surface underneath the tape coating shows localized rust while Specimen 3b shows very severe general rusting on the pipeline metal surface.

Specimen 4a (Above ground) External Tape coating surface

Specimen 4b (Below ground) External Tape coating surface



Specimen 4a (Above ground) External metal surface underneath Tape coating

Specimen 4b (Below ground) External metal surface underneath Tape coating

Figure 4.4 Presents the Close Visual Examination of Pipeline 4:

Specimen 4a external tape coating surface was observed with blisters, surface abrasion and significant degradation while Specimen 4b external tape coating surface was observed with prevalent blistering and general degradation.

Specimen 4a pipeline metal surface underneath the tape coating shows severe rusting with active general corrosion on the metal surface while Specimen 4b shows more severe rusting with active general corrosion on the pipeline metal surface when compared with specimen 4b. Corrosion scale build up already taking place.

Table 4.1 The findings from the close visual inspection.

	Test Item	Conditions	PE + Butyl Rubber Adhesive			
Zone			Specimen 1	Specimen 2	Specimen 3	Specimen 4
Above soil level (a)	Pipe Surface	S. A	NF	NF	F	F
	Pipe Surface	U.C.C	NF	F	F	F
	PE Coating	Cracks	NF	NF	NF	NF
	PE Coating	Blistering	F	F	F	F
Below soil level (b)	Pipe Surface	S. A	NF	F	F	F
	Pipe Surface	U.C.C	NF	F	F	F
	PE Coating	Cracks	NF	NF	NF	NF
	PE Coating	Blistering	F	F	F	F

Table definitions: S. A: Surface Appearance (if anomalies are present or not)

U.C.C: Under-Coating Corrosion

NF: Not Found

F: Found

4.1.2 SEM Result

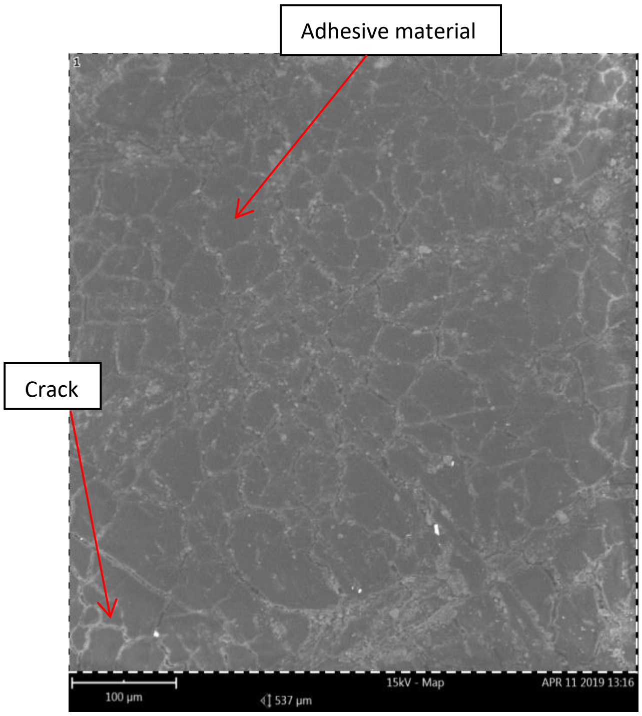


Table 4.2. **Chemical composition of specimen 1a**

Element Number	**Element Symbol**	**Element Name**	**Atomic Conc.**	**Weight Conc.**
6	C	Carbon	85.64	66.65
14	Si	Silicon	5.70	10.37
13	Al	Aluminum	5.07	8.87
26	Fe	Iron	1.01	3.65
83	Bi	Bismuth	0.21	2.83
55	Cs	Caesium	0.27	2.29
47	Ag	Silver	0.27	1.85
11	Na	Sodium	0.57	0.84
12	Mg	Magnesium	0.45	0.70
15	P	Phosphorus	0.33	0.66
16	S	Sulfur	0.31	0.65
23	V	Vanadium	0.20	0.64
6	C	Carbon	85.64	66.65

Figure 4.5 Presents image of SEM of the Tape coating taken above ground from Pipeline 1:

Tape specimen 1a shows no significant evidence of corrosion product on surface of tape/pipe interface. Weblike cracks on the tape surface indicates general adhesive degradation resulting in shrinkage, embrittlement due to long exposure to the elements.

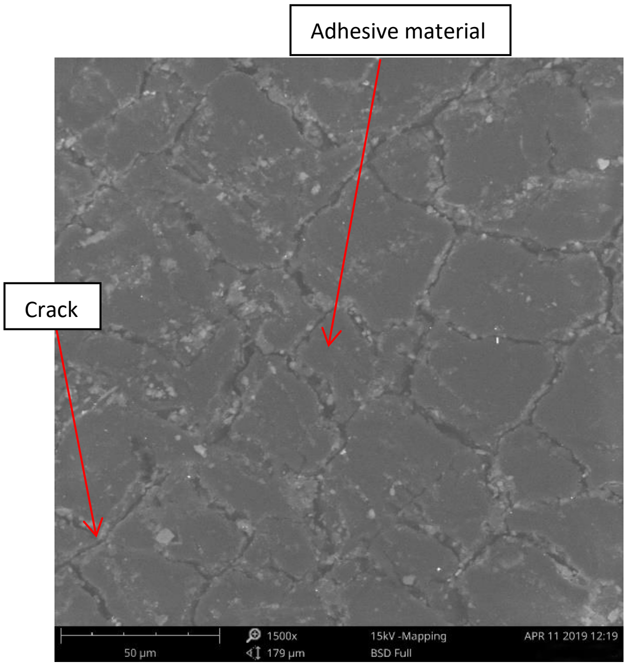


Table 4.3. **Chemical composition of specimen 1b**

Element Number	**Element Symbol**	**Element Name**	**Atomic Conc.**	**Weight Conc.**
6	C	Carbon	87.52	69.41
14	Si	Silicon	4.77	9.62
13	Al	Aluminum	4.12	7.89
26	Fe	Iron	1.11	3.12
83	Bi	Bismuth	0.24	2.72
55	Cs	Caesium	0.26	2.13
47	Ag	Silver	0.25	1.79
11	Na	Sodium	0.52	0.8
12	Mg	Magnesium	0.41	0.65
15	P	Phosphorus	0.31	0.62
16	S	Sulfur	0.29	0.63
23	V	Vanadium	0.20	0.62

Figure 4.6 Presents image of SEM of the Tape coating taken below ground from Pipeline 1:

Tape specimen 1b shows no significant evidence of corrosion product on surface of tape/pipe interface, mere general corrosion. Weblike cracks on the tape surface indicates more general adhesive degradation resulting in shrinkage, embrittlement due to long exposure to the elements as compared to tape specimen 1a.

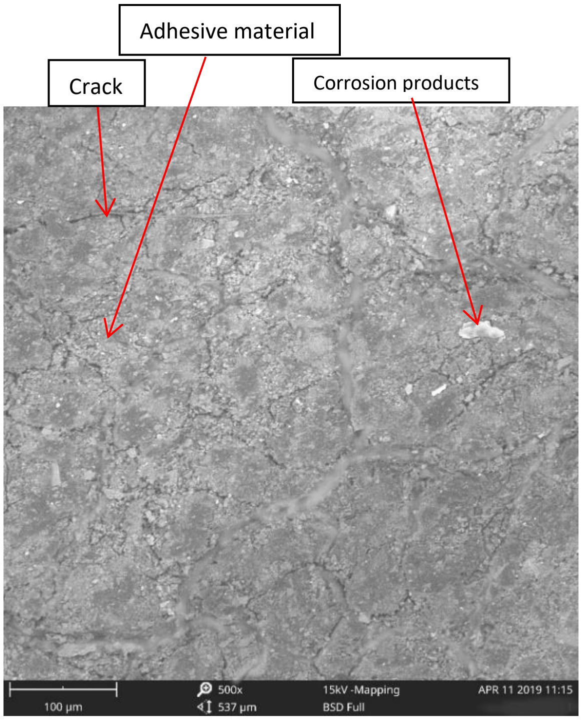


Table 4.4 Chemical composition of specimen 2a

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	91.20	76.20
14	Si	Silicon	3.00	5.86
13	Al	Aluminum	2.48	4.66
55	Cs	Caesium	0.28	2.56
83	Bi	Bismuth	0.17	2.43
26	Fe	Iron	0.44	1.72
20	Ca	Calcium	0.46	1.28
19	K	Potassium	0.33	0.90
11	Na	Sodium	0.55	0.87
51	Sb	Antimony	0.10	0.87
12	Mg	Magnesium	0.41	0.69
16	S	Sulfur	0.29	0.65
52	Te	Tellurium	0.06	0.57

Figure 4.7 Presents image of SEM of the Tape coating taken above ground from Pipeline 2:

Tape specimen 2a shows more evidence of corrosion products on surface of tape/pipe interface. Weblike cracks on the tape surface also indicates general adhesive degradation resulting in shrinkage, embrittlement due to long exposure to the elements.

Table 4.5 Chemical composition of specimen 2b

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	93.01	79.48
14	Si	Silicon	3.04	5.09
13	Al	Aluminum	2.01	4.22
51	Sb	Antimony	0.27	3.72
83	Bi	Bismuth	0.12	1.85
26	Fe	Iron	0.32	1.39
11	Na	Sodium	0.26	0.71
82	Pb	Lead	0.04	0.81
22	Ti	Titanium	0.21	0.74
42	Mo	Molybdenum	0.12	0.7
12	Mg	Magnesium	0.25	0.51
15	P	Phosphorus	0.22	0.43
16	S	Sulfur	0.13	0.35

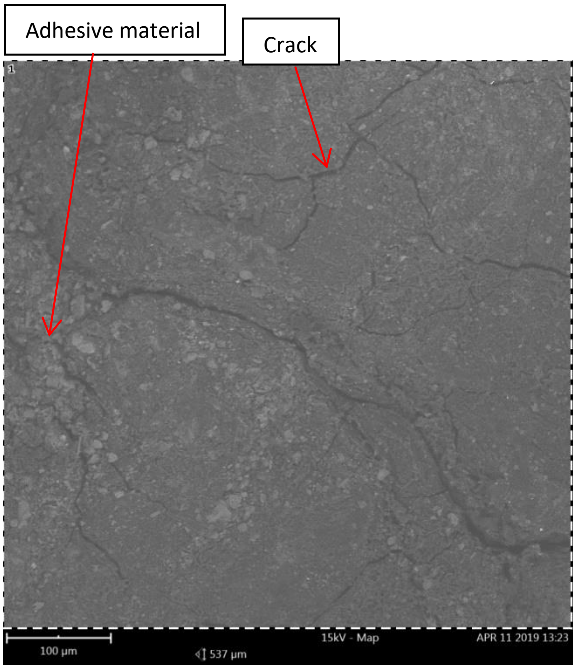


Figure 4.8 Presents image of SEM of the Tape coating taken below ground from Pipeline 2:

Tape specimen 2b shows more evidence of corrosion products on surface of tape/pipe interface compared to specimen 2a. Weblike cracks on the tape surface also indicates general adhesive degradation resulting in shrinkage, embrittlement due to long exposure to the elements. A significant layer of adhesive material also noted on the tape coating surface.

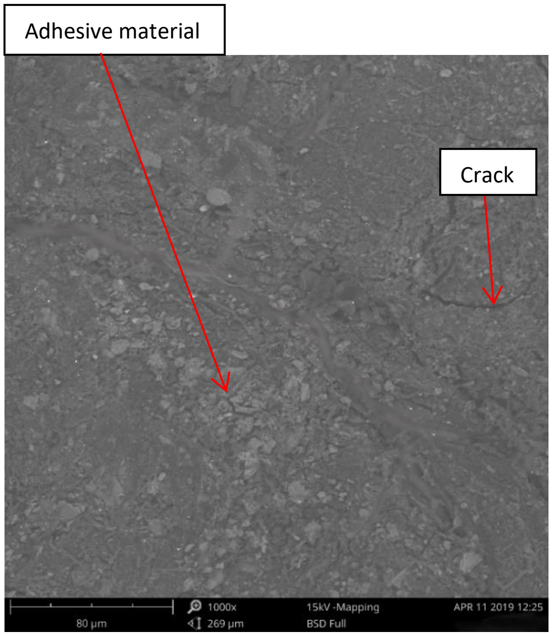


Table 4.6: Chemical composition of specimen 3a.

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	92.15	78.07
14	Si	Silicon	3.05	6.05
13	Al	Aluminum	2.26	4.29
51	Sb	Antimony	0.44	3.74
83	Bi	Bismuth	0.13	1.90
26	Fe	Iron	0.36	1.40
11	Na	Sodium	0.55	0.90
82	Pb	Lead	0.06	0.83
22	Ti	Titanium	0.22	0.75
42	Mo	Molybdenum	0.11	0.72
12	Mg	Magnesium	0.31	0.52
15	P	Phosphorus	0.21	0.46

Figure 4.9 Presents image of SEM of the Tape coating taken above ground from Pipeline 3:

Tape specimen 3a shows more evidence of corrosion products on surface of tape/pipe interface. Weblike cracks on the surface indicates general adhesive degradation resulting in shrinkage, embrittlement due to long exposure to the elements. A significant layer of adhesive material also noted on the tape coating surface.

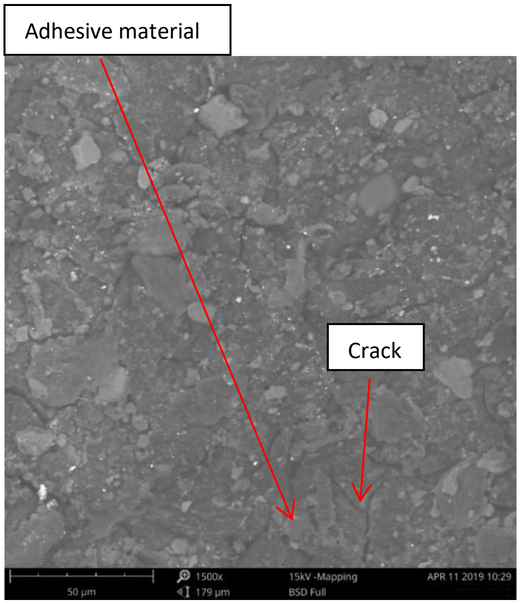


Table 4.7: Chemical composition of specimen 3b.

Element Number	**Element Symbol**	**Element Name**	**Atomic Conc.**	**Weight Conc.**
6	C	Carbon	92.94	79.48
14	Si	Silicon	2.83	5.66
13	Al	Aluminum	2.14	3.95
51	Sb	Antimony	0.41	3.42
42	Mo	Molybdenum	0.09	0.69
83	Bi	Bismuth	0.11	1.81
82	Pb	Lead	0.05	0.81
26	Fe	Iron	0.32	1.33
11	Na	Sodium	0.38	0.89
22	Ti	Titanium	0.17	0.73
15	P	Phosphorus	0.19	0.44
12	Mg	Magnesium	0.26	0.47

Figure 4.10 Presents image of SEM of the Tape coating taken below ground from Pipeline 3:

Tape specimen 3b shows more evidence of corrosion products on surface of tape/pipe interface as compared to specimen 3b. Weblike cracks on the surface indicates general adhesive degradation resulting in shrinkage, embrittlement due to long exposure to the elements. A significant layer of adhesive material also noted on the tape coating surface.

Table 4.8 **Chemical composition of specimen 4a**

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	97.10	89.74
14	Si	Silicon	0.86	1.85
50	Sn	Tin	0.14	1.27
51	Sb	Antimony	0.13	1.25
13	Al	Aluminum	0.60	1.25
82	Pb	Lead	0.08	1.22
47	Ag	Silver	0.10	0.87
11	Na	Sodium	0.28	0.49
22	Ti	Titanium	0.13	0.48
19	K	Potassium	0.14	0.41
20	Ca	Calcium	0.05	0.16
12	Mg	Magnesium	0.21	0.39
56	Ba	Barium	0.02	0.24
16	S	Sulfur	0.09	0.21
15	P	Phosphorus	0.07	0.16

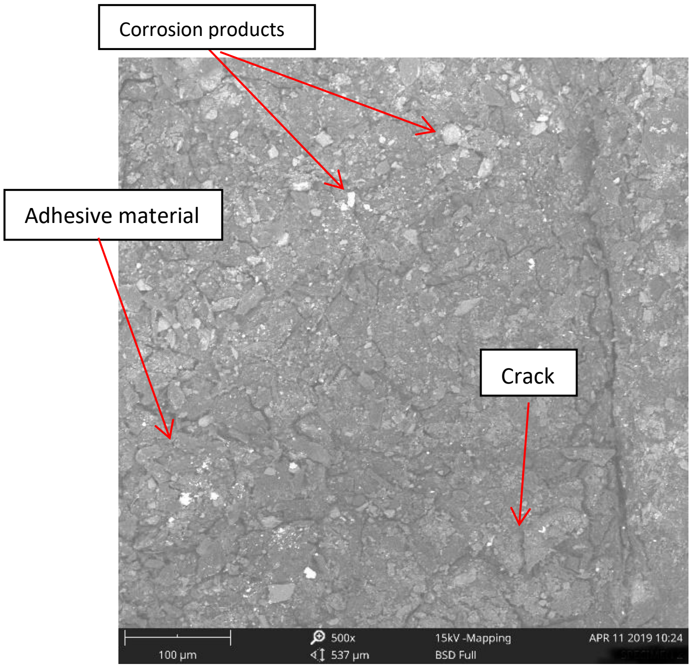


Figure 4.11 Presents image of SEM of the Tape coating taken above ground from Pipeline 4:

Tape specimen 4a shows spread of corrosion products on surface of tape/pipe interface. Weblike cracks on the surface indicates general adhesive degradation resulting in shrinkage, embrittlement due to long exposure to the elements. A significant layer of adhesive material also noted on the tape coating surface.

Table 4.9 **Chemical composition of specimen 4b**

Element Number	**Element Symbol**	**Element Name**	**Atomic Conc.**	**Weight Conc.**
6	C	Carbon	98.11	89.99
14	Si	Silicon	0.49	1.79
50	Sn	Tin	0.13	1.25
51	Sb	Antimony	0.11	1.23
82	Pb	Lead	0.06	1.19
47	Ag	Silver	0.07	0.85
11	Na	Sodium	0.15	0.46
19	K	Potassium	0.12	0.44
22	Ti	Titanium	0.1	0.41
56	Ba	Barium	0.01	0.23
12	Mg	Magnesium	0.14	0.43
16	S	Sulfur	0.07	0.22
15	P	Phosphorus	0.05	0.14
20	Ca	Calcium	0.02	0.15

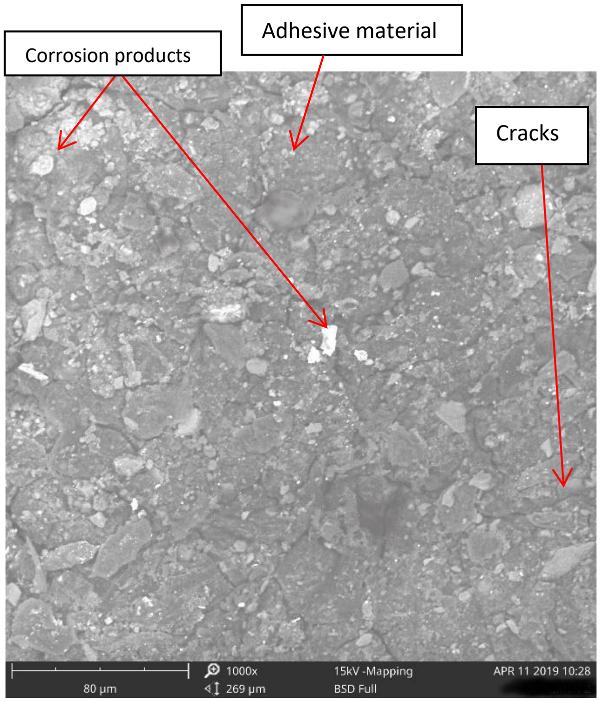


Figure 4.12 Presents image of SEM of the Tape coating taken below ground from Pipeline 4:

Tape specimen 4b shows more spread of corrosion products on the surface of tape/pipe interface and evidence of scaling. Weblike cracks on the surface indicates general adhesive degradation resulting in shrinkage, embrittlement due to long exposure to the elements. A significant layer of adhesive material also noted on the tape coating surface.

4.1.3. Soil Resistivity Test Result

The results from the soil resistivity test are shown in Table 4.10.

Table 4.10.

Specimen	Soil Resistivity (Ω.cm)	Corrosivity rating
Specimen 1 location	9800	Mildly corrosive
Specimen 2 location	8300	Mildly corrosive
Specimen 3 location	8600	Mildly corrosive
Specimen 4 location	8900	Mildly corrosive

4.1.4. Adhesive Test Result

The results obtained here shows that the bond between the metal surface and adhesive/tape are good but prolong exposure to the field environment resulted in the deterioration at the metal surface/adhesive interface for both above and below ground.

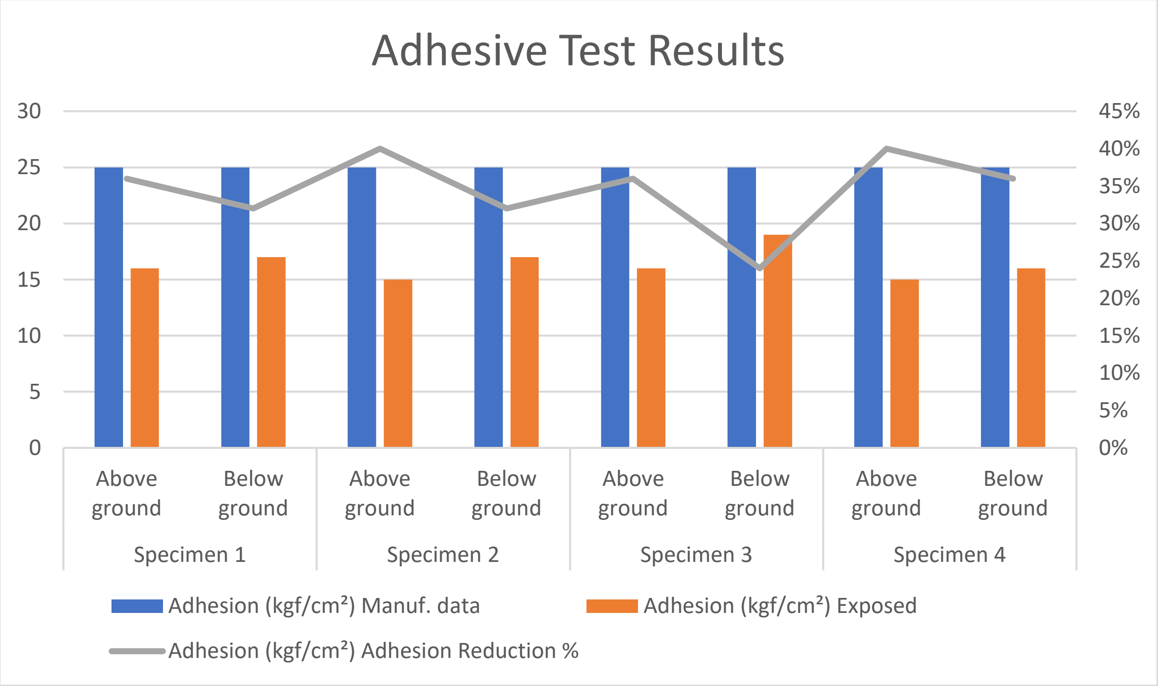


Figure 4.13. Showing graphical representation of Adhesive test result.

The result from the graph shows reduction in adhesive strength ranging from 24% to 40%. Strength reduction is more above ground due to high variation in exposure to weather elements**.**

4.1.5. Holiday Test Result

The results from the holiday tests are as shown below.

The Figures shows scan of 12 inches (two scans of 6 inches each) taken above and below ground with the area of discontinuity noted. The sum of areas of discontinuities indicated from the test with reference to the total area tested per section is used to determine the percentage area of discontinuity.

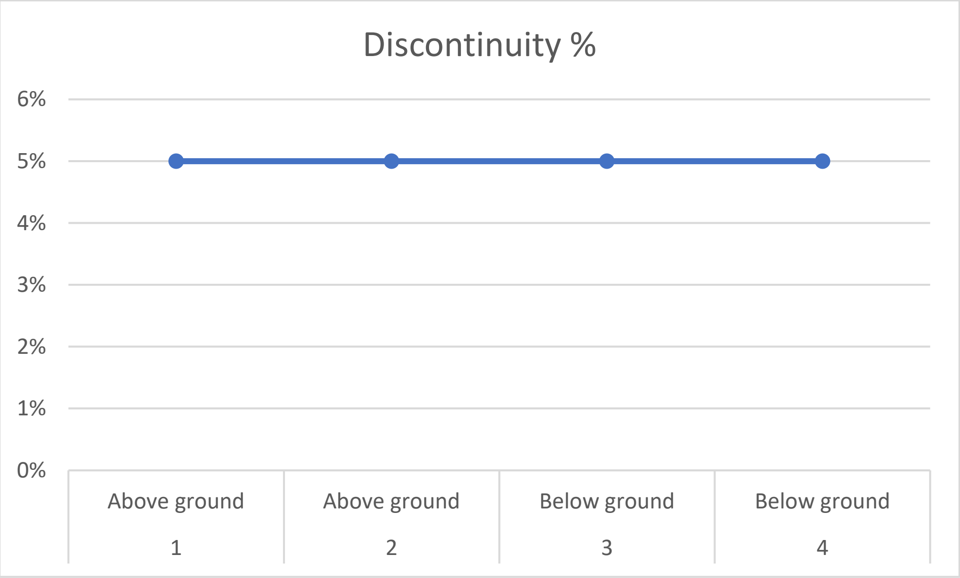


Figure 4.14 Shows graphical presentation of percentage discontinuity from scan on specimen 1 from Pipeline 1**.**

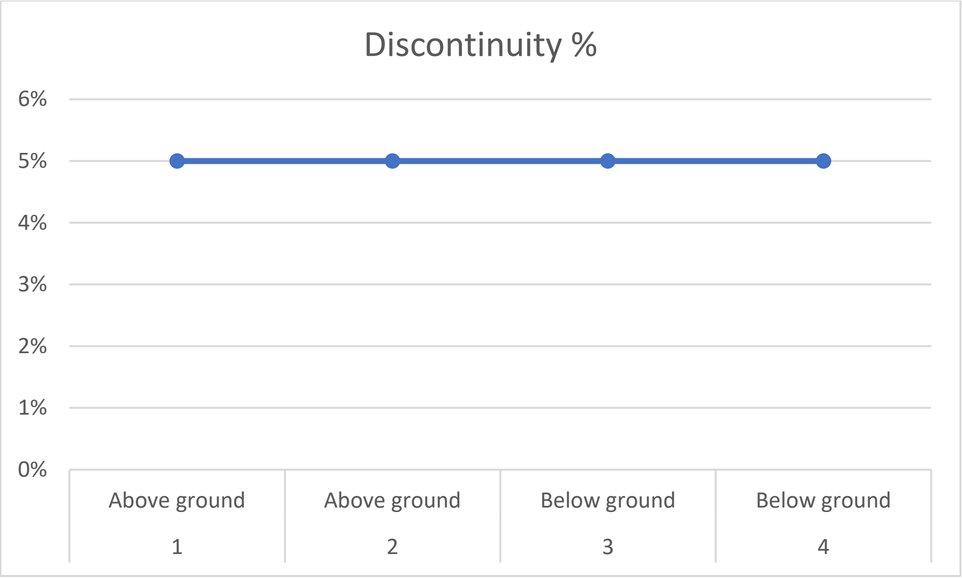


Figure 4.15 Shows graphical presentation of percentage discontinuity from scan on specimen 2 from Pipeline 2.

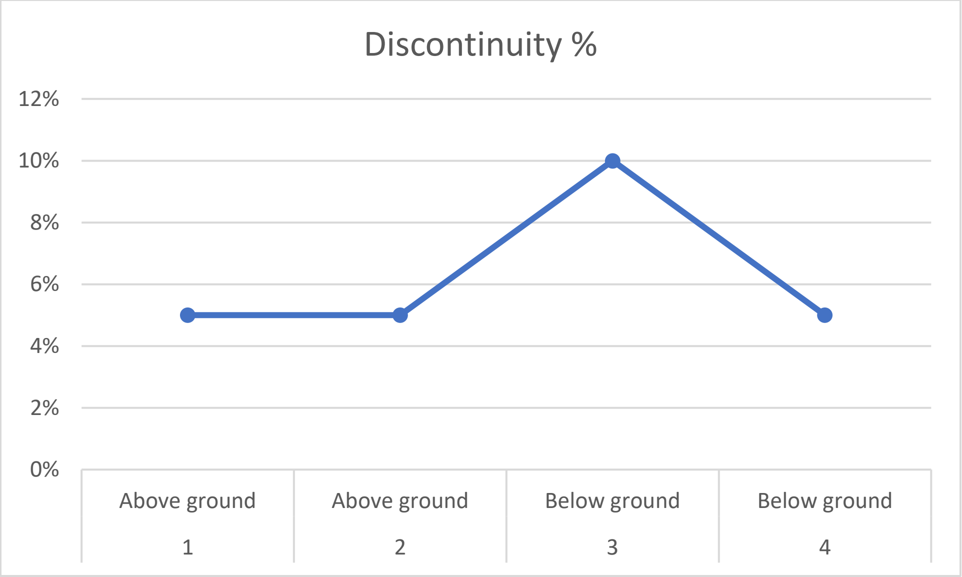


Figure 4.16 Shows graphical presentation of percentage discontinuity from scan on specimen 3 from Pipeline 3.

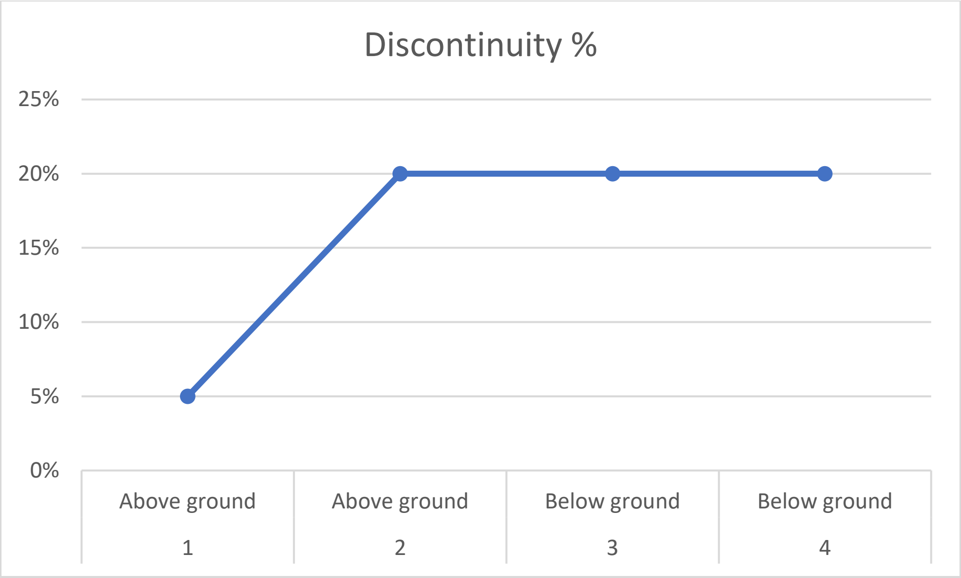


Figure 4.17 Shows graphical presentation of percentage discontinuity from scan on specimen 4 from Pipeline 4.

4.2 Discussion

4.2.1 Close Visual Examination Results on the Effectiveness of Organic Coating (Tapes) on the Corrosion of Mild Steels

The visual examination of the results in fig 4.1 to 4.4 shows that there was degradation on the tape coating surface and rusting on the pipeline metal surface, both for above ground and below ground. The tape coating degradation seems to increase from specimen 1 to specimen 4. This can be attributed to specimen 1 been farthest from human activities while specimen 4 is the closest. Human activities around the tape coating could have affected the ability of the polyethylene tape coating to function as effectively, however, specimen 1 to 3 still shows a good resistance against mechanical coating damage which is in agreement with Yoshiyuki et al,1990, whose survey indicated that polyethylene coating has good resistance against mechanical coating damage but differ in terms of corrosion protection where Yoshiyuki et al,1990 noted that polyethylene coating provided good corrosion protection over the 14years period covered by their survey, specimen 1 to 4 did not provide the same protection after 14years. This can be attributed to the form in which the polyethylene coating is applied, one as an organic coating (paint) while the other as an organic coating (Tape).

It is worthy to note that a polyethylene tape coating does not provide a continuous spread on the pipeline metal surface, rather it has points of joining as it spirals around the pipeline section. These joints are the easiest points of failure especially from mechanical damages from human interactions giving rise to water/moisture ingress at failed edges, areas of pinholes or other exposed area causing localized to general external corrosion on the pipeline metal surface.

The external surfaces of the polyethylene tape coating have lost its luster due to exposure to the elements. The tape coating system on Pipelines 1 to 4 (Fig 4.1 to 4.4) was noted to withstand the external abrasive impacts from the soil due it’s good resistance to abrasion and good elastic property. This is evident in the level of degradation (abrasion) observed on the coating surface and further confirmed the good resistance against mechanical coating damage noted by Yoshiyuki et al,1990.

The evidence of blistering prevalent on the surfaces of the polyethylene tape coating may have resulted from thermal expansion and contraction of locally failed/disbonded sections with trapped air known as holiday. These holidays which could be introduced at the point of installation or when the tape coating begin to fail is exposed to temperature variation from flowing crude oils or atmospheric, causing the trapped air to undergo thermal expansion and contraction leading to the growth of blisters which may not be readily visible initially but become visible over time.

4.2.2 Scanning Electron Microscopy Results on the Effectiveness of Organic Coating (Tapes) on the Corrosion of Mild Steels

The results from the SEM analysis shown on figure 4.5 to 4.12 indicates the spectra on the surfaces are consistent with the visual observation and the presence of iron on polymer sides proved that the failure is at the adhesive/metal oxide layer. This is in agreement with Ismaliza et al, 2013, who experimented on Evaluation of Rubber/Mild Steel Bonds Failure after Exposure in Marine Environment. The SEM images from that experiment discovered mark of grit line on the failed rubber surfaces suggested that the failure is at the primer/metal interface, which is similar results with Ismaliza et al, 2013, even though the test environment was different. The chemical composition on the surfaces of the tape specimen further indicates a superficial external corrosion on pipelines 1 to 3, including 4a of pipeline 4 while 4b indicates a more active external corrosion compared to the other specimens and supports that the failure was from corrosion activities on the adhesive/metal interface . The evidence of coagulation failure was noted, with cracks prevalent due to contraction of the adhesive material from long exposure.

The presence of metallics particles on the micrograph, more visible on specimen 4a & b agree with the visual evidence of undercoating corrosion on the metal surface.

4.2.3 Soil Resistivity Result on the Effectiveness of Organic Coating (Tapes) on the Corrosion of Mild Steels

Results from the soil resistivity test shows that the soil on which the specimens were evaluated has resistivity values that indicates a mildly corrosive soil. The result in Table 4.10 revealed that the coating evaluation of the polyethylene tape coating on all specimen provided similar corrosion protection in the mildly corrosive environment over the 14year period as evident from the visual examination.

Specimen 1 shows a higher corrosion resistance than specimen 2 to 4 which can be attributed to the higher soil resistivity around specimen 1. This is supported by Lim et, al 2013, who in their article, The Relationship between Soil Resistivity and Corrosion Growth in Tropical Region noted that the higher the soil resistivity, the lower the corrosivity.

Other factors such soil type (ability to retain water) and human interaction could have accelerated the corrosion noted on specimen 2 to 4 making the correlation between the soil resistivity and its corrosivity not evident as Polyethylene has immunity to large variations in pH as noted in the investigation carried out on Organic coating (Polyethylene coating) by Amadi et al, 2014.

4.2.4 Adhesion Result on the Effectiveness of Organic Coating (Tapes) on the Corrosion of Mild Steels

The results obtained here implies that the bonding between the coating and dolly was more than the substrate and the metal surface hence the failures were coagulative in nature between the metal surface and adhesive layer for above and below ground. There is evidence of reduced adhesive strength when compared to manufacturer's adhesive strength values. This is shown in Figure 4.13. Figure 4.5 to 4.12 shows adhesive layers that have hardened, became brittle (visible weblike cracks from images) and lost its ductility to resist impact/movement from service conditions. The butyl rubber adhesives used as bonding layer, the metal surface corrode, and such corrosion process may compromise the performance of the adhesive surface, either at the bonded interface or adjacent to it. There are three distinct failure processes could occur on the adhesive joint durability; interfacial failure due to water hydrolysis of the adhesive from the substrate, the degradation of the adhesive itself in the service environments, and the interfacial failure as a result of cathodic or anodic activity at the substrate, referred to as either cathodic delamination or anodic undermining (Watts, 2010). This is in agreement with Ismaliza et al, 2013, whose experiment on Evaluation of Rubber/Mild Steel Bonds Failure after Exposure in Marine Environment, where the failure was at the primer/metal interface also exhibited similar results even though the test environment was different.

The adhesion strength that was reduced significantly over time is also in agreement with Yoshiyuki et al., 1990, whose experiment involved exposure of polyethylene coating in a marine environment for 15 years observed significant adhesion strength reduction. The percentage reduction in adhesion strength from this evaluation was between 24% to 40% which is more than that gotten by Yoshiyuki et al., 1990, which stood at 4% to 24% at different test environments.

The percentage reduction of adhesion strength was also noted to be more on the specimen above ground than specimen below ground. This can be attributed to the higher temperature variation and exposure to ultraviolet rays by the specimen above ground resulting in higher adhesive deterioration when compared to the specimen below ground that are not directly exposed to sunlight.

The works of Amadi et al, 2014 and Malik et al., 1999 had limited exposure time hence the deterioration at the adhesive layer was no significant hence the coating adhesion was significantly good and failure from adhesive tests was at the dolly/coating interface.

4.2.5 Holiday Test Result on the Effectiveness of Organic Coating (Tapes) on the Corrosion of Mild Steels

Results from the holiday test assessing the areas of Tape coating discontinuity (Disbondment) are shown in Figure 4.14 to 4.17. The profile of the polyethylene tape is measured 6 inches length in the axial direction per section under assessment, from above grade toward below grade. Discontinuity in the surface adhesion (Holiday) was noted on all the specimens between the Polyethylene tape coating and the pipeline external. This is like the failure observed by Alrudayni, 2015. The transformation of the adhesive layer from a soft and high adhesive strength material with high surface energy to a hard and brittle material (as evident on the SEM image) also contributed to the disbondment as the tape resistance to mechanical and thermal stresses are reduced. Trapped air within the system during installation could not be ruled out as the cause of the micro void space (holiday) underneath the polyethylene tape coating. The process of cold installing of the tape does not normally include holiday tests after installation hence no valid record to show the absence of holiday.

Specimen 4 was noted with the most discontinuity which could be attributed to external factors from human interaction. This could have cause failures at the tape edges allowing moisture ingress and subsequent under-coating corrosion.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The study carried out was to evaluate the organic coating (polyethylene tapes) performance on the soil to air interface of mild steels pipelines. Having evaluated the specimens, the following conclusions were made:

i. The evaluated results shown in table 4.1, the polyethylene tape coating provided good resistance against coating damage however, its limitation in providing effective corrosion protection is born from the fact that organic tape coating (Polyethylene Tape) does not provide a continuous spread over the pipeline surface, leaving multiple break points for failure other than through hole failure to occur.

ii. The results from the SEM analysis from tape Specimens 1a & 1b, 2a & 2b, 3a & 3b and 4a & 4b (Pipelines 1, 2, 3 and 4) indicates that the surfaces were consistent with the visual observation and the presence of metallics particles on polyethylene tape coating surfaces shows that the failure is at the adhesive/metal interface and undercoating corrosion (UCC) is taking place, however, it was less on specimens 1a & 1b compared to other specimens.

iii. The results from the Adhesion test failure of the adhesive bond suggested that the bond failure of the butyl rubber to metal surface may have been caused by a corrosion reaction which is evident on the SEM images and chemical compositions.

iv. The Adhesion test, Holiday test and SEM analysis shows that an organic tape coating that maintains a high mechanical and adhesion properties for a long time is required to inhibit corrosion and prevent delamination. Organic tape–metal bonding with butyl rubber adhesive layer exhibited higher surface energy (manufacturer’s data), which normally translates in high adhesion to the metal substrate, however, it is dependent on the quality control process during installation.

v. Results from the soil resistivity test shown in Table 4.10 shows that the soil on which the specimens were evaluated has resistivity values that indicates a mildly corrosive soil, but the correlation between soil resistivity and the polyethylene tape coating deterioration could not be established.

vi. Tape coating will serve better in an environment void of human activity which can inflict external damages which can accelerate the rate of failure.

5.2. Recommendation

1. This investigation was limited to one type of organic tape coating (Polyethylene Tape), further investigation is recommended for other organic tape coating use for corrosion protection of pipeline transition sections.

2. An investigation on pipelines with Tape coating installed on soil with a different resistivity, a lesser resistivity preferable be investigated to established the effect of soil resistivity on Polyethylene tape coating which could not be fully establish in this investigation.

3. It is also recommended that other modern techniques such as Electrochemical Impedance Spectroscopy (EIS) be used to characterize the electrical properties of organic coatings and their adhesion to metal surfaces as numerous ways exist to study the effectiveness of polymer-metal adhesion, which includes adhesion test carried out in this investigation. This will provide the unique advantages of impedance techniques where data relating to the coating performance can be obtained in situ, in a non-destructive manner, leading to a detailed understanding of the probable mechanism of adhesion loss. It should be noted that possibility for destructive examination on pipeline coating may not always be possible.

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APPENDIX

Table 6.1: Field readings of soil resistivity value for the various specimen sites.

Specimen	Soil Resistivity (Ω.cm)	Soil Resistivity (Ω.cm)	Soil Resistivity (Ω.cm)	Soil Resistivity (Ω.cm)	Average Soil Resistivity (Ω.cm)
Specimen 1 location	9900	9800	9600	9900	**9800**
Specimen 2 location	8900	9000	9100	8600	**8900**
Specimen 3 location	8700	8500	8600	8600	**8600**
Specimen 4 location	8600	8200	8100	8300	**8300**

Soil Resistivity Test

Equipment: Resistance Meter (Megger DET4TCR2)

Test Voltage: 50 V/128Hz

Technique: Wenner four-electrode method

Figure 6.1: Test kit

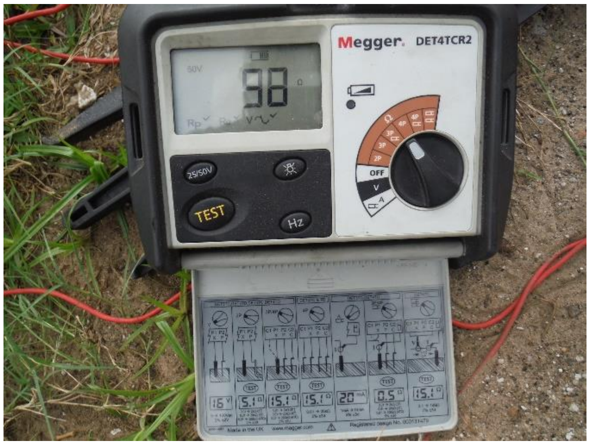

Figure 6.2: Resistance meter display

Holiday test

Equipment: Elcometer 236

Coating type: Polyethylene tape

Test Voltage: 600 V/100µm to 900 V/100µm

Technique: NACE RP 0274

Figure 6.3: Voltage set up

Table 6.2. Data from scan carried out on specimen 1 from Pipeline 1.

No.	Section	Scan size (Inch)	Discontinuity %
1	Above ground	6	5%
2	Above ground	6	5%
3	Below ground	6	5%
4	Below ground	6	5%

Table 6.3. Data from scan carried out on specimen 2 from Pipeline 2

No.	Section	Scan size (Inch)	Discontinuity %
1	Above ground	6	5
2	Above ground	6	5
3	Below ground	6	5
4	Below ground	6	5

Table 6.4. Data from scan carried out on specimen 3 from Pipeline 3

No.	Section	Scan size (Inch)	Discontinuity %
1	Above ground	6	5
2	Above ground	6	5
3	Below ground	6	10
4	Below ground	6	5

Table 6.5. Data from scan carried out on specimen 4 from Pipeline 4

No.	Section	Scan size (Inch)	Discontinuity %
1	Above ground	6	5
2	Above ground	6	20
3	Below ground	6	20
4	Below ground	6	20

SEM Analysis

Equipment: SEM Machine Model Phenom ProX

Figure 6.4: SEM machine setup

Adhesion testing

Table 6.2: Field data from adhesion testing

PE Specimen	Zones	Adhesion (kgf/cm²)	Adhesion (kgf/cm²)	Adhesion (kgf/cm²)	Average Adhesion (kgf/cm²)
Specimen 1	Above	16	16	17	16
	Below	17	16	18	17
Specimen 2	Above	15	16	14	15
	Below	17	16	17	17
Specimen 3	Above	16	17	16	16
	Below	19	19	20	19
Specimen 4	Above	16	15	15	15
	Below	16	16	16	16

Table 6.3: The adhesive strength of organic coating (Polyethylene tape) exposed for 14 years

		Adhesion (kgf/cm²)			
Specimen	Zone	Manuf. data	Exposed	Adhesion Reduction %	Remark
Specimen 1	Above ground	25	16	36%	Coagulation Failure. Adhesive failure between adhesive layer and pipe surface.
	Below ground	25	17	32%	Coagulation Failure. Adhesive failure between adhesive layer and pipe surface.
Specimen 2	Above ground	25	15	40%	Coagulation Failure. Adhesive failure between adhesive layer and pipe surface.
	Below ground	25	17	32%	Coagulation Failure. Adhesive failure between adhesive layer and pipe surface.
Specimen 3	Above ground	25	16	36%	Coagulation Failure. Adhesive failure between adhesive layer and pipe surface.
	Below ground	25	19	24%	Coagulation Failure. Adhesive failure between adhesive layer and pipe surface.
Specimen 4	Above ground	25	15	40%	Coagulation Failure. Adhesive failure between adhesive layer and pipe surface.
	Below ground	25	16	36%	Coagulation Failure. Adhesive failure between adhesive layer and pipe surface.

Table 6.2: Pipeline specification

API 5L X56 Specifications	**Chemical Composition**	**Yield Strength** min. (KSI)	**Tensile Strength** min. (KSI)	**Yield to Tensile** Ratio (max)	**Elongation %**
	C (0.16) **Si (**0.45) **Mn** (1.65) **P** (0.020) **S** (0.010) **V (**0.07) **Nb (**0.05) **Ti (**0.04)	56	71	0.93	19