UNIVERSITI TEKNIKAL MALAYSIA MELAKA

EVALUATION OF ALOE VERA EXTRACT AS AN ECO-FRIENDLY COROSSION INHIBITOR FOR CARBON STEEL IN 5M HCl, RIVER WATER AND 3.5wt.% NaCl MEDIUM

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A thesis submitted
in fulfillment of the requirements for the degree of
Bachelor of Mechanical Engineering Technology (Technology Maintenance) with Honours

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2024

DECLARATION

I declare that this project entitled “Evaluation of Aloe Vera Extract as an Eco-Friendly Corrosion Inhibitor for Carbon Steel in 5M HCl, River Water and 3.5wt.% NaCl Medium” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor of Mechanical Engineering Technology (Technology Maintenance) with Honours.

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DEDICATION

I dedicate this project to my family, whose unwavering love and support have been my guiding light throughout this journey. Your encouragement and belief in me have inspired me to reach new heights and overcome challenges.

To my friends, thank you for standing by my side and providing a constant source of motivation. Your camaraderie and shared experiences have made this project all the more meaningful and enjoyable.

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Lastly, I dedicate this project to myself—to the countless hours of hard work, determination, and perseverance. This is a testament to my commitment to excellence and personal growth.

May this project contribute to the field of study and inspire future students on their own academic journeys.

Thank you.

ABSTRACT

The corrosion of carbon steel in aggressive environments poses significant challenges in various industries, including oil and gas and marine applications. Corrosion refers to the gradual deterioration or degradation of a material, typically a metal, due to chemical or electrochemical reactions with its surrounding environment. It can cause equipment and machinery to malfunction, resulting in accidents or financial losses. Corroded metal can also release toxic substances, posing health risks and environmental hazards. Corrosion gives significant economic costs, requiring expensive maintenance and repairs, and it can cause physical injuries due to sharp edges or weakened structures. It is a natural process that occurs when metals are exposed to various factors such as moisture, oxygen, acids, salts, or other corrosive substances. In an effort to develop eco-friendly corrosion inhibitors, this project focuses on evaluating the effectiveness of Aloe Vera extract as a potential inhibitor for carbon steel in three different media which is river water, 3.5wt.% NaCl and 5M HCl medium. The objectives of this study is to evaluate the effectiveness of green inhibitors derived from natural sources which is aloe vera extract in preventing corrosion of metal surfaces in different mediums, to investigate the influence of the immersion period on the inhibition efficiency of the green inhibitors and also to compare the inhibition efficiency of aloe vera leaves as plant-based green inhibitors of low carbon steel in three different mediums. The experimental study involves immersing low carbon steel in river water, 3.5wt.% NaCl and 5M HCl medium. In this research study, a mechanical testing had been done, which is to evaluate the analysis of the hardness and microstructure of the low carbon steel. The sample has been divided into two sample which is in medium with and without the presence of aloe vera extract. Each medium from each sample contained six low carbon steel specimen and has been observed for 7, 14, 21, 28 and 35 days. The specimen had been taken out according to the days that were required, and the result was observed by visual inspection and calculation of weight loss measurement, corrosion rate and inhibitor efficiency. The mechanism of absorbtion of inhibitors on the surface of low carbon steel materials had been studied by using Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray (EDX). The SEM study of the surface on low carbon steel was done to prove the effectiveness of the eco-friendly inhibitor as a corrosion preventative. Total weight loss result after 35 days for specimen in 5M HCl with the absence of aloe vera extract is 1.297 gram which is higher compared to specimen in 5M HCl with the presence of aloe vera extract, 0.722 gram. Corrosion rate for specimen in 5M HCl with the absence of aloe vera extract is 0.0175 mm/year which is compared to specimen in 5M HCl with the presence of aloe vera extract, 0.0097 mm/year. SEM and EDX analysis proved that specimen surface in 5M HCl with the absence of aloe vera extract got the most pitting and has more corroded compared to specimen surfaces in 5M HCl with the presence of aloe vera extract. Inhibitor efficiency percentages 5M HCl has the highest percentages which is 57.5%. The findings of this study hold significant implications for the development of eco-friendly corrosion inhibitors derived from natural sources. Aloe vera extract shows promising potential as an alternative to traditional inhibitors, providing a sustainable and environmentally friendly solution for corrosion protection of carbon steel in aggressive environments.

ABSTRAK

Hakisan keluli karbon dalam persekitaran yang agresif menimbulkan cabaran yang ketara dalam pelbagai industri seperti minyak dan gas dan marin. Hakisan merujuk kepada kemerosotan dan kakisan secara beransur yang biasa terjadi kepada logam akibat tindak balas kimia atau elektrokimia terhadap persekitaran sekeliling. Ia boleh menyebabkan peralatan dan jentera mengalami kerosakan, yang boleh menyebabkan kemalangan atau kerugian kewangan. Logam yang teroksidasi juga boleh melepaskan bahan toksik, yang boleh mengancam kesihatan dan membawa risiko kepada alam sekitar. Hakisan memberikan kos ekonomi yang signifikan, memerlukan penyelenggaraan dan pembaikan yang mahal, dan ia boleh menyebabkan kecederaan fizikal disebabkan oleh tepi tajam atau struktur yang lemah. Ia adalah proses semula jadi yang berlaku apabila logam terdedah kepada pelbagai faktor seperti kelembapan, oksigen, asid, garam, atau bahan menghakis lain. Dalam usaha membangunkan perencat kakisan mesra alam, projek ini memberi tumpuan kepada penilaian keberkesanan ekstrak lidah buaya sebagai perencat berpotensi untuk keluli karbon dalam tiga media berbeza iaitu air sungai, larutan 3.5*wt.% NaCl* dan larutan 5M *HCl*. Objektif kajian ini adalah untuk menilai keberkesanan perencat hijau yang diperolehi daripada sumber semula jadi iaitu lidah buaya dalam mencegah kakisan permukaan logam dalam medium yang berbeza, untuk menyiasat pengaruh tempoh rendaman terhadap kecekapan perencatan perencat hijau dan juga untuk membandingkan kecekapan perencatan daun aloe vera sebagai perencat hijau berasaskan tumbuhan keluli karbon rendah dalam tiga medium berbeza. Dalam kajian penyelidikan ini, ujian mekanikal telah dilakukan untuk menganalisis kekerasan dan mikro struktur keluli karbon rendah. Sampel telah dibahagikan kepada dua sampel iaitu dengan dan tanpa kehadiran ekstrak lidah buaya. Setiap medium daripada setiap sampel akan mengandungi enam spesimen keluli karbon rendah dan perlu diperhatikan selama 7, 14, 21, 28 dan 35 hari. Spesimen akan dibawa keluar mengikut hari yang diperlukan, dan hasilnya akan diukur melalui pemeriksaan visual dan pengiraan ukuran penurunan berat badan, kadar kakisan dan kecekapan perencat. Mekanisme penyerapan perencat pada permukaan bahan keluli karbon rendah telah dikaji dengan menggunakan Pengimbas Elektron Mikroskopik (SEM) dan Sinar-X Penyebaran Tenaga (EDX). Kajian SEM ke atas permukaan keluli karbon rendah dilakukan untuk membuktikan keberkesanan perencat mesra alam sebagai pencegahan kakisan. Jumlah hasil penurunan berat selepas 35 hari untuk spesimen dalam 5M *HCl* dengan ketiadaan ekstrak lidah buaya ialah 1.297 gram lebih tinggi berbanding spesimen dalam 5M *HCl* dengan kehadiran ekstrak lidah buaya, 0.722 gram. Kadar kakisan untuk spesimen dalam 5M *HCl* dengan ketiadaan ekstrak lidah buaya ialah 0.0175 mm/tahun dibandingkan dengan spesimen dalam 5M *HCl* dengan kehadiran ekstrak lidah buaya, 0.0097 mm/tahun. Analisis SEM dan EDX membuktikan bahawa permukaan spesimen dalam 5M *HCl* dengan ketiadaan ekstrak lidah buaya mendapat lubang yang paling banyak dan lebih berkarat berbanding permukaan spesimen dalam 5M *HCl* dengan kehadiran ekstrak lidah buaya. Peratusan kecekapan perencat 5M *HCl* mempunyai peratusan tertinggi iaitu 57.5%. Penemuan kajian ini mempunyai implikasi yang signifikan untuk pembangunan perencat kakisan mesra alam yang berasal dari sumber semula jadi. Ekstrak lidah buaya menunjukkan potensi yang menjanjikan sebagai alternatif kepada perencat tradisional, menyediakan penyelesaian yang mapan dan mesra alam untuk perlindungan kakisan keluli karbon dalam persekitaran yang agresif.

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LIST OF SYMBOLS AND ABBREVIATIONS

SEM	-	Scanning Electron Microscopy
EDX	-	Energy Dispersive X-Ray
W_0	-	Weight absence of inhibitor
Wi	-	Weight presence of inhibitor
I.E(%)	-	Percent inhibitor efficiency
mm/yr	-	Milimeter per year
HCl	-	Hydrochloric acid
NaCl	-	Sodium Chloride
ATR–FTIR	-	Fourier transform infrared spectroscopy
g	-	Gram
L	-	Litre
ml	-	Mililitre
g/L	-	Gram per litre
M	-	Mol/L

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Carbon steel is a type of steel that contains mainly carbon, with trace amounts of amounts of Manganese (Mn), Silicon (Si), Phosphorus (P), and Sulfur (S). It is a popular material in many industries due to its excellent mechanical properties, low cost, and versatility. Carbon steel is classified based on the amount of carbon it contains, which affects its properties. On top of that, the carbon content may be modified to produce various mechanical properties like strength, ductility, hardness, and so on. Carbon steels are often utilized in an expansion of applications, along with structural components such as steel frame structures, automotive tubing, device parts, and cookware (Dwivedi, Lepková and Becker, 2017). However, carbon steel is susceptible to corrosion, particularly in environments with high humidity, saltwater, or acidic substances. The factors affecting the corrosion rate of plain carbon steel are either material-dependent or environment-dependent, or a mixture of both (Uzorh, 2013).

Corrosion is a natural phenomenon that can cause significant damage to metal structures, leading to economic losses, safety hazards, and environmental pollution. Many industries, including oil and gas, maritime, and construction, deal with corrosion. Corrosion is is characterized as ‘a unidirectional electrochemical interaction between a substance such as metal, ceramic, or polymer and its environment can result in the material being eaten or a component of the environment being dissolved into the substance’ (Popoola, Olorunniwo and Ige, 2014). The process involves the transfer of electrons from the metal surface to an oxidizing agent, resulting in the degradation of the metal. Corrosion can occur in various environments, including aqueous solutions, atmospheric conditions, and high-temperature environments. Therefore, carbon steel often requires additional corrosion protection measures, such as coatings or inhibitors, to extend its lifespan and maintain its performance. Traditional methods of corrosion protection, such as coatings and cathodic protection, have limitations and drawbacks, leading to the development of alternative corrosion inhibitors.

Corrosion inhibitors are commonly used to protect metal surfaces from corrosion by forming a protective film on the metal surface. However, traditional corrosion inhibitors contain toxic and hazardous chemicals that pose risks to human health and the environment. In addition, it might be difficult and expensive to dispose of toxic compounds. Therefore, there is a need to develop green inhibitors that are environmentally friendly, sustainable, and non-toxic.

Traditional corrosion inhibitors contain chemicals such as chromates, phosphates, and heavy metals, which have negative impacts on the environment and human health. These inhibitors raise concerns about the disposal of hazardous waste and the risk of exposure to toxins. Therefore, there is a growing demand for the development of green inhibitors that are environmentally friendly, sustainable, and non-toxic.

Green inhibitors are derived from natural sources or waste materials, which have several advantages over traditional inhibitors. They are biodegradable, renewable, and cost-effective (Sharma *et al*., 2009). Green inhibitors have been found to be effective in preventing or reducing the rate of corrosion in various environments. Green inhibitors are eco-friendly corrosion inhibitors that are designed to reduce or prevent corrosion while minimizing their impact on the environment. Some examples of green corrosion inhibitors include organic Inhibitors, biopolymers, nanoparticles, ionic liquids and plant extract. These green inhibitors offer an effective and sustainable solution for corrosion protection. They can provide the same level of protection as traditional inhibitors while minimizing their impact on the environment. The development of green inhibitors for corrosion has gained significant attention in recent years. Researchers have explored various natural sources and waste materials as potential green inhibitors. These include plant extracts, essential oils, tannins, polysaccharides, chitosan, and lignin.

In this study, low carbon steel became decided on as the substrate and simulate in river water, 3.5w.t.% NaCl and 5M HCl solution and aloe vera as a green inhibitor. It is preferable for the aloe vera leaf extracts to establish a homogenous protective guard on the low carbon steel surface, separating the corrosive media from the reactive areas towards the low carbon steel. In particular, a range of research methodologies were used to acquire perception into the anti-corrosive mechanism of the barrier layer formed on the low carbon surface by aloe vera leaves, such as mechanical testing, visual inspection, weight loss measurement, corrosion rate, and inhibitor efficiency. We want the development of green inhibitors for corrosion is a promising alternative to traditional inhibitors. Green inhibitors are derived from natural sources or waste materials and have several advantages over traditional inhibitors. They are biodegradable, renewable, cost-effective, and non-toxic. The inhibitory properties of green inhibitors depend.

1.2 Problem Statement of Study

Corrosion weakens metals, compromising structural integrity and leading to failures in important industries like oil and gas and marine. It can cause equipment and machinery to malfunction, resulting in accidents or financial losses. Corroded metal can also release toxic substances, posing health risks and environmental hazards. Corrosion gives significant economic costs, requiring expensive maintenance and repairs, and it can cause physical injuries due to sharp edges or weakened structures. Preventive measures are essential to minimize these dangers and ensure the safety, longevity, and cost-effectiveness of metal structures and equipment. The aim of green inhibitor is to find a sustainable and effective solution to protect metal surfaces from corrosion while minimizing the environmental impact. Green inhibitors for corrosion aim to solve is the negative impact of traditional corrosion inhibitors on the environment. Traditional methods for corrosion protection often involve the use of toxic chemicals that can cause harm to the environment and human health. In addition, the disposal of these chemicals can be challenging and costly. Green inhibitors offer a potential solution to this problem by providing an eco-friendly alternative to traditional inhibitors. However, the challenge is to develop green inhibitors that can offer comparable or improved protection against corrosion while minimizing their impact on the environment. This requires research and development to identify and optimize the properties of green inhibitors, such as their effectiveness, stability, compatibility with different metal surfaces, and biodegradability. Green inhibitors offer a sustainable and eco-friendly alternative to traditional inhibitors. They are derived from natural sources and are non-toxic, biodegradable, and have a low environmental impact. Therefore it is important to create a green inhibitors for corrosion to develop effective and sustainable inhibitors that can offer comparable or improved protection against corrosion while minimizing their impact on the environment.

1.3 Objective of Study

The main aim of this research is to evaluate Aloe Vera leaf extract as an environmentally friendly corrosion inhibitor for low carbon steel in 3 different medium, which is river water, 3.5wt.% NaCl and 5M HCl medium. Specifically, the objectives are as follows:

i. To evaluate the effectiveness of green inhibitors derived from natural sources which is aloe vera extract in preventing corrosion of metal surfaces in different mediums.

ii. To investigate the influence of the immersion period on the inhibition efficiency of the green inhibitors.

iii. To compare the inhibition efficiency of Aloe Vera leaves as plant-based green inhibitors of low carbon steel in three different mediums.

1.4 Scope of Study

The scope of this research are as follows:

i. To observe the best method of green inhibitor to perform as anti-corrosion overall performance of inhibitor on a low carbon steel substrate for apply in the oil and gas sectors.

ii. Selection of suitable plants which are aloe vera leaves to be extracted as green organic inhibitors.

iii. Preparation of plant-based green organic inhibitors for extraction.

iv. Using Band Saw machine to cut the substrate material to the diameter of a 25 mm cylinder and a thickness of 10 mm.

v. Use a hardness test and an optical microscope to perform mechanical testing on the substrate.

vi. Conduct a corrosion test on the base metallic that was protected through the Aloe vera leaf corrosion inhibitor.

vii. To study corrosion behaviour via an immersion test in river water, 3.5w.t.% NaCl medium and 5M HCl medium.

viii. Divide the specimen into two samples with 18 specimens in each sample. Group one is the samples that have the presents of aloe vera extract and group two is the samples that not have the presents of aloe vera. Six specimens from sample one was immersed in river water, another six specimens in 3.5w.t.% NaCl and the last six specimens from group one is in 5M HCl. For the sample two also the same, six specimens was immersed in river water, another six specimens in 3.5w.t.% NaCl and the last six specimens in 5M HCl medium.

ix. All the samples was immerse in river water, 3.5w.t.% NaCl medium and 5M HCl medium for a period of 7, 14, 21, 28, and 35 days.

x. Utilize a Scanning Electron Microscope (SEM) and Energy Dispersive X-Ray (EDX) to study the corrosion behaviour on the substrate after a test.

1.5 Significant of Study

The study on green inhibitors for corrosion is significant for several reasons. Firstly, the development of effective and sustainable corrosion inhibitors is essential for preventing material degradation and extending the lifespan of industrial equipment and infrastructure. Green inhibitors derived from natural sources offer a promising solution to this problem, as they are renewable, biodegradable, and less harmful to the environment than traditional synthetic inhibitors.

Secondly, the use of green inhibitors can potentially reduce the cost and environmental impact associated with the production and disposal of synthetic inhibitors. The study can provide insights into the optimal concentration and application conditions for green inhibitors, thus enabling industries to maximize their benefits while minimizing their environmental impact.

Lastly, the study can contribute to the advancement of knowledge in the field of corrosion science and engineering. By investigating the mechanisms of inhibition and comparing the performance of green inhibitors with synthetic inhibitors, the study can shed light on the fundamental processes underlying corrosion prevention. With adding chemicals such as green inhibitors, it will assist industrial oil and gas companies in reducing corrosion of closed systems such as pipelines, pressure vessels, and tanks. In addition, the green inhibitor wil also be non-toxic, safe, affordable and biodegradable

1.6 Organization of Study

This study was divided into five chapters and the contents of which are summarized below, based on the objectives previously presented and the approach previously proposed:

i. Chapter 1. Introduction. This chapter represent the background, objectives, scope, significance, and organization of study.

ii. Chapter 2. Literature review. This chapter begins with an introduction to carbon steel and the various types of carbon steel. Later, an overview of corrosion and the subtopic which is a form of corrosion and corrosion behaviour on carbon steel. This chapter also covers corrosion methods, as well as corrosion inhibitors and types of corrosion inhibitors. Moreover, a brief discussion of the green inhibitor. Equally importantly, the summary of the literature review is present.

iii. Chapter 3. Research methodology. This chapter express the methods used to estimate the corrosion inhibitor formula, which offers with a procedure used in this analysis and was then carried out. It also extensively defined and described the study approach. Therefore, Chapter 3 describes the approach to PSM 1 and PSM 2.

iv. Chapter 4. Results and Discussion. This chapter needs to focus on discussing the effects of corrosion inhibitors which extract is more efficient, observed the mechanical properties and corrosion behavior of low carbon steel. Moreover, discusses the results and explained out of several tests performed and the calculation.

v. Chapter 5. Conclusion and Recommendations. In this section, highlights the main conclusions together with accomplishments of the work done in this research study and suggests areas for future potential. On the other hand, these guidelines are summarized, proposed similarly work is offered and evaluation is concluded.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Carbon Steel

Nowadays, carbon steel is a popular material used in various industries around the world. It is suitable for a variety of industrial applications due to its excellent strength and endurance. Due to its superior mechanical qualities and affordable price, carbon steel is commonly used in the manufacturing, automotive, construction sectors and many other applications.

Typically, carbon steel has a carbon content between 0.05% to 2.0%. Higher carbon concentrations increase the hardness and strength of the steel. According to a study published in the Journal of Materials Engineering and Performance, carbon steel's mechanical properties can be further enhanced through various heat treatment processes, such as quenching and tempering. These treatments can modify the material's hardness, strength, and ductility, enabling it to meet specific performance demands. Additionally, carbon steel can be alloyed with other elements, such as manganese, silicon, and chromium, to further enhance its properties, such as corrosion resistance and heat resistance.

Furthermore, carbon steel can be classified into different grades based on the amount of carbon and other alloying elements present. The American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE) have established a classification system for carbon steels, providing a standardized way to identify and differentiate various grades.

Carbon steel's versatility and wide range of applications can be attributed to its excellent machinability, weldability, and formability. It can be easily shaped and fabricated into different forms such as sheets, bars, and tubes, allowing to produce diverse components and structures.

2.1.1 Types of Carbon Steel

Generally, there are three types of carbon steel. Each type of carbon steel has different properties and purposes. Table 2.1 shows three main types of carbon steel, each with different chemical properties and characteristics (Dieter, G. E., 2000).

Table 2.1 shows three main types of carbon steel, each with different chemical properties and characteristics (Dieter, G. E., 2000)

Category of steel	Carbon content (wt.%)	Characteristics	Microstructure
Low carbon steel	0.04% ≤ carbon < 0.25%	High ductility, high weldability, high machinability, cost-effective, low hardenability, and good formability	Ferrite and perlite
Medium carbon steel	0.25% ≤ carbon< 0.60%	Medium ductility, medium weldability, medium hardenability, medium machinability, and wear resistance	Cementite and martensite
High carbon steel	0.60% ≤ carbon < 2.0%	Low ductility, low weldability, low machinability, high hardenability, high strength, wear resistance and low toughness	Ferrite and perlite

Low carbon steel, also known as mild steel, is a type of carbon steel that contains a low amount of carbon, typically 0.05-0.25%(Raghavan, 2018). Due to its low carbon content, low carbon steel can undergo plastic deformation without significant risk of cracking or failure. It can be easily formed into various shapes, including sheets, plates, and tubes (Dieter, 2017). However, it also has a lower strength and hardness. Low carbon steel is commonly used in oil and gas, marine, and manufacturing industries due to its affordability and ease of fabrication. Low carbon steel is also used in the production of sheet metal, wire, and other products that require a combination of strength and formability. Despite its advantages, low carbon steel is susceptible to corrosion and requires protection through methods such as painting, coating, or the use of inhibitors. Figure 2.1 shows Classification of steels (Totten, G.E, 2006)

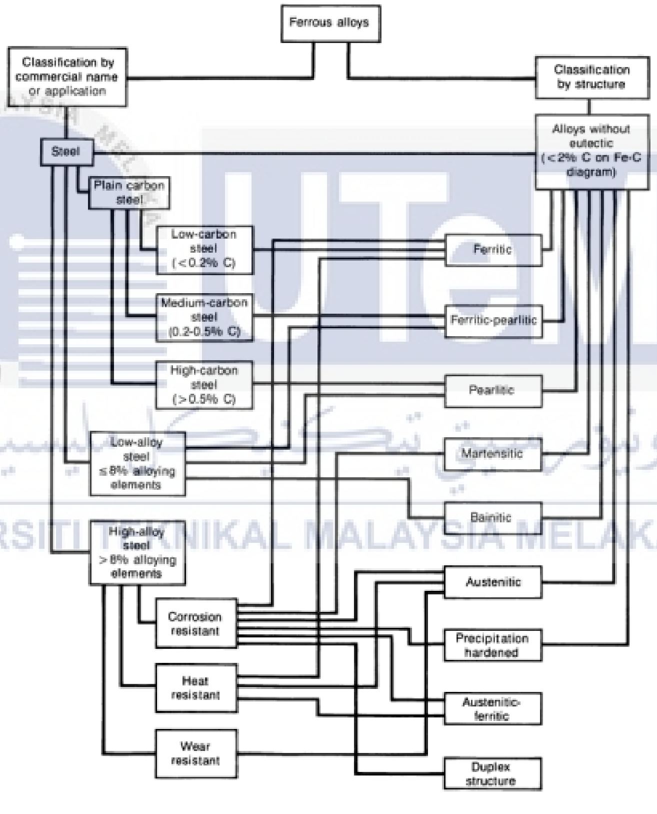


Figure 2.1 Classification of steels (Totten, G.E, 2006)

Medium carbon steel is a type of carbon steel that contains 0.3% to 0.6% carbon by weight. It is stronger and harder than low carbon steel, with higher wear resistance and toughness. This type of steel is commonly used for forging and heat treatment proceses, such as quenching and tempering, can be employed to improve the strength, hardness, and toughness of medium carbon steel (Dieter, 2017). Medium carbon steel also has good machinability and weldability, but it is more difficult to weld than low carbon steel It is utilized in the manufacturing of machinery and equipment, including shafts, couplings, and sprockets, where higher strength and wear resistance are required (Dieter, 2017). However, due to its higher carbon content, it is more prone to corrosion and requires proper protection to prevent rust. Overall, medium carbon steel offers a balance between strength and ductility, making it suitable for a variety of applications that require high strength and toughness.

Figure 2.2 AISI 1045 Medium Carbon Steel (Azom, 2012)

High carbon steel is a type of carbon steel that contains a carbon content between 0.60% and 1.4% by weight. This makes it harder and stronger than low and medium carbon steel. High carbon steel is favored in the manufacturing of knives and blades as it provides excellent edge retention, hardness, and corrosion resistance (Avner, 2007). However, the high carbon content also makes it more brittle and less ductile, which can lead to cracking and failure under high stress. To avoid this, high carbon steel is often heat-treated to improve its toughness and ductility. This involves heating the steel to a high temperature and then quenching it rapidly to harden it, followed by tempering to reduce its brittleness (Dieter, 2017). Overall, high carbon steel is a versatile material with many industrial applications, but it requires careful handling and processing to avoid cracking and other forms of failure.

Figure 2.3 High Carbon Steel (Rogers, 2016)

2.1.2 Low Carbon Steel

Low carbon steel, also known as mild steel, is a type of carbon steel that contains a relatively low amount of carbon, which is less than 0.3% (Mishra *et al*., 2020). This makes it one of the most widely used materials in the construction industry, as it is affordable, readily available, and easy to work with.

The low carbon content in this type of steel means that it has a high level of ductility, which makes it easy to shape and form into various shapes and sizes (Mahmoud *et al*., 2021). It is also relatively soft, making it easy to cut and weld. However, it is important to note that low carbon steel is not as strong as high carbon steel and is not suitable for high-stress applications.

In addition to its affordability and ease of use, low carbon steel has other advantages. It has excellent corrosion resistance, which makes it suitable for use in outdoor structures or applications where it will be exposed to moisture or other corrosive elements. It is also highly machinable, which means that it can be easily machined into different shapes and sizes (Sudhakar *et al*., 2020).

However, low carbon steel also has some disadvantages its relatively lower strength and hardness compared to higher carbon steels. The low carbon content results in a softer material, which may limit its suitability for applications that require high strength or hardness (Srivastava, 2016). It is also has limited hardenability, meaning it may not respond well to certain heat treatment processes aimed at increasing its hardness and strength. This limitation may restrict the range of achievable mechanical properties for low carbon steel components (Davis, 2001).

Overall, Low carbon steel is a versatile and widely used material that offers excellent mechanical properties, affordability, and weldability. Its high ductility, formability, and machinability make it suitable for a wide range of applications in industries such as oil and gas, marine, automotive, construction, and manufacturing industries for various applications, such as pipes, structural steel, and automotive parts. The addition of alloying elements and advancements in manufacturing techniques have further enhanced the properties and performance of low carbon steel.

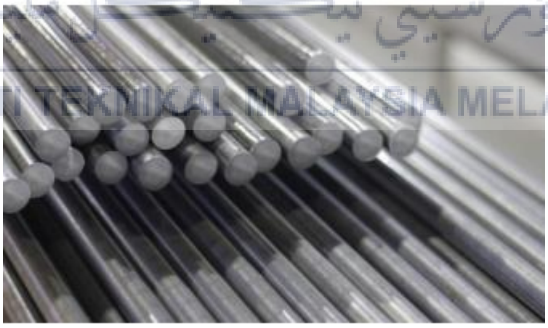


Figure 2.4 Low Carbon Steel (M.Khebra, 2012)

2.1.3 Applications of Low Carbon Steel

Low carbon steel is a popular material used in a wide variety of applications due to its unique characteristics. This type of steel contains a low percentage of carbon, typically no more than 0.3%, which makes it more ductile and malleable than other types of steel. Low carbon steel is also more affordable than other steel types, which makes it an attractive option for many industries.

One of the most common applications of low carbon steel is in the construction industry. It is used to build structures such as buildings, bridges, and pipelines. Its high strength and durability make it an ideal choice for structural applications (Yao *et al*., 2019). In addition, its malleability makes it easy to shape and mould into various forms, making it an essential material for construction projects.

Another industry that utilizes low carbon steel is the automotive industry. This material is commonly used to manufacture car bodies, chassis, and engine components Karunakaran *et al*., 2020). Its high strength and ability to be easily formed into various shapes make it a popular choice for automotive manufacturers. Low carbon steel is also corrosion-resistant, which makes it ideal for use in automotive components, including body panels, chassis, and suspension systems. Its formability, strength, and impact resistance contribute to the structural integrity and safety of vehicles (Kim *et al*., 2019). Low carbon steel is also commonly used in the manufacturing of home appliances such as refrigerators, stoves, and washing machines (Mohapatra *et al*., 2018). Its affordability and durability make it an ideal choice for appliance manufacturers. Additionally, low carbon steel is easy to clean and maintain, which is an important factor for appliances that are used on a daily basis.

Pipes used for transporting water, oil, and gas are often made from low carbon steel. Its high strength and resistance to corrosion make it an ideal choice for pipes used in various industries (Ghosh & Mallik, 2010). Low carbon steel pipes are also lightweight and easy to install, which is beneficial for industries that require large-scale pipe installations. In addition, low carbon steel is used in the manufacturing of agricultural equipment such as plows, cultivators, and harvesters. Its strength and durability make it an ideal choice for equipment that is exposed to harsh outdoor conditions. Low carbon steel is also easy to weld and repair, which is important for equipment that requires regular maintenance.

In conclusion, low carbon steel is a versatile material that is used in a wide range of industries due to its affordability, weldability, and ease of fabrication. Its high strength and durability make it an ideal choice for construction, automotive, appliances, pipes, and agriculture. As industries continue to evolve, low carbon steel is likely to remain a popular choice for many applications.

2.2 Overview of Corrosion

Corrosion is a natural process that occurs when metal and alloy failure induced by chemical or electrochemical exposure to the environment (Kadhim *et al*., 2021). It is the deterioration of metals due to chemical reactions with their surrounding environment, such as air, water, or soil. Corrosion can occur through several mechanisms, the most common of which are uniform corrosion, pitting corrosion, crevice corrosion, and galvanic corrosion. It can be influenced by various factors, including environmental conditions (humidity, temperature, pH, and presence of corrosive agents), material properties (composition, microstructure, and surface condition), and electrochemical factors (such as potential, current density, and polarization). Other considerations may be significant under some circumstances. In other words, the relative velocity of a solution due 16 to flow or agitation and mechanical loads on the material, and residual tension inside the material that representations of these causes (Up, 2019).

Other than that, (Cai *et al*., 2021) declared that various environmental conditions with diverse pathways affect the atmospheric corrosion process at the same time. Furthermore, relative humidity, temperature, and air pollution all have a significant effect and several studies have been conducted to show their effectiveness. As seen in Figure 2.5, these distinct properties have mostly been used in corrosion protection applications. (Hussain *et al*., 2020).

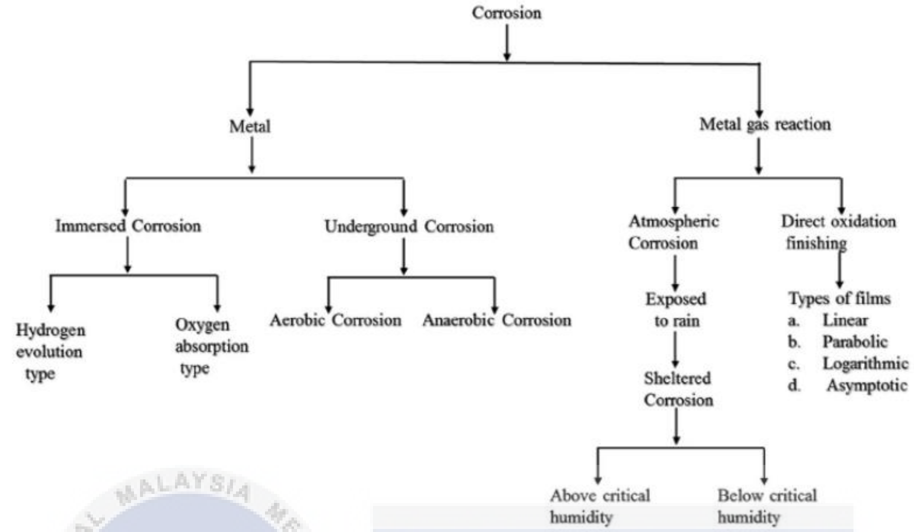


Figure 2.5 Flowchart of corrosion classification (Hussain *et al*., 2020).

Hence, iron and steel shared the same chemical compositions that allow them to revert to their weakest states. Iron and steel can react with gas and water which both are abundant in nature to produce hydrous iron oxides which is corrosion and its chemically similar to the first ore (Up, 2019). Generally, Figure 2.6 also depicts the corrosion cycle time of a stainless steel.

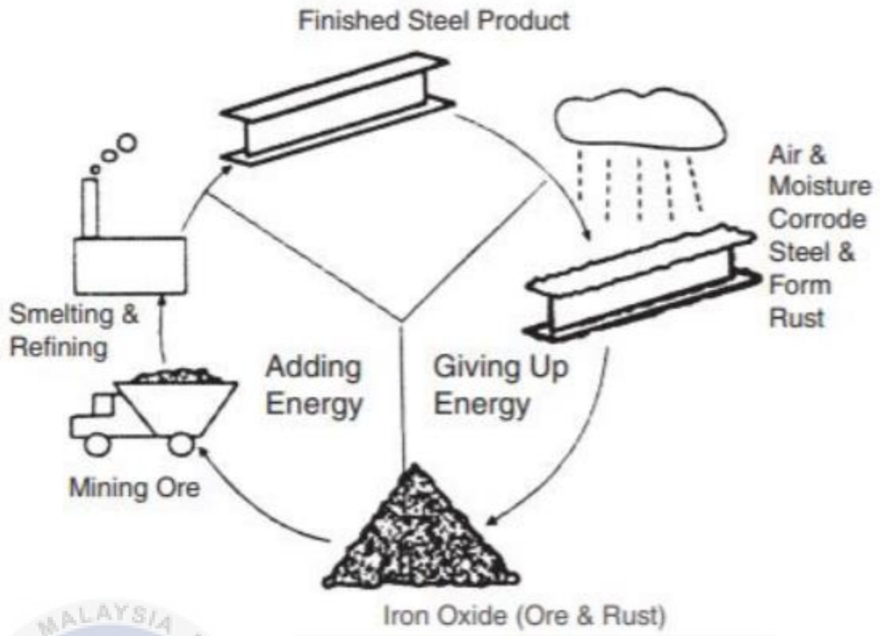


Figure 2.6 The corrosion cycle time of stainless steel (Up, 2019).

There are several types of corrosion, including uniform corrosion, localized corrosion, galvanic corrosion, and crevice corrosion. Uniform corrosion is the most common type and occurs when a metal's entire surface is evenly corroded. Localized corrosion, on the other hand, occurs in specific areas of a metal's surface, leading to pitting, cracking, or flaking. Galvanic corrosion is caused by the electrochemical reaction between two dissimilar metals that are in contact with each other. Crevice corrosion occurs in crevices or confined spaces where stagnant water can accumulate (A.G. Lekatou *et al*., 2023)

Corrosion can be prevented or minimized through various methods, such as the use of protective coatings, cathodic protection, corrosion inhibitors, material selection, and design modifications. Each method aims to create a barrier or alter the electrochemical reactions to reduce or eliminate corrosion (Shreir *et al*., 2010). These methods help to slow down or prevent the chemical reactions that lead to corrosion. In industries such as oil and gas, construction, and transportation, where metals are heavily used, corrosion prevention and control are critical. The cost of corrosion is high, and it is estimated that billions of dollars are spent annually on maintenance, repairs, and replacement of corroded equipment and structures. Understanding the different types of corrosion and taking preventative measures to control it is essential in ensuring the safety, reliability, and longevity of metals used in various industries.

2.2.1 Form of Corrosion

There are many different types of corrosion, each of which can be classified by the cause of the metal's chemical deterioration. Corrosion consists of a series of usually complex chemical reactions and may be initiated by several different mechanisms that are dependent on the surrounding environment. This has given rise to the various classifications of corrosion. All corrosion is not the same. The key to effective corrosion prevention and mitigation lies in a basic understanding of the type of corrosion being dealt with and the factors that are responsible for its formation. Figure 2.7 depicts the phase composition and it ought to be highlighted although the sorts of corrosion are distinctive in principle, there seem to be things wherever the corrode falls into one class and this can be applied to seeing the form of corrosion (Popoola, Olorunniwo and Ige, 2014).

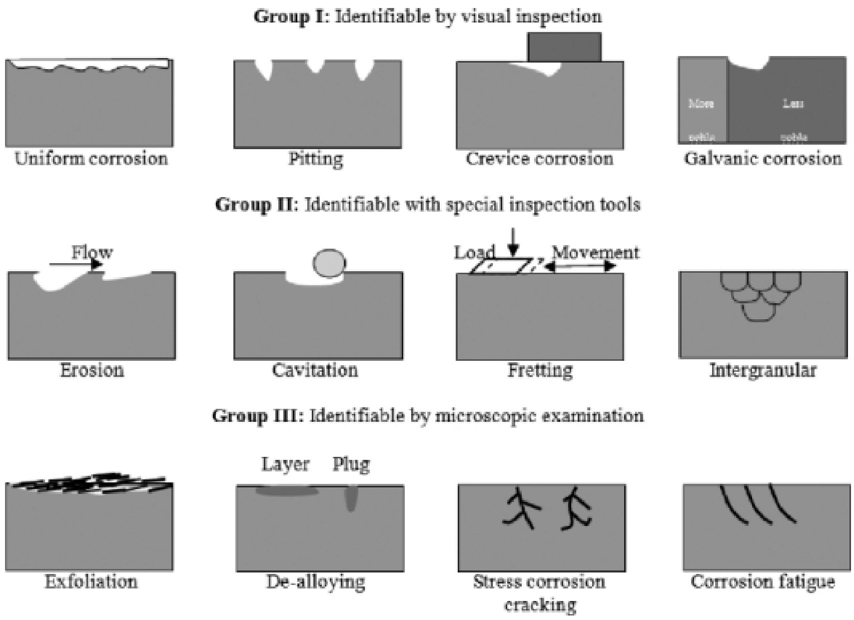
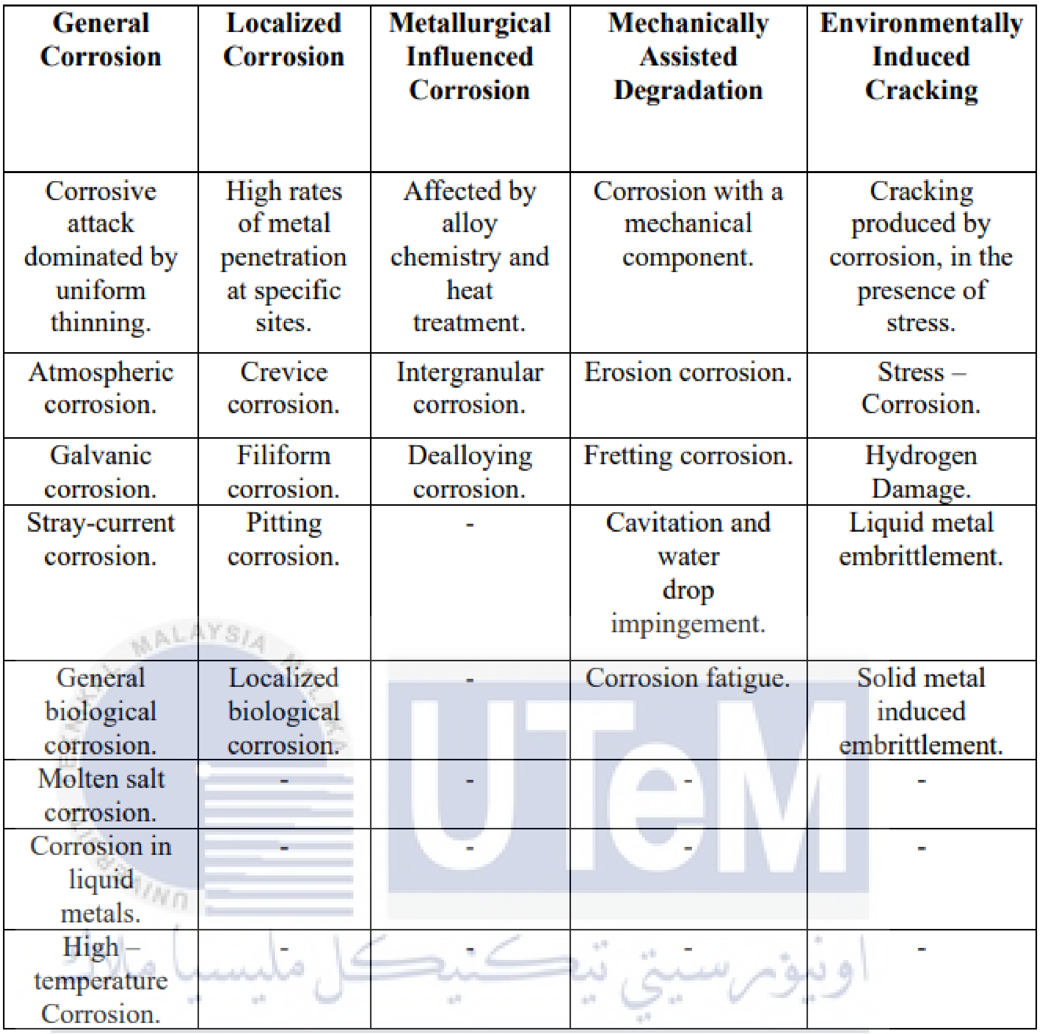


Figure 2.7 Various types of corrosion (Popoola, Olorunniwo and Ige, 2014)

Metals corrosion can be classified into eight sorts, which is wet corrosion, uniform or general corrosion, pitting corrosion, crevice corrosion, as well as corrosion underneath tubercles or deposits, thready corrosion, and poultice corrosion, galvanic corrosion, erosion-corrosion, as well as cavitation erosion, and fretting corrosion, intergranular corrosion, as well as sensitization and exfoliation, dealloying, as well as dezincification, and environmentally assisted cracking, as well as stress cracking corrosion, corrosion fatigue, and chemical element damage (Popoola, Olorunniwo and Ige, 2014). For instance, Table 2.2 categorizes corrosion types as general corrosion, localized corrosion, metallurgical influenced corrosion, mechanically aided deterioration, and environmentally induced cracking

Table 2.2 Classified of type corrosion (Popoola, Olorunniwo and Ige, 2014).



General Corrosion	**Localized Corrosion**	**Metallurgical Influenced Corrosion**	**Mechanically Assisted Degradation**	**Environmentally Induced Cracking**
Corrosive attack dominated by uniform thinning.	High rates of metal penetration at specific sites.	Affected by alloy chemistry and heat treatment.	Corrosion with a mechanical component.	Cracking produced by corrosion, in the presence of stress.
Atmospheric corrosion.	Crevice corrosion.	Intergranular corrosion.	Erosion corrosion.	Stress – Corrosion.
Galvanic corrosion.	Filiform corrosion.	Dealloying corrosion.	Fretting corrosion.	Hydrogen Damage.
Stray-current corrosion.	Pitting corrosion.	-	Cavitation and water drop impingement.	Liquid metal embrittlement.
General biological corrosion.	Localized biological corrosion.	-	Corrosion fatigue.	Solid metal induced embrittlement.
Molten salt corrosion.	-	-	-	-
Corrosion in liquid metals.	-	-	-	-
High – temperature Corrosion.	-	-	-	-

Uniform or general corrosion are defined as a type of corrosion attack that is distributed over the entire exposed surface of a metal. According to Davis (2003), uniform corrosion is the most common form of corrosion, characterized by a uniform loss of material over the entire surface of the metal. It occurs due to the reaction of the metal with the surrounding environment, such as moisture or chemicals. Uniform corrosion is a common form found in ferrous metals and alloys not protected by surface coatings and/or cathodic protection. Although it may seem less damaging than other forms of corrosion, uniform corrosion can still cause significant material loss over time if not properly controlled. Figure 2.8 shows uniform corrosion that occurs (Lazzari, 2017).

Figure 2.8 Uniform corrosion that occurs (Lazzari, 2017)

The following elements that have an impact on uniform corrosion:

i. Corrosive Agents: Corrosive agents such as chlorides, sulfates, acids, and pollutants can significantly accelerate the rate of corrosion (Fontana & Greene, 2005).

ii. Pollution Levels: High levels of pollutants in the environment can exacerbate corrosion by increasing the concentration of aggressive chemical species and the corrosive potential (Revie & Uhlig, 2008).

iii. Relative Humidity: Higher relative humidity provides a more conducive environment for corrosion processes, including uniform corrosion (Shreir, Jarman, & Burstein, 2013).

iv. Water Quality: The chemical composition of water, including its pH, dissolved oxygen content, and the presence of contaminants, can significantly influence the corrosion behavior of materials in contact with water (Shreir, Jarman, & Burstein, 2013).

Pitting is one of the most destructive types of corrosion, as it can be hard to predict, detect and characterize. Pitting corrosion is localized corrosion that creates small pits or holes on the metal's surface. It often occurs in the presence of chloride ions or other aggressive environments (Revie & Uhlig, 2008). It is a local anodic point, or more commonly a cathodic point, forms a small corrosion cell with the surrounding normal surface. Once a pit has initiated, it grows into a “hole” or “cavity” that takes on one of a variety of different shapes. Pits typically penetrate from the surface downward in a vertical direction. Pitting corrosion can be caused by a local break or damage to the protective oxide film or a protective coating; it can also be caused by non-uniformities in the metal structure itself. Pitting is dangerous because it can lead to failure of the structure with a relatively low overall loss of metal. Figure 2.9 shows pitting corrosion that occurs (Kossakowski, Paweł, 2019).

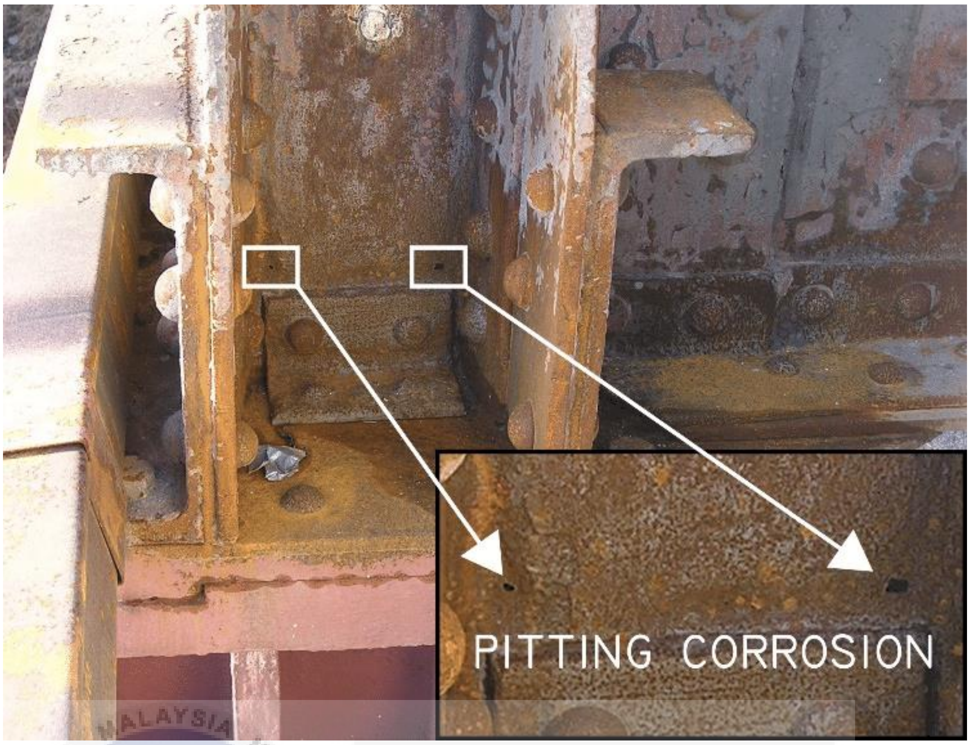


Figure 2.9 Pitting corrosion that occurs (Kossakowski, Paweł, 2019).

Possible factors that have a substantial impact on pitting corrosion include:

i. Environment: The presence of aggressive environments, such as chloride ions, can significantly enhance the occurrence and severity of pitting corrosion (Revie & Uhlig, 2008).

ii. Alloy Composition: The composition of the alloy, particularly the presence of alloying elements like chromium, molybdenum, and nickel, can affect the susceptibility to pitting corrosion (Fontana & Greene, 2005).

iii. Microstructure: The presence of preferential paths for localized corrosion, such as grain boundaries or second-phase particles, in the material's microstructure can facilitate the initiation and propagation of pitting corrosion (Shreir, Jarman, & Burstein, 2013).

iv. Surface Condition: Surface defects, scratches, and imperfections can act as initiation sites for pitting corrosion, allowing localized attack to occur (Mansfeld & Little, 1999).

v. Applied Stress: The presence of applied tensile stress on the material can promote the development and propagation of pits, leading to accelerated pitting corrosion (Cook & Hinds, 2015).

Crevice corrosion occurs in confined spaces or crevices, such as gaps between two metal surfaces or under deposits or gaskets. The restricted access to oxygen can lead to localized corrosion (Fontana & Greene, 2005). Crevice corrosion is also a highly penetrative type of localized form of corrosion and usually results from a stagnant microenvironment in which there is a difference in the concentration of ions between two areas of a metal. Crevice corrosion occurs in shielded areas such as those under washers, bolt heads, gaskets, etc. where oxygen is restricted. These smaller areas allow for a corrosive agent to enter but do not allow enough circulation within, depleting the oxygen content, which prevents re-passivation. As a stagnant solution builds, pH shifts away from neutral. This growing imbalance between the crevice (microenvironment) and the external surface (bulk environment) contributes to higher rates of corrosion. Crevice corrosion can often occur at lower temperatures than pitting. Proper joint design helps to minimize crevice corrosion. Figure 2.10 shows crevice corrosion that occurs (Steel Fabrication Services, 2021).

Figure 2.10 Crevice corrosion that occurs (Steel Fabrication Services, 2021).

i. Presence of a Crevice: The presence of a crevice, such as gaps, overlaps, threads, or under-deposit areas, provides a localized environment that can lead to the initiation and propagation of crevice corrosion (Mansfeld & Little, 1999).
ii. Differential Aeration: Differential aeration, caused by oxygen concentration cells or variations in oxygen availability within a crevice, can significantly enhance the occurrence and severity of crevice corrosion (Fontana & Greene, 2005).
iii. Electrolyte Concentration: Higher concentrations of aggressive electrolytes, such as chlorides or sulfates, within a crevice can accelerate the onset and progression of crevice corrosion (Revie & Uhlig, 2008).
iv. pH and Temperature: pH and temperature variations within a crevice can affect the electrochemical reactions and corrosion kinetics, influencing the severity of crevice corrosion (Melchers, 2018).
v. Material Selection: The choice of materials, particularly their resistance to localized corrosion, can significantly impact the susceptibility to crevice corrosion (Shreir, Jarman, & Burstein, 2013).

Overall, understanding the different forms of corrosion and their causes is essential in preventing and mitigating corrosion in various industries. Proper selection of materials, protective coatings, and design considerations can help minimize the effects of corrosion, ensuring the safety and reliability of structures and equipment.

2.2.2 Corrosion Behaviour on Carbon Steel

Corrosion is a significant concern for carbon steel, which is a type of steel that contains less than 2% carbon. Carbon steel is widely used in various industries, including construction, oil and gas, and also manufacturing, due to its affordability, strength, and versatility. However, carbon steel is susceptible to corrosion, which can compromise its structural integrity and lead to equipment failure.

The corrosion behaviour of carbon steel depends on several factors, including the environment, temperature, and pH. Carbon steel is particularly vulnerable to uniform corrosion, which occurs when the metal is exposed to a corrosive environment, such as saltwater or acidic solutions. The corrosion rate of carbon steel can increase with increasing temperature and acidity, leading to faster metal loss and thinner walls. Despite the fact that the fast interactions of ratios, temperatures, and pollutants are typically nonlinear, using average values to clarify real-world regional conditions is ineffective. They are frequently influenced by a number of variables in random activities. Since those atmospheric variables span a wide range, it is not required to treat the entire atmosphere as a steady-state (Cai *et al.*, 2021)

Pitting corrosion is distinguished by the formation of a hollow, void, or pit in a very small space or for a purpose. A trace amount of corrosion agent like rust on the soil obscures the pits or holes. A clean, hollow, or small hollow forms while a cathodic reaction in a huge area which is coating sustains an anodic reaction in a small region that represent uncovered steel and oxidation occurs in the metal inside the absence of oxygen (D&D Coatings, 2019). This can be study as Figure 2.11 illustrates shown.

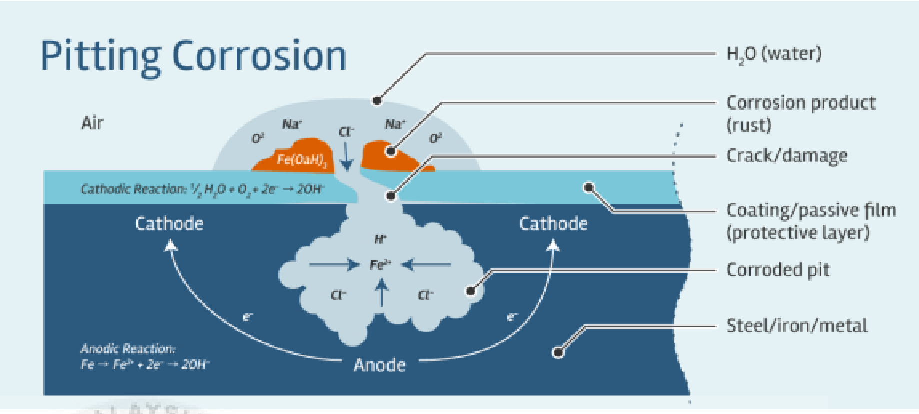


Figure 2.11 Pitting corrosion diagram showing (D&D Coatings, 2019).

2.3 Corrosion Protection Method

Corrosion protection methods are crucial to prevent or reduce the damage caused by corrosion to metals. Corrosion protection methods are applied to various metals like steel, aluminium, copper, and others. Various techniques and strategies have been developed to protect metals from corrosion in different environments. Corrosion protection methods can be divided into several categories based on the approach used. These methods can be broadly classified into three categories which is the applications of protectives coatings, the applications of inhibitors, and cathodic protection.

2.3.1 Types of Corrosion Protection Method

Protective coatings are the most common and cost-effective method for corrosion protection. A protective coating creates a barrier between the metal surface and the environment. This can be achieved through various materials, such as paint, epoxy, or other coatings. Protective coatings are widely used to provide a physical barrier between the metal surface and the corrosive environment. They act as a sacrificial layer that shields the metal from direct contact with corrosive agents. Coatings can be classified into organic coatings such as paints and polymer coatings, metallic coatings such as galvanization and electroplating, and ceramic coatings such as oxide coatings and nitride coatings. Each type of coating offers specific advantages and limitations depending on the application requirements (Wang *et al*., 2017). Figure 2.12 shows the example of corrosion protection (Voegtlin, 2021).

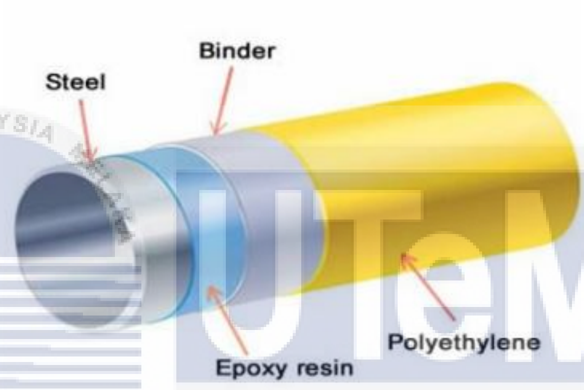


Figure 2.12 Example of corrosion protection (Voegtlin, 2021).

Cathodic protection is another method used to protect metals from corrosion. Cathodic protection involves the use of a sacrificial anode or impressed current to protect the metal from corrosion. A sacrificial anode is made of a metal that is more reactive than the metal being protected. When the sacrificial anode corrodes, it protects the metal from corrosion. Impressed current cathodic protection uses an external power source to force electrons onto the metal surface, preventing corrosion. Cathodic protection is a useful method for protecting underground pipelines, ships, and offshore structures.

Alloying is a method used to improve the corrosion resistance of metals. Alloying involves adding other metals to the base metal to create a more corrosion-resistant material.

For example, adding chromium and nickel to steel creates stainless steel, which is highly resistant to corrosion. Alloying can be expensive, but it can be an effective way to create a metal that is resistant to a specific corrosive environment.

Environmental modifications are another method for preventing corrosion. Modifying the environment can help prevent corrosion. For example, reducing the amount of moisture or acidity in the environment can slow down the corrosion rate. This can be achieved by controlling the temperature, humidity, and pH levels of the environment. Proper ventilation and drainage can also help prevent corrosion in some cases.

Design modifications are another method of corrosion protection. Designing equipment and structures to minimize the formation of crevices and tight spaces can help prevent crevice corrosion. Additionally, using materials that are resistant to the corrosive environment or applying protective coatings can also help reduce the effects of corrosion.

Maintenance is another essential factor in corrosion protection. Regular maintenance can help prevent corrosion by identifying and repairing small defects before they turn into larger problems. This can include cleaning and painting metal surfaces, replacing damaged coatings, and monitoring the environment for changes that may affect the corrosion rate.

In conclusion, corrosion protection methods are critical for preventing or reducing the damage caused by corrosion to metals. A combination of methods may be necessary to provide the most effective corrosion protection. The selection of the best method depends on the type of metal, the corrosive environment, and the application.

2.3.2 Corrosion Inhibitor

Corrosion inhibitors are substances used to prevent or reduce the rate of corrosion on metal surfaces. Corrosion inhibitors work by forming a protective film on the metal surface, which acts as a barrier between the metal and the corrosive environment. The film can also interfere with the electrochemical reaction that causes corrosion.

Corrosion inhibitors can be classified into organic and inorganic inhibitors. Organic inhibitors are usually organic compounds containing nitrogen, sulphur, or oxygen. These inhibitors are effective in acidic environments and are commonly used for corrosion protection in the oil and gas industry. Inorganic inhibitors, such as phosphates, silicates, and molybdates, are effective in alkaline environments and are often used in cooling water systems. Organic, inorganic, or a mixture of the two inhibitors will prevent corrosion through adsorption on the metal surface or the creation of a surface barrier-type precipitate by interacting with metal ions (Nahlé *et al.*, 2010). The effectiveness of a corrosion inhibitor depends on various factors, such as the concentration of the inhibitor, the temperature, the pH of the environment, and the type of metal. The effectiveness of the inhibitor can also be affected by the presence of other substances in the environment, such as salts or oxygen. Therefore, the selection of the appropriate inhibitor for a specific application requires careful consideration of the environmental factors and the properties of the metal.

These are three mechanism of the inhibitor by (Hart, 2016):

i. The inhibitor is a chemicals adsorbate on the surface of the metal, providing a protecting thin coating of inhibitor impact, or by a mixture of inhibitor ions and metal ions.

ii. The inhibitor stimulates the emergence of a coating on the aluminous surface by protecting the base metal with a chemical compound.

iii. The inhibitor reacts with a probably corrosive part prevailing in aqueous solution, leading to a complex.

Corrosion inhibitors can be manufactured or natural and can be defined using the criteria listed below (Hart, 2016):

i. Chemical composition which is organic or inorganic.

ii. The action mechanism is anodic, cathodic, or an anodic-cathodic combination, as well as an adsorption action.

iii. The inhibitors act as oxidants or not.

More than that, organic inhibitors have cathodic and anodic properties, as well as protective impact via film absorption. Figure 2.13 shows the classifications of corrosion inhibitors (Hart, 2016)

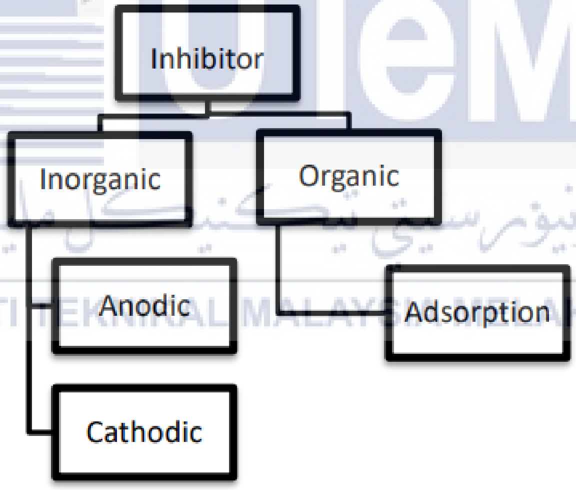


Figure 2.13 Classifications of corrosion inhibitors

Corrosion inhibitors are widely used in various industries, such as oil and gas, power generation, water treatment, and metal manufacturing. The use of corrosion inhibitors can help reduce maintenance costs, extend the life of equipment, and improve safety. The concentration of the inhibitor make a great influence on its performance. However, it is important to note that corrosion inhibitors are not a permanent solution to corrosion and require regular monitoring and maintenance to ensure their effectiveness.

2.3.2.1 Inorganic Corrosion Inhibitor

Inorganic corrosion inhibitors are substances that are used to protect metal surfaces from corrosion by forming a passive layer on the metal surface. These inhibitors are typically made of inorganic compounds such as embrace salt, nitrite, silicate, and phosphate which contains an anodic elements. These compound also have a very good performance in anticorrosion coating application but it has a very high toxicity (Mulyaningsih, 2019). They are commonly used in cooling water systems, boilers, and other industrial applications.

Inorganic corrosion inhibitors work by reacting with the metal surface to form a protective layer that acts as a barrier to the corrosive environment. For example, phosphates react with metal ions to form a protective layer of insoluble metal phosphate. Silicates react with metal ions to form a silica layer that protects the metal surface. Chromates and molybdates form a thin film of oxide on the metal surface that prevents corrosion (Diamanti, M. V., & Zinovyev, A.,2018).

Metals or inorganic elements are crucial to living things when they appear in trace amounts. For example, chromium and chromates compounds are commonly use as corrosion inhibitors in aqueous system as for their great performance but they highly toxic and not permitted to use. Lanthanide also shown to be hazardous as sodium chloride (Singh *et al.*, 2022).

The effectiveness of inorganic corrosion inhibitors depends on several factors, including the concentration of the inhibitor, the pH of the environment, the presence of other chemicals in the environment, and the type of metal. It is important to select the appropriate inhibitor for a specific application to ensure its effectiveness (Shehnazdeep and B. Pradhan, 2022).

Inorganic corrosion inhibitors are widely used in various industries, such as power generation, oil and gas, and metal manufacturing. They provide an effective and economical way to protect metal surfaces from corrosion and extend the life of equipment. However, it is important to use them in conjunction with other corrosion protection methods and to monitor their effectiveness regularly. Table 2.3 shows some inorganic inhibitors (Kesavan, Gopiraman and Sulochana, 2012).

Table 2.3 Inorganic Inhibitors (Kesavan, Gopiraman and Sulochana, 2012).

Inhibitor	Metal	Medium
$CeCl_3$ AA5083	Galvanized Steel	NaCl
$CeCl_3.7H2O$	Tinned iron	NaCl
La $(NO_3)_3$, Sm $(NO_3)_3$, $LaCl_3$, and $SmCl_3$	AISI 434 SS	NaCl

2.3.2.2 Organic Corrosion Inhibitor

Organic corrosion inhibitors are chemical compounds that are used to prevent or reduce the rate of corrosion on metal surfaces. These inhibitors are typically made of organic compounds containing nitrogen, oxygen, or sulphur (Ramirez, A., & Singh, R., 2017). They are commonly used in acidic environments and in industries such as oil and gas, petrochemical, and automotive.

Organic corrosion inhibitors work by forming a protective layer on the metal surface, which acts as a barrier between the metal and the corrosive environment. The protective layer can also inhibit the electrochemical reaction that causes corrosion. Organic inhibitors can also absorb into the metal surface, forming a monolayer that protects the metal from further corrosion (Liu, G., & Zhang, S., 2019).

The effectiveness of organic corrosion inhibitors depends on various factors, such as the concentration of the inhibitor, the pH of the environment, the temperature, and the type of metal. The inhibitors can also be affected by the presence of other chemicals in the environment. Therefore, the selection of the appropriate inhibitor for a specific application requires careful consideration of the environmental factors and the properties of the metal (Obot, I. B., & Obi-Egbedi, N. O., 2009).

Organic corrosion inhibitors can be classified into three types: anodic inhibitors, cathodic inhibitors, and mixed inhibitors. Anodic inhibitors work by reacting with the metal surface to form a passive layer that prevents further corrosion. Cathodic inhibitors work by reducing the rate of cathodic reaction, thereby slowing down the electrochemical reaction that causes corrosion. Mixed inhibitors work by a combination of both anodic and cathodic inhibition (Sahoo, P. K., Das, P., & Patil, S., 2017).

However, it is important to note that the use of organic corrosion inhibitors is not a permanent solution to corrosion and requires regular monitoring and maintenance to ensure their effectiveness. The inhibitors can also have negative impacts on the environment and human health if not handled properly. Therefore, it is important to follow the appropriate safety guidelines when using organic corrosion inhibitors.

2.4 Green Inhibitors

Green inhibitors, also known as environmentally friendly inhibitors, are a class of corrosion inhibitors that are derived from natural sources and are considered safer for the environment and human health compared to traditional chemical inhibitors. Green inhibitors are gaining popularity due to increasing awareness of environmental concerns and the need for sustainable solutions. Green inhibitors are used to prevent metals and alloys from corroding as they come into contact with aggressive environmental protection (Li *et al*., 2021).

Green inhibitors can be derived from various sources, including plant extracts, animal products, and waste materials. For example, extracts from plants such as neem, turmeric, and aloe vera have been found to have corrosion inhibiting properties. Similarly, proteins derived from animal sources such as egg white and casein have been used as corrosion inhibitors. Waste materials such as rice husk and sawdust have also been studied as potential sources of green inhibitors. Green inhibitors work by forming a protective layer on the metal surface, like traditional inhibitors, as illustrated in Figure 2.14. Overall, they are rich in ingredients with very high inhibition efficiency and are thus known as "Green Inhibitors." Green corrosion inhibitors that are perishable and free of harmful metals and alternative toxic chemicals (Al-Akhras and Mashaqbeh, 2021).

Figure 2.14 Mechanism of corrosion inhibition (Chung *et al*., 2019).

The efficiency of a green inhibitor, or any corrosion inhibitor, can be determined by several factors. According to a study by Hosseini *et al*. (2018), the efficiency of a green inhibitor is influenced by:

i. Inhibition Efficiency: The ability of the inhibitor to effectively reduce the corrosion rate of the metal substrate. This is typically evaluated through corrosion rate measurements or electrochemical techniques.

ii. Absorption Behavior: The extent of adsorption of the inhibitor molecules onto the metal surface. Strong adsorption of the inhibitor molecules leads to the formation of a protective film that hinders the corrosion process.

iii. Film Formation: The formation of a protective film on the metal surface, which acts as a barrier against corrosive species. The quality and stability of the film are important for long-term corrosion protection.

iv. Environmental Factors: The influence of environmental conditions, such as temperature, pH, and electrolyte composition, on the inhibitor's efficiency. These factors can affect the adsorption and film-forming behavior of the inhibitor.

v. Inhibitor Concentration: The concentration of the inhibitor in the corrosive environment. Higher concentrations of the inhibitor may lead to increased protection, up to a certain optimum concentration.

2.4.1 Plant Extraction

Plant extracts have been used as natural sources of corrosion inhibitors for many years due to their availability, low cost, and biodegradability. Extracts from various parts of plants, such as leaves, bark, seeds, and roots, have been studied for their potential to inhibit corrosion of metals. The main advantage of using plant extracts as corrosion inhibitors is their environmentally friendly nature. Plant extracts are non-toxic and biodegradable, reducing the risk of environmental pollution and health hazards. Additionally, plant extracts can be obtained from a wide variety of plants, making them a sustainable and renewable source of inhibitors.

The effectiveness of plant extracts as corrosion inhibitors depends on various factors, such as the chemical composition of the extract, the concentration, the type of metal, and the environmental conditions. Some of the common plant extracts used as corrosion inhibitors include neem, turmeric, aloe vera, and garlic. Plant extracts can be applied to the metal surface in various forms, such as as a solution, suspension, or emulsion. They can also be used in combination with other inhibitors to improve their effectiveness. However, the use of plant extracts as corrosion inhibitors requires careful consideration of their compatibility with the metal and the environment, as well as their stability over time. Table 2.4 shows commercial plant use as extraction of inhibitor corrosion.

Table 2.4 Commercial plant use as extraction of inhibitor corrosion

Author name (Year)	Plant name	Medium	Substrate	% Efficiency	Findings
Ramya *et al*. (2020)	Cassia alata leaf	1M HCl	Carbon steel	94%	The results showed that Cassia alata leaf extract exhibited good inhibitory properties, with an inhibition efficiency of up to 94% at a concentration of 400 ppm
El-Sayed *et al*. (2018)	Anethum graveolens	1M HCl	Carbon steel	94.2%	The results showed that Anethum

					graveolens extract exhibited good inhibitive properties, with an inhibition efficiency of up to 94.2% at a concentration of 200 ppm.
Abboud *et al*. (2018)	Ocimum basilicum	1M HCl	Carbon steel	97%	The results showed that Ocimum basilicum extract exhibited good inhibitive properties, with an inhibition efficiency of up to 97% at a concentration of 200 ppm.
Fouda *et al*. (2019)	Melissa officinalis	3.5w.t.% NaCl	Carbon steel	90.9%	The results showed that Melissa officinalis extract exhibited good inhibitive properties, with an inhibition efficiency of up to 90.9% at a concentration of 200 ppm.
Mokhtar *et al*. (2018)	Psidium guajava leaf	1M HCl	Carbon steel	93%	The results showed that Psidium guajava leaf extract exhibited good inhibitory properties, with an inhibition efficiency of up to 93% at a concentration of 400 ppm.
Tairi *et al*. (2019)	Eucalyptus globulus	1M HCl	Carbon steel	98%	The results showed that Eucalyptus globulus leaf extract exhibited good inhibitory properties, with an inhibition efficiency of up to 98% at a concentration of 300 ppm.

2.4.2 Aloe Vera Extraction

One such eco-friendly inhibitor is Aloe Vera extract, which has been reported to possess inhibitive properties against corrosion. Aloe vera, scientifically known as Aloe barbadensis Miller, is a perennial plant belonging to the Asphodelaceae family. It is native to arid regions and is cultivated worldwide for various purposes. The plant consists of thick, fleshy leaves containing a gel-like substance in the inner parenchymatous tissue. This gel is the primary component of interest for its medicinal properties (Surjushe *et al*., 2008). The extract from the leaves of Aloe Vera contains several compounds, including polysaccharides, anthraquinones, and organic acids, which have been found to possess inhibitive properties against corrosion.

Figure 2.15 Aloe Vera leaves (Carla Greenwood, 2021)

Aloe vera possesses a complex chemical composition. The gel derived from the leaves of aloe vera contains various bioactive compounds, including polysaccharides, such as acemannan and glucomannans, which are responsible for its gel-like consistency and have immunomodulatory and wound healing properties. Additionally, aloe vera gel contains vitamins, such as vitamin C, E, and beta-carotene, which possess antioxidant activity. It also contains minerals like calcium, magnesium, zinc, and potassium, which are essential for various physiological functions. Phenolic compounds, including flavonoids and phenolic acids, contribute to the antioxidant and anti-inflammatory potential of aloe vera. Enzymes like bradykinase and catalase, present in the gel, are known for their anti-inflammatory and antioxidant effects. These diverse chemical constituents collectively contribute to the therapeutic properties of aloe vera (Surjushe *et al*., 2008). Table 2.5 shows the taxonomic position of aloe vera.

Table 2.5 Aloe vera taxonomic classification (International Aloe Science Council, 2002)

Taxonomic Classification	Plant Example
Division	Magnoliophyta
Class	Liliopsida
Order	Asparagales
Family	Xanthorrhoeaceae
Genus	Aloe
Species	Aloe vera

As shown in Table 2.6, this study offered a collection of other researchers' investigations on aloe vera leaves for use as inhibitors, and also a review of their performance (%) against chemical elements of the extraction

Table 2.6 Aloe vera leaves extract as inhibitor.

Author Name (Year)	Chemical Constituent	Substrate	%Efficiency	Finding
Okafor *et al*. (2012)	1 M HCl	Carbon Steel	94.4%	The results showed that Aloe Vera extract exhibited good inhibitive properties, with an inhibition efficiency of up to 94.4% at a concentration of 5 g/L.
Singh *et al*. (2018)	3.5% NaCl	Carbon Steel	90.7%	The results showed that Aloe Vera extract exhibited good inhibitive properties, with an inhibition efficiency of up to 90.7% at a concentration of 3 g/L.
Ali *et al*. (2019)	1M HCl	Carbon steel	94.2%	The results showed that Aloe Vera extract exhibited good inhibitive properties, with an inhibition efficiency of up to 94.2% at a concentration of 1 g/L.
Sudhakar *et al*. (2018)	CH_3COCl	Carbon steel	98%	The results showed that Aloe Vera extract exhibited good inhibitive properties, with an inhibition efficiency of up to 98% at concentration of 6 g/L

Preparation of stock solution of aloe vera leaves extract from the previous study shows in Table 2.7

Table 2.7 Aloe vera leaves extract method.

Author name (Year)	Method
Ali k. *et al* (2016)	1. Aloe vera was obtained naturally from the cultivated plant, which was cultivated in Iraq. 2. The lower part of the Aloe Vera plant was cut off because it contains a toxic substance that causes an allergic reaction if applied directly to the skin. 3. This reaction is caused by anthraquinones and glycosides and it flows from the cut leaf to get dried with or without the effect of temperature

	4. The toxic substance was disposed of by soaking the cut part for 20 min in distilled water. 5. The water was replaced every 5 min. The colour of the toxic substance turns yellow as the water mixes with the substance. 6. After 20 min, it can be observed that the water returns to pure distilled water free of discoloration. Aloe vera was cut from both sides to extract the gel. Weigh 20 g of gel and add it to 100 ml of distilled water. 7. The resulting material was placed on a magnetic stirrer device and two magnetic bars were added because the material is of a viscous nature that is difficult to disintegrate. The temperature was fixed at 60 Celsius degrees and the rotation rate was 10 rounds per minute. 8. This was done for 10 min and then the solution was left to cool. 9. The resulting solution was filtered, which is a solution of a viscous colloidal nature. 10. The resultant impurities, which are difficult to disintegrate plant materials resulting from the skimming process, were removed before preparation. 11. Filtering was carried out using a funnel and gauze.
A.A. Maan *et al* (2021)	1. The leaves with uniform maturity, size, colour and freshness are selected and washed with tap water followed by rinsing with distilled water (Pinzon *et al*., 2018; Shah & Hashmi, 2020). 2. In some studies, rinsing with mild chlorine solution (as a disinfectant) has also been reported (Rasouli *et al*., 2019). 3. After washing, the leaves are prepared by cutting their base (1 inch), top (2–4 inches) and sharp spines. For some applications, aloin (a bitter and yellow-brown coloured compound) can be removed from the leaves by immersing them vertically in a water container for an hour (Rafieian *et al*., 2019). 4. The green coloured outer cortex layer is removed, and the colourless gel matrix is scooped out with the help of a spoon. The extracted gel is crushed in a domestic blender. 5. In some studies, further homogenization of blended gel using a homogenizer (10,000 rpm) has also been reported. 6. The mixture is then filtered to remove impurities, pasteurized, cooled and stabilized with ascorbic or citric acid (Kanatt & Makwana, 2020; Khatri *et al*., 2020; Parven *et al*., 2020). 7. The separation of anthraquinones, a laxative compound, is also reported through activated carbon filtration (Nasution *et al*., 2015). 8. The prepared gel extract is stored at refrigerated temperature. 9. Water is the major component (~98%) of fresh Aloe vera gel. Remaining proportion consists mostly of carbohydrates (>60% of total solids), mainly mono- and polysaccharides. 10. Partially acetylated mannans (acemannan) have been reported to be the primary polysaccharides by some researchers while others have reported pectic substances as primary polysaccharides.

	11. These variations occur due to geographical and seasonal variations as well as the extraction and processing techniques (Hamman, 2008). 12. Monosaccharides are present in the form of D-glucose, D-mannose, arabinose, galactose and xylose (Suriati *et al.*,2020). 13. Other compounds such as proteins, dietary fibers, lipids, minerals, vitamins, enzymes and different active compounds are present in minor quantities (Minjares-Fuentes *et al.*, 2016).
J. Wu *et al.* (2022)	1. Dry leaves of aloe, Aloe vera, were purchased from Xinglong Plantation from Hainan Province in China. 2. To prepare herbal extracts, 10 g leaves were pre-soaked in 100 ml distilled de-ionized water for 30 min following by heating reflux extraction at 100 ◦C for 2 h. 3. Removed the dregs by centrifugation at 12,000 × g. The herbal extracts were finally frozen dry and stored in -20 ◦C. 4. For herbal fractionation, 9 g extracts were dissolved in 200 ml water and loaded onto a column containing 150 g pre-treated macroporous resin D101. 5. After overnight absorbing, the resin was eluted with 400 ml water and followed by being eluted with 600 ml 95% ethanol. The water and ethanol eluents were subsequently dried at 30 ◦C and generated the fractions, AHW and AHE, respectively. 6. The fraction of AHW was further dissolved in 10 ml water and precipitated with 40 ml ethanol at 4 ◦C, overnight. 7. The supernatant (AHW-S) and precipitation (AHW-P) fractions were obtained. The aloe vera extract, AHW and AHW-P were dissolved in water and degermed with 0.22 µm filter. AHE and AHW-S were dissolved in DMSO. 8. All samples were stored in -20 ◦C.

In conclusion, Aloe Vera extract has been found to possess inhibitive properties against corrosion of carbon steel in different corrosive environments. The inhibitive mechanism of Aloe Vera extract is mainly through adsorption or film formation on the metal surface. The use of Aloe Vera extract as a corrosion inhibitor is a promising approach to develop eco-friendly and sustainable corrosion inhibitors.

2.5 River Water

Malacca's river water was used for this project. Malacc river is a river located in Malacca, Malaysia. It holds historical significance as it played a vital role in the development of the city of Malacca, which was once a bustling trading port in Southeast Asia. Malacca river flows through the heart of the city, cutting across the historical district. It is surrounded by charming buildings, colonial-era architecture, and cultural landmarks, which adds to its aesthetic appeal. In recent years, the river has undergone extensive restoration and beautification efforts. The riverbanks have been revitalized with walkways, landscaped gardens, and vibrant murals. The river itself has been cleaned and transformed into a vibrant waterway, with boats and river cruises offering a unique way to explore the city.

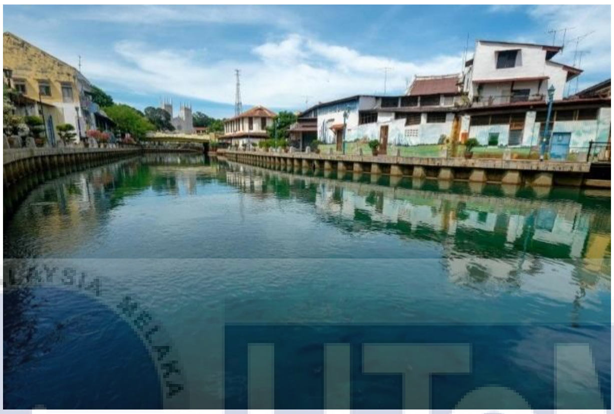


Figure 2.16 Malacca river

Malacca river has become a popular tourist attraction, drawing visitors who are interested in exploring the city's rich history and cultural heritage. It provides a picturesque backdrop for leisurely strolls, boat rides, and waterfront dining experiences. Overall, Malacca river is not only a physical waterway but also a symbol of Malacca's past and present. It showcases the city's historical roots while serving as a vibrant and rejuvenated focal point for locals and tourists alike. In this study Malacca river water as one of the medium to immerse the substrate.

2.6 3.5wt.% NaCl Medium

3.5 wt.% NaCl refers to a solution of sodium chloride where the concentration of NaCl is 3.5% by weight. This solution is commonly used as a standard reference solution in various scientific and industrial applications. The 3.5 wt.% NaCl solution is particularly significant in the field of corrosion studies. It is used as a corrosive environment in laboratory experiments to simulate the effects of saltwater or saline conditions on materials, especially metals. One of the main applications of the 3.5 wt.% NaCl solution is in corrosion testing, where it serves as a representative electrolyte for studying the corrosion behaviour and performance of materials.

It is often employed in standardized tests such as ASTM G31 (Standard Practice for Laboratory Immersion Corrosion Testing of Metals) and ASTM G48 (Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride Solution). The choice of the 3.5 wt.% NaCl solution as a reference solution is based on its similarity to the salt content found in seawater, which is approximately 3.5% salinity. By subjecting materials to this solution, researchers can evaluate their corrosion resistance, pitting susceptibility, and other relevant properties in a controlled and standardized manner.

2.7 5M HCl Medium

5M HCl refers to a hydrochloric acid solution with a concentration of 5 moles per liter (M). Hydrochloric acid (HCl) is a strong acid commonly used in various laboratory applications, industrial processes, and chemical reactions. 5M HCl is a highly concentrated solution that is known for its corrosive properties and strong acidity. It is widely used for pH adjustment, chemical synthesis, and acid-base reactions in the laboratory. The high concentration of HCl in the solution allows for efficient and rapid reactions in many chemical processes. The high concentration of HCl in the 5M solution makes it a powerful reagent for chemical synthesis. It is commonly used in organic chemistry reactions, such as hydrolysis, esterification, and condensation reactions. The strong acidity of 5M HCl enables efficient and rapid reactions, making it valuable in various laboratory-scale and industrial-scale synthetic processes. The 5M HCl solution serves as a potent acid for acid-base reactions. It can act as a proton donor, reacting with bases to form salts and water. This property makes it crucial in various titration procedures, neutralization reactions, and pH determination experiments.

2.8 Summary of Literature Review

On the whole, carbon content in low carbon steel ranges from 0.05% to 0.25%, with up to 0.4% manganese content. In this study, low carbon steel acted as a substrate. Moreover, microstructures are made up of ferrite and pearlite constituents. Otherwise, we also discuss how corrosion is characterized as the failure of metals and alloys caused by chemical or electrochemical exposure to their surroundings. Corrosive metals are classified into eight types based on wet or aqueous corrosion.

Furthermore, this chapter covered the plants that are most commonly used in this study. Since each of these plants had its own composition that supported metal or other materials to resist corrosion. Therefore, the corrosion proetction method on the carbon steel surface was also discussed in this chapter. Specifically, the green inhibitor has been used in this study which are aloe vera leaves and their composition extraction. On the other hand, the substrate has been gathered by an immersion test in river water, 3.5wt.% NaCl and 5M HCl.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter detail out the research methodology from start until end of processes such as materials, stage preparation, fabrication processes, and testing. The process flow diagram, shown in Figure 3.1, shows the procedures necessary to finish this research, including input and output. Aloe vera leaves were therefore extracted, and the substrate was a cylindrical low carbon steel specimen with dimensions of 25 mm in diameter and 10 mm in thickness. The correct amount of the plant was obtained when the aloe vera leaves were removed into a solution and filtered. Additionally, to remove the waste component, both plant extractions are blended, crushed, and then heated using a magnetic stirrer.

The boiled raw material has then been filtered to remove the fiber and other composition such as the water composition to obtain the extraction. Eventually, at the appropriate temperature, the extract has been put in the oven for a few days to ensure that the water composition is reduced. As a result, when the extraction comes out of the oven, it resemble as a jelly. In order to figure out the efficiency of aloe vera extract as green inhibitor for low carbon steel, it has been immersed with river water, 3.5%w.t. NaCl medium, and 5M HCl medium and poured to the container containing the specimen to be immersed for observation over the necessary number of days. The observation was made to determine the inhibitor's efficiency by calculating the weight loss, corrosion rate, inhibitor efficiency that occurs on the substrates and SEM and EDX to determine the extraction's inhibition efficiency against low carbon steel surface.

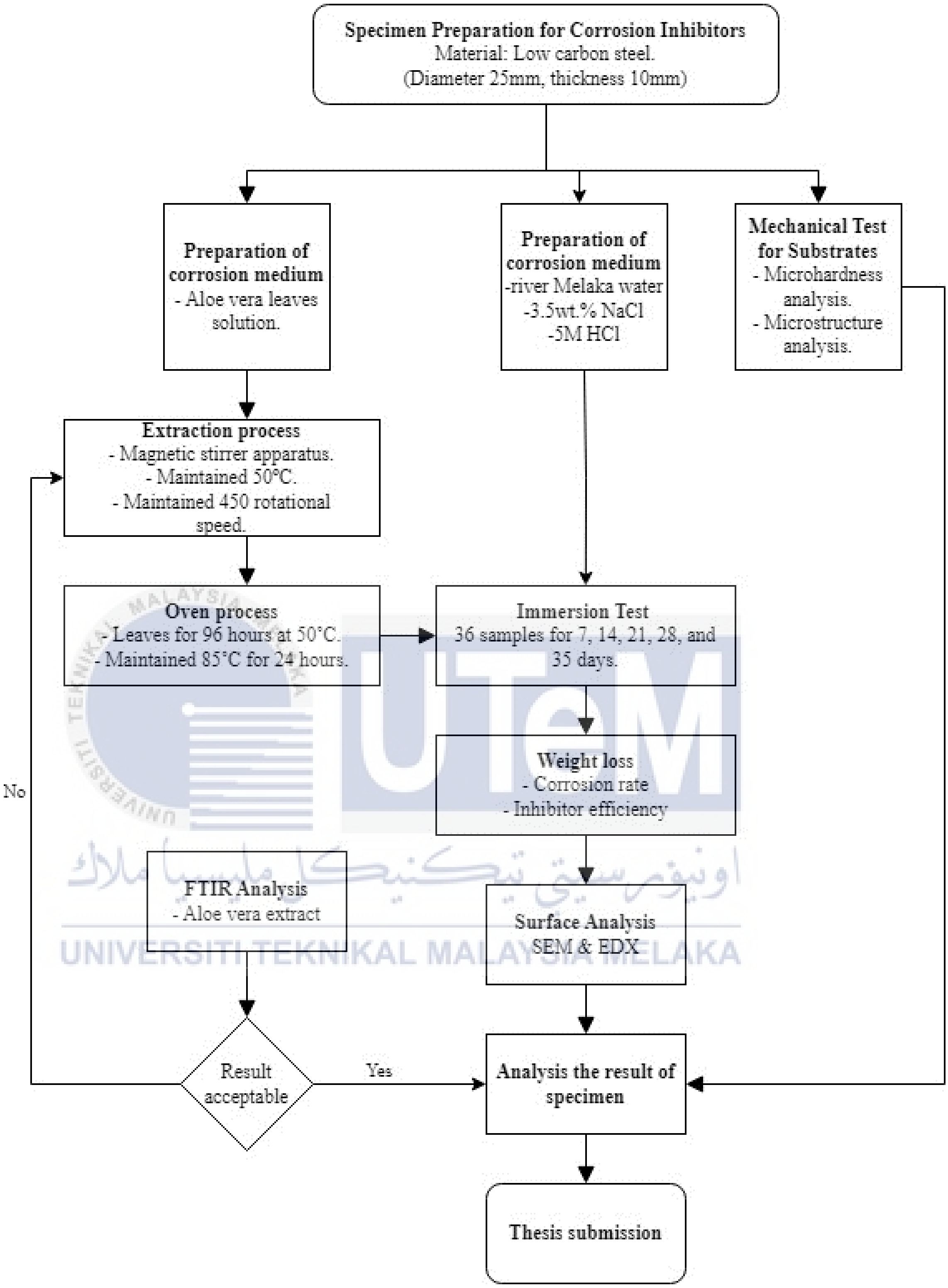


Figure 3.1 The process flow for this study.

Specimen Preparation for Corrosion Inhibitors Material which is low carbon steel with diameter 25mm and 10mm thickness. Preparation of corrosion medium which is aloe vera leaves solution. Immersion test in river water, 3.5wt.% NaCl and 5M HCl. 36 samples for 7, 14, 21, 28, and 35 days. Extraction process using magnetic stirrer apparatus, maintained 50ºC, maintained 450 rotational speed, oven process, leave for 96 hours at 50˚C and aintained 85˚C for 24 hours. ATR-FTIR analysis for aloe vera extract. Mechanical test for substrates (microhardness analysis and microstructure analysis). Surface Analysis SEM & EDX. Calculation of weight loss (corrosion rate and inhibitor efficiency). Analysis the result of specimen. Thesis submission

3.2 Sample Preparation

The substrates which is low carbon steel has been prepared by using Band Saw cutting machine at FTKMP laboratory as shown in Figure 3.2 operation of Band Saw cutting machine.

Figure 3.2 Band Saw cutting machine.

Additionally, as shown in Figure 3.3, this specimen has dimensions that are roughly coin-shaped with a 25 mm diameter and a 10 mm thickness. These measurements were made using vernier callipers.

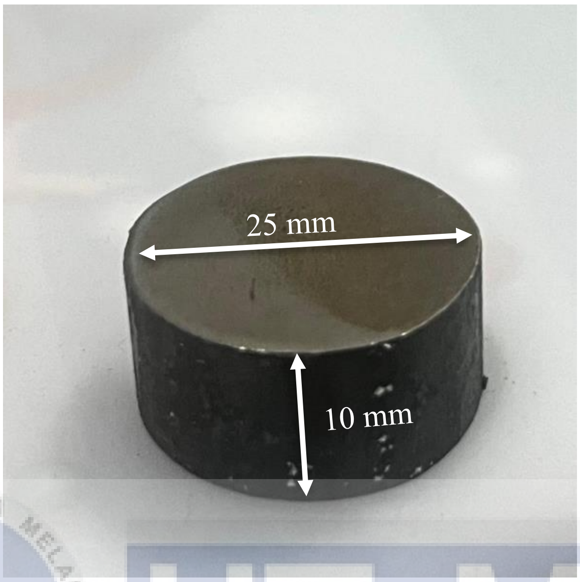


Figure 3.3 Substrates used as a corrosion test.

Before mounting in the mounting press machine, the specimen were cut into four little pieces with a chainsaw. At the Material Science Laboratory, mounting presses and equipment are used to enclose specimens of metal, ceramic, or other materials, particularly one small specimen, with a mounting compound and appropriate mounting resin. This allows for sample preparation for examination with microscopes, hardness testers, or spectrometers, including polishing, grinding, and other operations. The mounting metallography press machine is depicted in Figure 3.4.

Figure 3.4 Kemet Mounting Metallography Press.

The specimen has been crushed with abrasive paper at grits of 60, 150, 360, 600, 800, and 1200 to get a smooth surface. Furthermore, as shown in Figure 3.5 that each abrasive paper has been crushed for a few minutes in a grinding machine. Before switching to a new grade of paper, the specimen was meticulously cleaned with purified water to prevent contamination from the coarse grit that was present on the specimen's surface.

Figure 3.5 Mecapol Metallographic Polishing machine.

3.3 Inhibitor Extraction

Before the extraction process is complete, the raw materials such as aloe vera leaves went through extraction from the solid to the liquid state. Moreover, the raw material had to be processed in order to create the extracts, which requires the use of the proper apparatus.

3.3.1 Aloe Vera Extraction

To obtain the best extraction yield, 40 g of dry aloe vera leaves were blended together with 500 mL of deionized water. After that, the blended ingredients were poured into the beaker and the 1000 mL of deionized water was added. Then, boiled it for 1 hour at 50˚C using a magnetic stirrer until the extraction concentrated. Moreover, the filtrate of the aloe vera leaves extraction had been separated from the residue using filter paper. Later, the extracted juice was put on the aluminium foil and a hole was made. Additionally, the extraction juice was ready to be inserted into the oven. The juice was put into the laboratory oven at 50˚C for 96 hours and kept constant at 85˚C for 24 hours. Lastly, a series of aloe vera leaf extractions were performed, as Figure 3.6 depicts the process of extraction of aloe vera leaves.

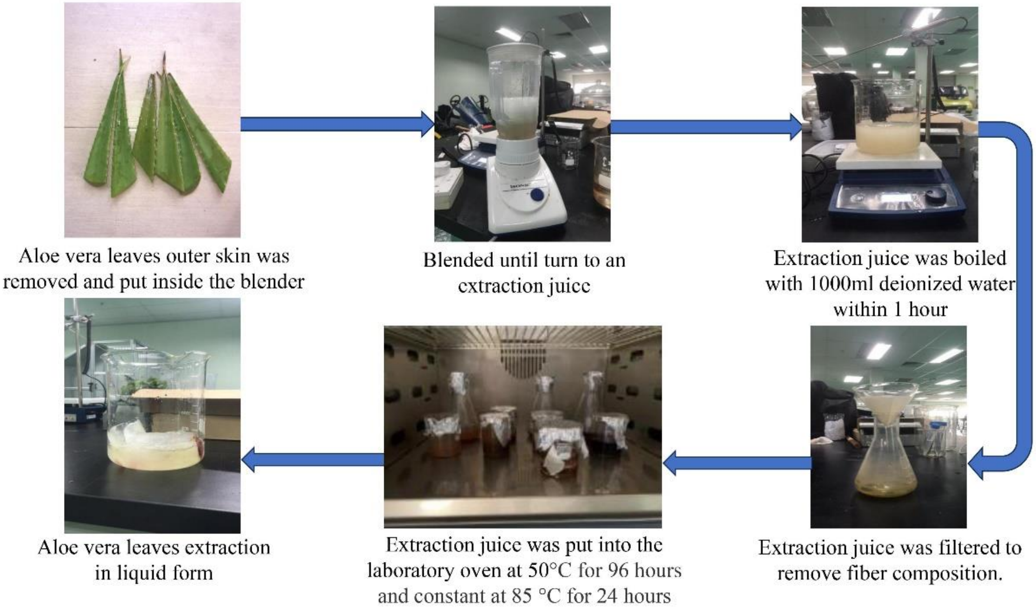


Figure 3.6 Aloe Vera leaves extraction processed.

3.3.2 Attenuated Total Reflectance – Fourier Transform Infrared Spectroscopy (ATR – FTIR)

ATR – FTIR spectroscopy is among the most efficient tools for identifying functional groups in membranes and also some possible molecular interactions between membrane chemical compounds (Mohamed *et al*., 2017). Therefore, the ATR-FTIR machine at Fakulti Kejuruteraan Pembuatan (FKP) laboratory was used in order to determine the composition of the extraction content for aloe vera leaf extraction. Hence, the chemical bonding and atoms in some natural raw material compositions assist in the corrosion prevention of substrates and other metals. Furthermore, ATR – FTIR can be used to demonstrate the inhibition efficiency of the extraction of raw materials. The ATR – FTIR machine is depicted in Figure 3.8.

Figure 3.7 Jasco FT/IR-6100 machine.

3.4 Mechanical Testing

Mechanical properties are the physical properties that a material exhibits when forces are applied to it. In this research, the purpose of mechanical testing is to evaluate the hardness and microstructure of low carbon steel. It is impossible to handle the corrosion of carbon steel in an acidic medium. Therefore, etching is performed, and the process is to enhance the contrast on surfaces in order to visualize the microstructure or macrostructure. Moreover, the substrates that have low carbon steel morphology and the hardness of the low carbon steel content as well as their material properties were investigated.

3.4.1 Microstructure Testing

Microstructure analysis is used in a variety of industries to identify the properties of a substance at various stages of testing. As a result, the aim of this study is to research the connection between microstructure, surface condition, and inhibitor efficiency in corrosion. Due to the high hardness and low ductility, we have learned from this research that yield strength and ultimate tensile or compressive strength are difficult to determine. As a result, pre-corrosion diminishes inhibitor effectiveness, though the effect is microstructure dependent. Using an optical inverted research microscope, we can examine the microstructure of low carbon steel substrates, as shown in Figure 3.8. Furthermore, low carbon steels are arguably produced in greater quantities than other alloys. In view of the fact that the carbon concentration in these alloys is low and inadequate to strengthen them by heat treatment while they are strengthened by cold work.

Figure 3.8 Axio Upright Light Microscope.

3.4.2 Hardness Testing

Hardness measurement is a method for assessing the strength or durability penetration when test surfaces are very solid or soft, or when testing small areas of composite. It may provide precise and dependable data on the surface properties of materials with multi-phase, non-homogeneous, or crack-resistant microstructures. A cylindrical probe guided to the surface under such loads had been used in the hardness test process. Typically, abuse has a set period of residency. To determine hardness, the scale or depth of a cylinder probe had been measured in traditional mechanical experiments. The level of aggression is classified into two categories which is macrohardness and microhardness. Two common microhardness techniques are the Vickers and Knoop hardness checks (Wang *et al.*, 2019). Hence, the regular Rockwell scale for the substrate of this research is indenter type ball – 1.588 mm, the total force is 294.2 N and the hardness symbol is HRB. Figure 3.9 shows the machine that is used for microhardness testing.

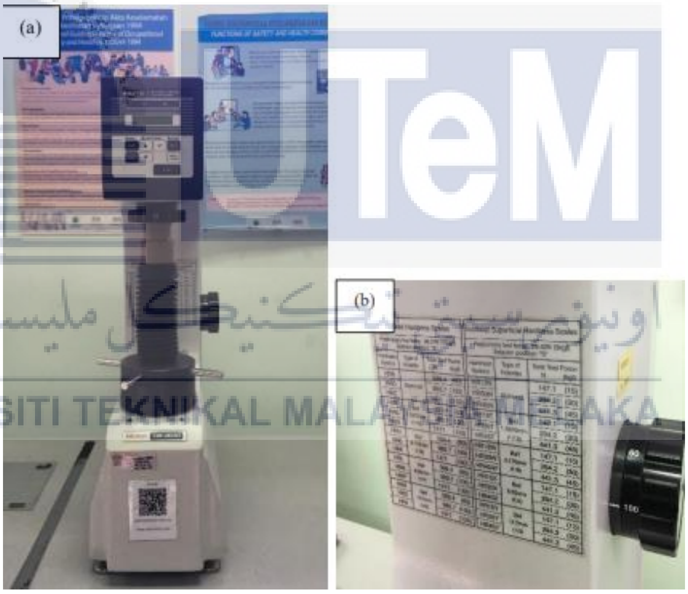


Figure 3.9 Mitutoyo Automated Rockwell Hardness Testing Machine (a) and (b).

3.5 Corrosion Test

Corrosion testing is to determine corrosion materials resistance to environmental conditions such as temperature, humidity, and salt water. Aluminium alloys are subjected to a wide variety of corrosion tests, and in this research study the low carbon steel has been used in corrosion tests. On the other hand, these must be personalised for specific types of corrosion, so that those typically used during surface attacks such as pitting and intergranular corrosion and can be distinguished from those used during penetrating attacks such as exfoliating corrosion. Corrosion has the potential to permanently harm materials, equipment, properties, and pipelines. This loss is not only expensive to repair financially but the resulting deterioration of the machinery results in downtime in production (Kadhim *et al.*, 2021). The detail of ASTM G1 as shown in Appendix A.

3.5.1 Immersion Test

Immersion testing is the most commonly used technique for monitoring metal corrosion in aqueous solutions and the process of corrosion degradation caused by the length of time exposed to a corrosive atmosphere, as well as other factors that may contribute to the corrosion period. The detail of ASTM G1 and G31 are shown in Appendix A and Appendix B. Moreover, immersion tests are used in industries that are prone to immersion conditions and they provide uniform results for corrosion of alloys. These factors also include the solution’s composition, temperature, oxygenation, volume, velocity, and the impact of the sea surface, specimen material selection, specimen immersion method, test time, and specimen cleaning procedure. Apart from that, everything simply concludes with a list of elements that can be used in the regular immersion test sample as well as Figure 3.10 depicts an illustration of the immersion test set-up that had been performed in this research study.

Figure 3.10 Immersion test set up.

3.5.1.1 Visual Inspection

Great importance has previously been dedicated to the numerous facets of the inspection process, and the results show that the factors impacting inspection efficiency are nuanced and difficult to regulate. The fact that the majority of manufacturers use visual inspection techniques suggests that this is not widely understood and that there is a completely erroneous belief in the efficiency of 100% pure visual inspection. Therefore, the sample has been divided into two group, which are: samples with the presence of aloe vera extract that was immersed in river water, 3.3w.t.% NaCl and 5M HCl and samples without the presences of aloe vera that also was immersed in river water, 3.3w.t.% NaCl and 5M HCl through this research. Each medium for each solution contains six low carbon steel specimens and has been observed within 7, 14, 21, 28, and 35 days as shown in Table 3.1. The specimen was taken out according to the day that had been decided, and the result was confirmed, as was the calculation for weight loss measurement and corrosion rate.

Table 3.1 Sample A of Immersion Test (with the presences of aloe vera extract)

Medium	Day 7	Day 14	Day 21	Day 28	Day 35
River water	1	1	1	1	1
3.5w.t.% NaCl	1	1	1	1	1
5M HCl	1	1	1	1	1

Table 3.2 Sample B of Immersion Test for (without the presence of aloe vera extract)

Medium	Day 7	Day 14	Day 21	Day 28	Day 35
River water	1	1	1	1	1
3.5w.t.% NaCl	1	1	1	1	1
5M HCl	1	1	1	1	1

3.5.1.2 Weight Loss Measurement

Weight loss measurements have been execute at various concentrations by immersing substrates in an HCl acid solution with various types of inhibitors, or even without inhibitors. The specimens have then been removed and inspected for 7, 14, 21, 28, and 35 days approximately and had washed with acetone, cleaned, and measured using microbalance. Furthermore, all analyses were carried out and measured using a formula. Apart from that, the study was performed several times and the average data has been recorded. The inhibitor concentrations used in the weight loss analysis were measured in parts per million (ppm) by weight. Using the equations mentioned below, the weight loss or surface coverage (θ) was calculated.

Weight loss (θ) = Wo – Wi Wo -------------------------------- (1)

Where, Wo represents weight loss without the inhibitor and Wi denotes weight loss with the inhibitor.

3.5.1.3 Corrosion Rate

The corrosion rate is the rate at which a particular metal deteriorates in extremely particular conditions. The rate is controlled through environmental conditions due to the composition and condition of the steel. Moreover, corrosion rates within the U.S. are usually calculated in mils per year. In other words, the corrosion rate is determined by the number of millimetres (thousandths of an inch) per year that are penetrated.

The corrosion rate was calculated in this research by using this equation:

$$Corrosion\ Rate\ (mm/year) = \frac{KW}{ATD} \text{ -------------------------------- } (2)$$

Where:

K = Constant, 8.76 mm/y (mils(10^4)per year)

W = Mass loss (gram) A = Exposed area ($A=\pi r^2+\pi r^2$)

T = Immersion time (hours)

D = Density in g/cm^3 (7.87 g/cm^3)

3.5.1.4 Inhibitor Efficiency

When the inhibitor concentration, immersion duration, and temperature are increased and the inhibition efficiency increases. In order to investigate the inhibitor efficiency over substrate corrosion, the inhibitor efficiency (I.E%) was evaluated by the subsequent formula:

I.E % = Wo – Wi Wo × 100 -------------------------------- (3)

Where, I.E is inhibition efficiency, Wo = weight loss without inhibitor, Wi = weight loss with an inhibitor.

3.6 Surface Study by Scanning Electron Microscopy (SEM) and Energy Dipersive X-ray (EDX)

The surface morphology has an important impact on the conditions of re-agent adsorbent and dispersion, and knowledge of the surface layer composition authorizes analysis of the shield’s characteristics while being up-to-date with an energetic component-appropriate solvent and through high-temperature processes. Scanning electron microscopy (SEM) with a proper set of attachments could also be used to examine the morphology and chemical composition of the surface layer (Stepanova *et al*., 2018). The effect of inhibitors and corrosion on the surface of low carbon steel were investigated in this research study. As a result, employing a focussed stream of powerfully energetic electrons, the SEM generates a number of signals on the surface of a solid object.

Additionally, the effects of inhibitors and corrosion on the surface of low carbon steel were investigated in this research. As a result, employing a focused stream of powerfully energetic electrons, the SEM generates a number of signals on the surface of a solid object. In general, the SEM results offer information about the morphology of the material such as shape, structure, colour, scale, and pattern. Furthermore, the sample in the SEM must be conductive, and the imaging period is between 0.1 and 1 minute. The whole field of view measures one millimetre. The dimensions of the SEM are two-dimensional and shows in Figure 3.11.

Figure 3.11 Zeiss SEM machine analysis.

In contrast, Energy-dispersive X-ray spectroscopy (EDX) is a form of spectrum analysis in which a ray impacts a specimen, activating an electron in an inner shell, triggering its emission and therefore the development of an electron hole within the element's electronic structure. Besides, an electron from an elevated energy shell fills the gap and will ejecting the energy gap between the 2 shells as X-rays that strike the detector. As a result, the amount of energy is constant for each part and detection provides important information about the presence of certain elements (Polini and Yang, 2017). The EDX machine analysis is shown in Figure 3.12.

Figure 3.12 JSM-6010PLUS/LV EDX machine analysis.

3.7 Summary of Methodology

In summary, this chapter describes the method proposed for developing a new corrosion inhibitor formula. The study approach’s main goal is to generate faster, less stringent, and more accurate calculations, resulting in more efficient performance. Besides, the method’s ultimate aim is to succeed. The subsequent chapter has now introduced several cases to check and build on the suggested approaches presented in this chapter. Equally important, the corrosion performance of the inhibitor has been evaluated using an immersion test in which each sample contains six low carbon steel specimens and has been observed within required days. The specimen was taken out according to the week that had been decided, and the result was calculated for weight loss measurement and corrosion rate. Furthermore, the microstructure and microhardness were examined to determine the inhibitor’s effectiveness on substrates that are low carbon steel. The shape and chemical content of the outer layer were examined using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX). Accordingly, as an outcome of this corrosion inhibition, corrosion efficiency and corrosion incidence against low carbon steel substrates would be considerably enhanced.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results and analysis of the development of an efficient, low-cost, and environmentally friendly corrosion inhibitor. A study was conducted on the use of a biodegradable aloe vera leaf extract as a corrosion inhibitor for carbon steel in three different mediums: river water, 5M HCl, and 3.5wt.% NaCl. This chapter aims to identify the most effective extract in reducing the effects of corrosion on low-carbon steel and to reveal its mechanical qualities.

To determine the best inhibitor, we conducted an immersion test and observed the composition in the extraction reaction. We also periodically inspected the specimen visually to assess its level of corrosion. Subsequently, the weight loss of the specimen was measured to calculate the corrosion rate and inhibitor efficiency. Additionally, the properties of the corrosion inhibitor were examined using scanning electron microscopy (SEM), energy dispersive X-ray (EDX), and attenuated total reflectance – fourier transform infrared pectroscopy (ATR – FTIR). The corroded surface of the specimen was analyzed using SEM, and the material composition was identified using EDX. SEM and EDX morphological analysis confirmed the results, demonstrating the extract's strong inhibitory efficiency over a wide temperature range.

4.2 Sample Composition

To confirm that the material used is low carbon steel, Glow Discharge Spectrometry (GDS) was used to determine its detailed composition, as shown in Appendix C. This technique is used to directly determine the elemental composition of a material. The elemental values of low carbon steel are presented in Table 4.1 below.

Table 4.1 Glow Discharge Spectrometry (GSD) table.

Element	Composition (wt%)
Iron (Fe)	98.4
Carbon (C)	0.174
Manganese (Mn)	0.620
Phosphorus (P)	0.0277
Sulfur (S)	0.0212
Silicon (Si)	0.176
Copper (Cu)	0.280
Nickel (Ni)	0.0777
Chromium (Cr)	0.135

4.3 Mechanical Testing

Mechanical testing was conducted at the Material Science Laboratory to determine the microstructure of the specimen and its hardness, which was used to test the strength of low carbon steel for this research.

4.3.1 Microstructure Testing

In this test, low carbon steel underwent surface treatment through polishing and etching using appropriate chemical reagents. The surface of the low carbon steel was then analyzed using an optical microscope with varying magnifications of lenses to observe its microstructure. Microscopic studies serve various purposes, with one of the most important being the identification of materials. Furthermore, the microstructure test is essential to demonstrate the significance of the chemical composition of low carbon steel. As the carbon content of the steel increases, the amount of pearlite produced in the metal microstructure also increases.

Figure 4.1 (a) and (b) show the microstructure of ferrite and pearlite on low carbon steel, which can only be observed at high magnification. To ensure accurate results, it is necessary to use a specimen with small dimensions, such as one per four of a circular low carbon steel. It is important to focus on the most representative areas for this research. The specimen should be obtained from a section of the piece under research to include both fundamental observations.

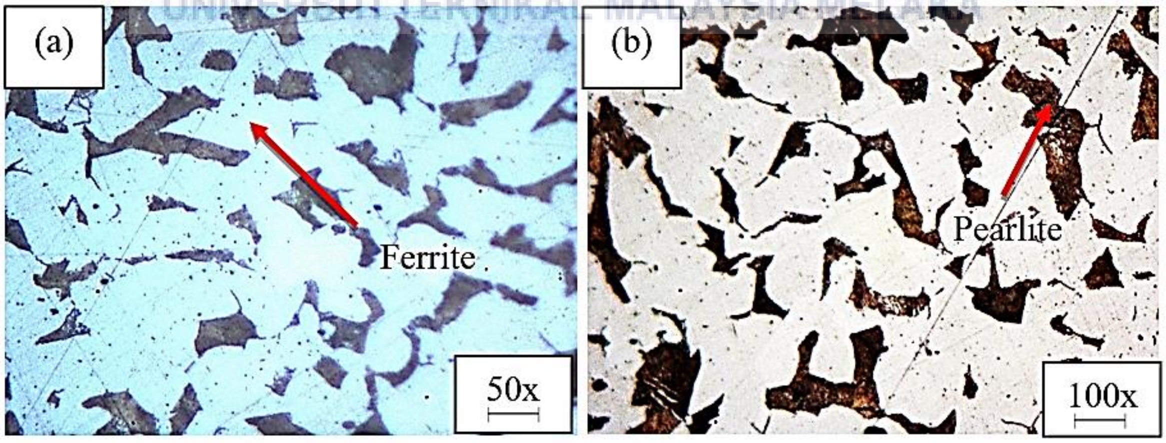


Figure 4.1 Microstructure Analysis at Magnification (a) 50 µm and (b) 100 µm

4.3.2 Hardness Testing

Hardness testing is a mechanical test used to measure a material's resistance to deformation, indentation, or scratching. It provides information about the material's mechanical properties, such as strength and wear resistance. In this case, the low carbon steel's strength was demonstrated through the Rockwell Hardness Testing method, which was conducted in the Material Science Laboratory. The method selection depends on the indentation hardness of the substrate. The Rockwell test is a method for measuring the depth of penetration of an indenter under a large load (major load) compared to the depth of penetration under a smaller preload (minor load). The result is a dimensionless number labelled HRA, HRB, HRC, and so on, up to HRV, with varying total test force. In this research, the substrate was evaluated using the regular Rockwell scale with a ball indenter of 1.588 mm, a total force of 294.2 N, and a hardness symbol of HRB. Figure 4.2 displays the specimen with holes.

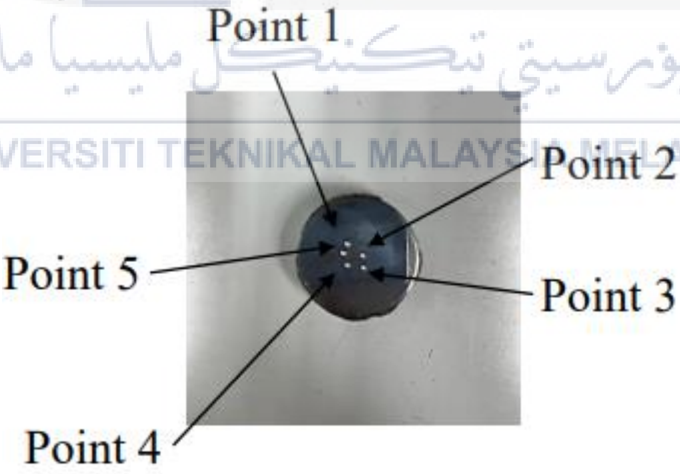


Figure 4.2 Specimen with holes

Table 4.2 presents the results of the Rockwell hardness test on substrates at five points, displaying the best overall average reading. The corresponding bar chart in Figure 4.3 illustrates the results of the hardness testing.

Table 4.2 Microhardness Test Result

Hardness Rockwell Ball	**Point 1**	**Point 2**	**Point 3**	**Point 4**	**Point 5**
Reading (HRB)	75.7	75.6	75.4	76.2	76.5
Average	75.88				

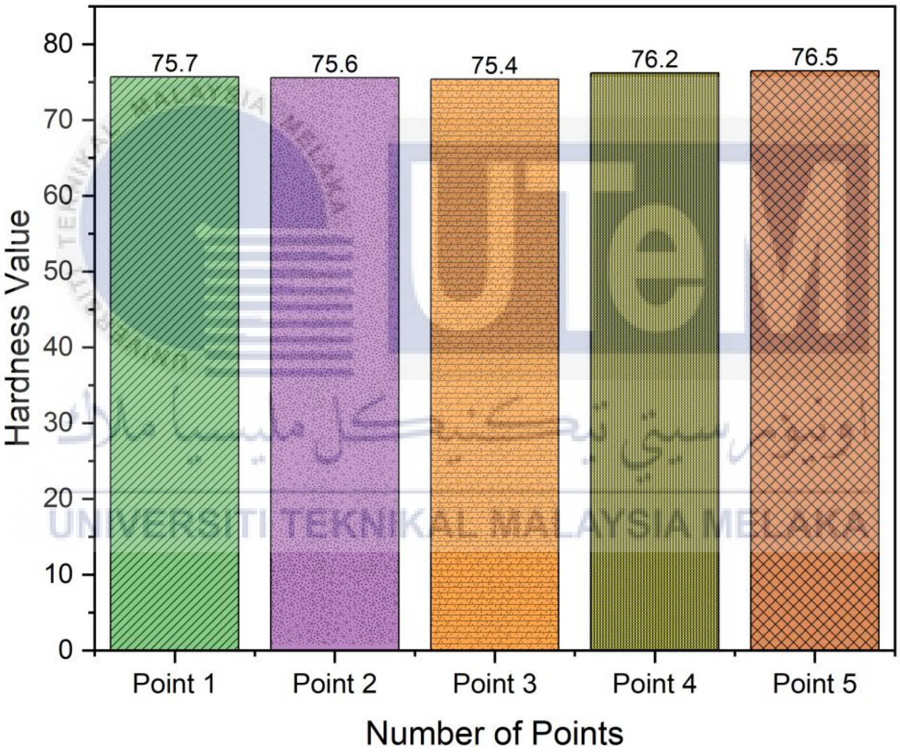


Figure 4.3 Bar Chart of Hardness Rockwell Test.

4.3.3 Attenuated Total Reflectance – Fourier Transform Infrared Spectroscopy (ATR – FTIR) Analysis of Aloe Vera Extract

This research used attenuated total reflectance – fourier transform infrared spectroscopy (ATR – FTIR), which can be defined as a technique used to study the interaction of infrared (IR) radiation with matter. ATR – FTIR provides information about the molecular composition, structure, and functional groups present in a sample. The ATR – FTIR spectrometer generates high-resolution spectral data over a large spectral range simultaneously. Table 4.3 shows the wavelength of peaks used and their corresponding functional groups. The pattern graph indicates that both extracts had the same peak pattern over the wave number, despite different transmittance levels, as shown in Figure 4.4.

Table 4.3 Wavelength of peaks used for ATR – FTIR analysis and corresponding functional groups.

Wavelength Area (cm^{-1})	Functional Groups
675-995	C-H
1000-1300	C-O
1340-1470	C-H
1550-1640	N-H
2850-2970	C-H
3200-3600	O-H

4.3.4 ATR – FTIR Analysis of Aloe Vera Leaves

The functional groups of information contained in the chemical compounds of aloe vera leaves extract can be identified using ATR – FTIR. Figure 4.5 depicts the infrared spectrum of aloe vera leaves extract. The ATR – FTIR of aloe vera leaves extraction graph shows the greatest and lowest peaks for the transmittance of the aloe vera leaves extract composition over the wavenumber. Furthermore, a chemical bond’s stretching vibration is responsible for the formation of a huge broad peak at 3332 cm-1 , which corresponds to the O–H stretching frequency. The stretch C–H peak of 2850 cm-1 was followed by the high of 2186 cm-1 . Also, at 1629 cm-1 corresponds to C=O group, the C–O stretch at 1083 cm−1 .

The peak at 1040 might be contributed to the presence of methoxy group. As a result, the peaks in the ATR – FTIR analysis graph may be used to explain the chemical composition of the raw materials used to protect the substrates from corrosion, with the composition including the best inhibitors to prevent adsorption towards the corroded substrates.

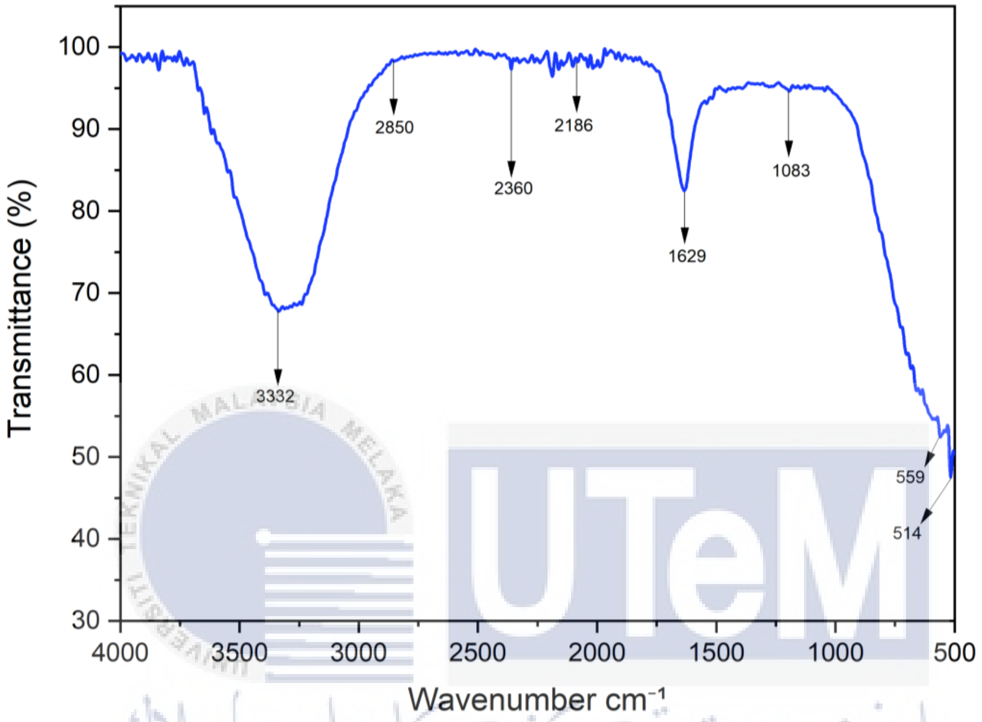


Figure 4.4 ATR – FTIR spectroscopy of aloe vera leaves extract graph.

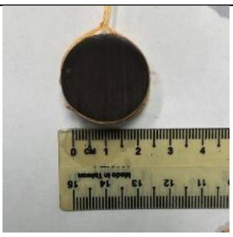
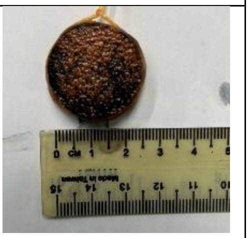
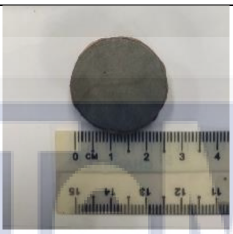
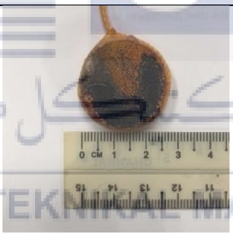
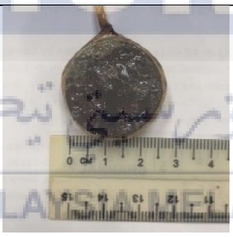
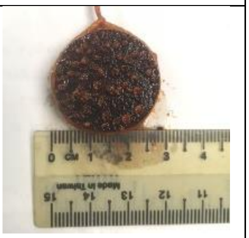
4.4 Corrosion Test

Corrosion testing involves procedures and methodologies to study the resistance of materials to corrosion in order to assess their durability, performance and suitability for specific applications. The primary objective of corrosion testing is to simulate and predict how materials will react in different environmental conditions and identify potential corrosion-related issues. This process is essential for industries where corrosion can result in substantial economic losses, safety concerns, and environmental impacts.

4.4.1 Visual Inspection

Table 4.4 and table 4.5 displays the results of the visual inspection before and after immersing the 25mm x 10mm specimen in river water, 5M HCl and 3.5wt.% NaCl with the presence and absence of aloe vera extract. The specimen was found to be corroded after the immersion test. After observing the specimens for the required period, it was found that the specimen with the absence of aloe vera extract experienced more corrosion than the specimens with the presence of aloe vera, which had lesser amount of corrosion. Although corrosion was visible for the specimens with the presences of aloe vera extract, it was not as severe as specimens with the absence of aloe vera extract. It shows that specimens with the presence of aloe vera extract are more effective as inhibitors in this corrosion test. Overall, specimens with the absence of aloe vera extract in 5M HCl is the most corroded specimen while specimens with the presence of aloe vera extract in river water is the least corroded specimen. Table 4.4 and table 4.5 shows the surface of low carbon steel before and after cleaning. Additionally, the reddish-brown colour on the surface is a defined corrosion product. As the number of immersion days increases, corrosion products become more visible on the surface of low carbon steel. For example, the surface of the specimen on day 35 showed more corrosion than on day 7.

Table 4.4 Result before and after specimen with the absence of aloe vera

Days	Immersion effect before and after clean with acetone	**River water**	**5M HCl**	**3.5wt.% NaCl**
7	Before clean			
	After clean			
14	Before clean			
	After clean			
21	Before clean			

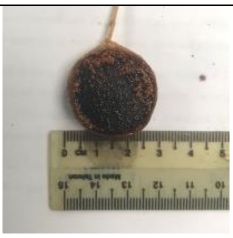
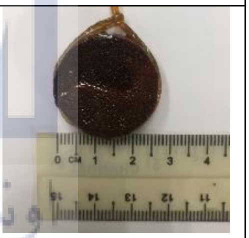
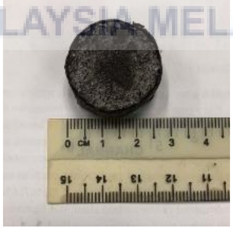
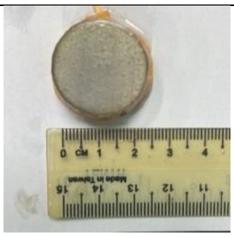
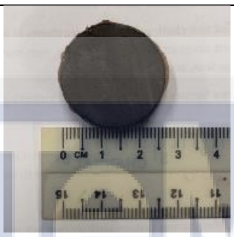
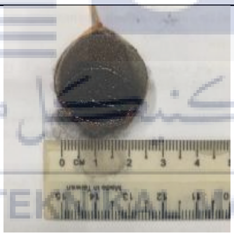
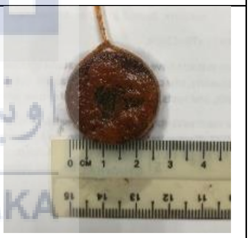
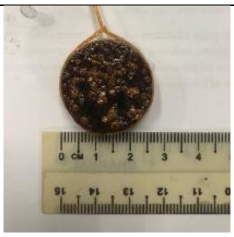
	After clean			
28	Before clean			
	After clean			
35	Before clean			
	After clean			

Table 4.5 Result before and after specimen with the presence of inhibitor

Days	Immersion effect before and after clean with acetone	**River water**	**5M HCl**	**3.5wt.% NaCl**
7	Before clean			
	After clean			
14	Before clean			
	After clean			
21	Before clean			

	After clean			
28	Before clean			
	After clean			
35	Before clean			
	After clean			

4.4.2 Weight Loss Measurement

The aim of measuring weight loss is to compare the weight of a specimen before and after immersion is to determine if it has increased or decreased. Weight loss measurements were conducted on low carbon steel specimens. Table 4.6 shows the increase and decrease in weight loss as the specimen is exposed, and equation (1) is used. Additionally, specimens in the given conditions exhibited weight improvement due to surface corrosion. To determine weight loss in the specimen pre and post immersion, the response was observed.

Figure 4.6 displays the weight loss of specimen with the absence of aloe vera extract in three different mediums: river water, 5M HCl, and 3.5wt.% NaCl. The weight loss of the specimens varies with the solutions and increases accordingly. After 35 days, specimens with the absence of aloe vera extract in three different medium were compared. It shows that the total weight loss of specimen with the absence of aloe vera extract in river water is 0.672 grams, 1.297 grams for specimen with the absence of aloe vera extract in 5M HCl, and 0.923 grams for specimen with the absence of aloe vera extract in 3.5wt.% NaCl. Specimen with the absence of aloe vera extract in 5M HCl has the highest total weight loss compared to other specimen with the absence of aloe vera extract. Table 4.6 illustrates the increase in weight loss as the exposure time to the corrosion process increases.

Table 4.6 Weight loss of specimen with the absence of aloe vera extract

Days	**Weight loss before and after (g)**	**River water**	**5M HCl**	**3.5wt.% NaCl**
7	Before	38.146	39.554	39.549
	After	37.779	38.896	39.128
	Total weight loss (g)	**0.367**	**0.658**	**0.421**
14	Before	38.252	38.512	34.244
	After	37.769	37.750	33.662
	Total weight loss (g)	**0.483**	**0.762**	**0.582**
21	Before	38.754	33.204	38.839
	After	38.187	32.320	38.142
	Total weight loss (g)	**0.567**	**0.884**	**0.697**
28	Before	35.121	37.351	40.738
	After	34.530	36.298	39.934
	Total weight loss (g)	**0.594**	**1.053**	**0.804**
35	Before	40.792	38.752	41.418
	After	40.120	37.455	40.495
	Total weight loss (g)	**0.672**	**1.297**	**0.923**

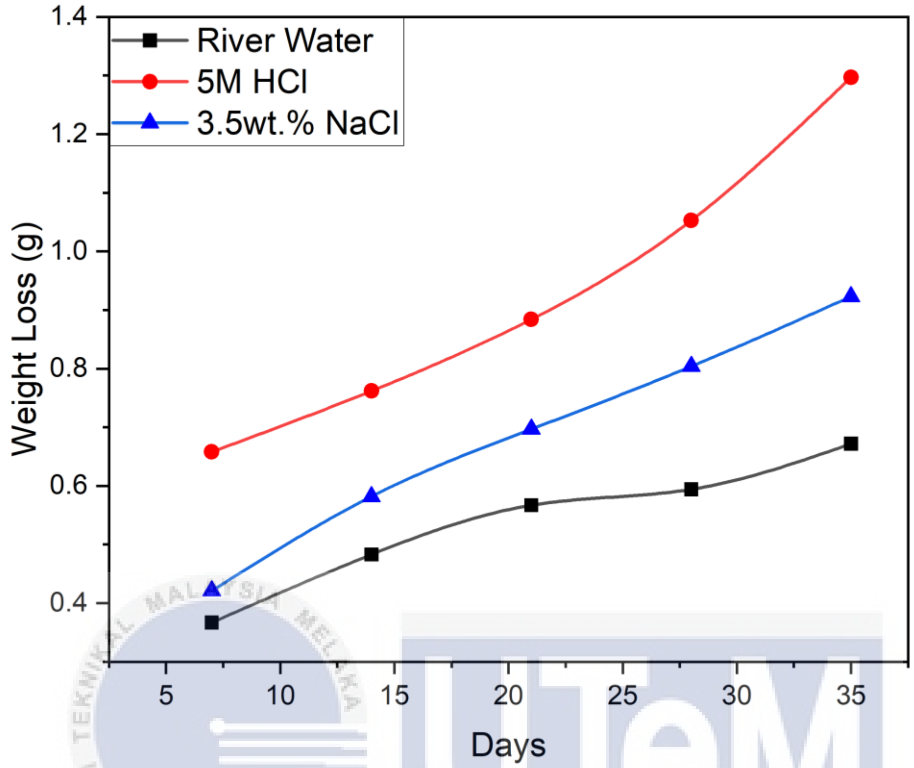


Figure 4.5 Weight loss graph of specimen with the absence of aloe vera extract

Figure 4.7 displays the weight loss of specimen with the presence of aloe vera extract in three different mediums: river water, 5M HCl, and 3.5wt.% NaCl. The weight loss of the specimens varies with the solutions and increases accordingly. After 35 days, specimens with the presence of aloe vera extract in three different medium were compared. It shows that the total weight loss of specimen with the presence of aloe vera extract in river water is 0.596 grams, 0.722 grams for specimen with the presence of aloe vera extract in 5M HCl, and 0.674 grams for specimen with the presence of aloe vera extract in 3.5wt.% NaCl. Specimen with the presence of aloe vera extract in 5M HCl has the highest total weight loss compared to other specimen with the presence of aloe vera extract. Table 4.7 illustrates the increase in weight loss as the exposure time to the corrosion process increases.

Table 4.7 Weight loss of specimen with the presence of aloe vera extract

Days	**Weight loss before and after (g)**	**River water**	**5M HCl**	**3.5wt.% NaCl**
7	Before	36.743	36.635	39.186
	After	36.500	36.168	38.880
	Total weight loss (g)	**0.243**	**0.467**	**0.306**
14	Before	40.396	34.375	39.955
	After	40.032	33.841	39.524
	Total weight loss (g)	**0.364**	**0.534**	**0.431**
21	Before	36.331	36.713	36.284
	After	35.842	36.072	35.717
	Total weight loss (g)	**0.489**	**0.641**	**0.569**
28	Before	40.075	35.563	36.788
	After	39.561	34.870	36.173
	Total weight loss (g)	**0.514**	**0.693**	**0.615**
35	Before	38.253	35.015	37.678
	After	37.657	34.293	37.004
	Total weight loss (g)	**0.596**	**0.722**	**0.674**

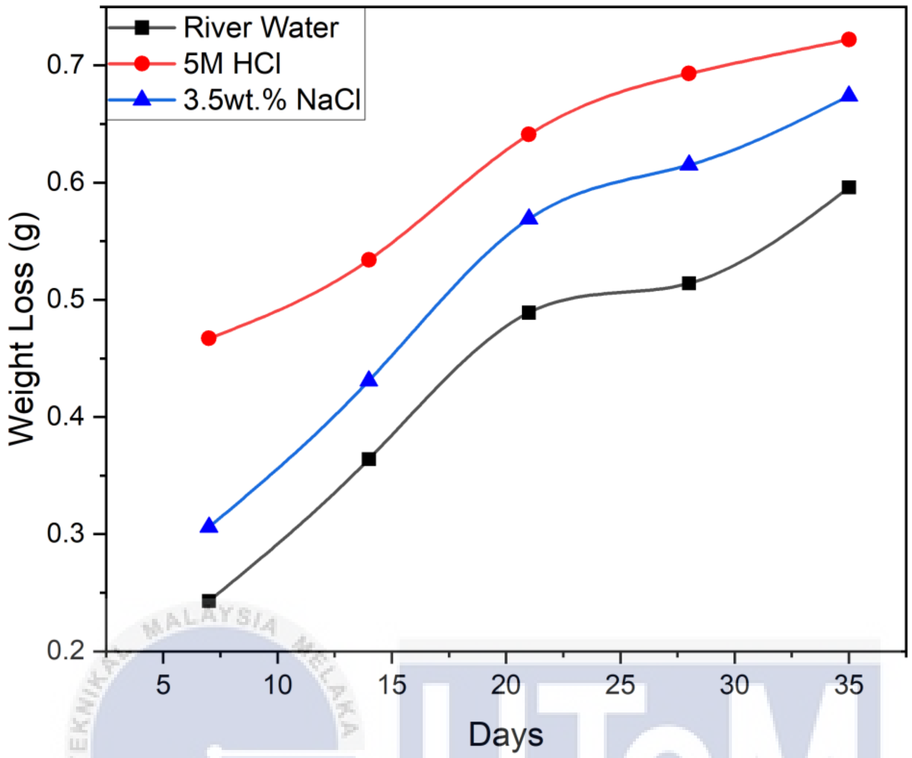


Figure 4.6 Weight loss graph of specimen with the presence of aloe vera extract

Overall, we can conclude that total weight loss for specimen with the absence of aloe vera extract is higher than specimen with the presence of aloe vera extract.

4.4.3 Corrosion Rate

The rate of corrosion is the rate at which a specific metal deteriorates in extremely specific conditions. The rate of corrosion is controlled by environmental conditions because of the composition and condition of the metal. Environmental conditions, as well as the composition and condition of the metal, control the rate of corrosion. It is important to use precise technical terms when discussing this topic. Corrosion rate can be expressed by the amount of corrosion loss in thickness per year. The calculation of the result was measured using Equation (2). When the exposure time increase, the corrosion rate decrease.

Table 4.8 shows the corrosion rate of specimen with the absence of aloe vera extract in three different medium: river water, 5M HCl and 3.5 wt.% NaCl. Figure 4.8 illustrates the correlation between the corrosion rate and specimen with the absence of aloe vera extract in different medium. On day 35, a comparison was made between the different types of medium. The specimen with the absence of aloe vera extract in river water showed a slight decrease, with a value of 0.0091 mm/year, by the increasing exposure time. For comparison, specimen with the absence of aloe vera extract in 5M HCl had a value of 0.0175 mm/year and specimen with the absence of aloe vera extract in 3.5 wt.% NaCl had a value of 0.0125 mm/year, as shown in Figure 4.8.

Table 4.8 Corrosion rate of specimen with the absence of aloe vera extract

Days	Types of Solution	K	W(g)	A	T	D	Corrosion Rate
7	River water	$8.76 \times 10^4\ mm/y$	0.367	312.5π	168	$7.87\ g/cm^3$	0.0248
	5M HCl		0.658			$7.87\ g/cm^3$	0.0444
	3.5wt.% NaCl		0.421			$7.87\ g/cm^3$	0.0284
14	River water	$8.76 \times 10^4\ mm/y$	0.483	312.5π	336	$7.87\ g/cm^3$	0.0163
	5M HCl		0.762			$7.87\ g/cm^3$	0.0257
	3.5wt.% NaCl		0.582			$7.87\ g/cm^3$	0.0196
21	River water	$8.76 \times 10^4\ mm/y$	0.567	312.5π	504	$7.87\ g/cm^3$	0.0128
	5M HCl		0.884			$7.87\ g/cm^3$	0.0199
	3.5wt.% NaCl		0.697			$7.87\ g/cm^3$	0.0157
28	River water	$8.76 \times 10^4\ mm/y$	0.594	312.5π	672	$7.87\ g/cm^3$	0.0100
	5M HCl		1.053			$7.87\ g/cm^3$	0.0178
	3.5wt.% NaCl		0.804			$7.87\ g/cm^3$	0.0136
35	River water	$8.76 \times 10^4\ mm/y$	0.672	312.5π	840	$7.87\ g/cm^3$	0.0091

	5M HCl		1.297			$7.87\ g\ /cm^3$	0.0175
	3.5wt.% NaCl		0.923			$7.87\ g\ /cm^3$	0.0125

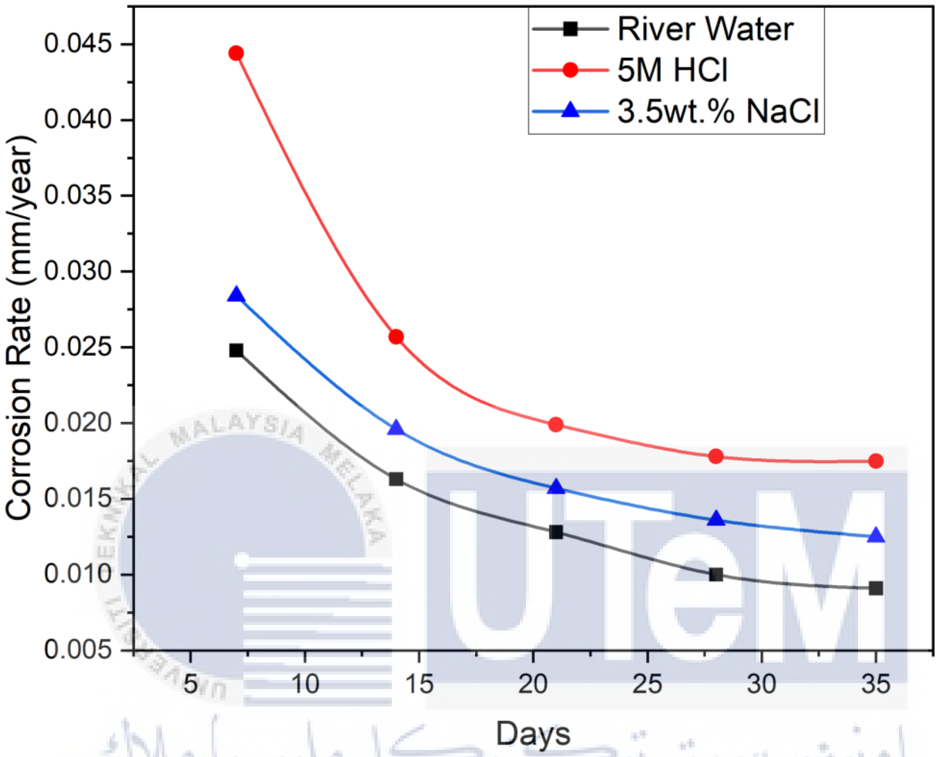


Figure 4.7 Corrosion rate graph of specimen with the absence of aloe vera extract

Table 4.9 shows the corrosion rate of specimen with the presence of aloe vera extract in three different medium: river water, 5M HCl and 3.5 wt.% NaCl. Figure 4.9 illustrates the correlation between the corrosion rate and specimen with the presence of aloe vera extract in different medium. On day 35, a comparison was made between the different types of medium. The specimen with the presence of aloe vera extract in river water showed a slight decrease, with a value of 0.0080 mm/year, in accordance with the increasing exposure time. For comparison, specimen with the presence of aloe vera extract in 5M HCl had a value of 0.0097 mm/year and specimen with the presence of aloe vera extract in 3.5 wt.% NaCl had a value of 0.0091 mm/year, as shown in Figure 4.9.

Table 4.9 Corrosion Rate of specimen with the presence of inhibitor

Days	Types of Solution	K	W(g)	A	T	D	Corrosion Rate
7	River water	$8.76 \times 10^4\ mm/y$	0.243	312.5π	168	$7.87\ g/cm^3$	0.0164
	5M HCl		0.467				0.0315
	3.5wt.% NaCl		0.306				0.0206
14	River water	$8.76 \times 10^4\ mm/y$	0.364	312.5π	336	$7.87\ g/cm^3$	0.0123
	5M HCl		0.534				0.0180
	3.5wt.% NaCl		0.431				0.0145
21	River water	$8.76 \times 10^4\ mm/y$	0.489	312.5π	504	$7.87\ g/cm^3$	0.0110
	5M HCl		0.641				0.0144
	3.5wt.% NaCl		0.569				0.0128
28	River water	$8.76 \times 10^4\ mm/y$	0.514	312.5π	672	$7.87\ g/cm^3$	0.0087
	5M HCl		0.693				0.0117
	3.5wt.% NaCl		0.615				0.0103
35	River water	$8.76 \times 10^4\ mm/y$	0.596	312.5π	840	$7.87\ g/cm^3$	0.0080
	5M HCl		0.722				0.0097
	3.5wt.% NaCl		0.674				0.0091

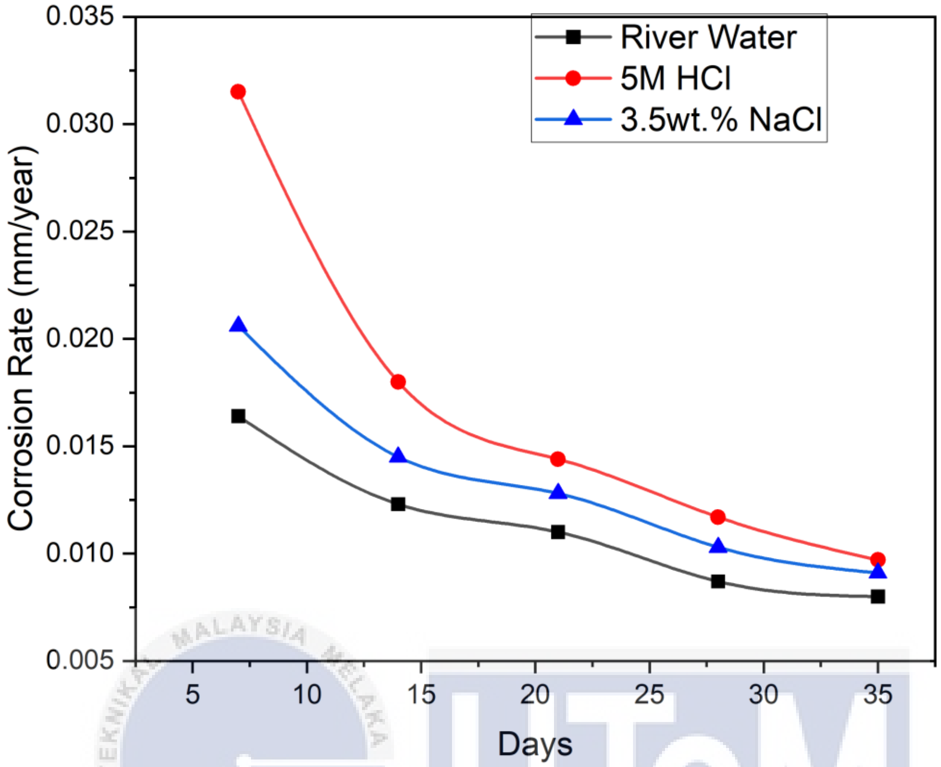


Figure 4.8 Corrosion rate of specimen with the presence of inhibitor

Overall, we can conclude that corrosion rate for specimen with the absence of aloe vera extract is higher than specimen with the presence of aloe vera extract.

4.4.4 Inhibitor Efficiency

This research aims to determine the inhibitor efficiency on substrate corrosion in different types of solutions, as shown in Table 4.10 and Figure 4.10. The inhibitor structure plays a significant role in the adsorption mechanism. Equation (3) was used for the calculation. The inhibitor efficiency percentage increased with exposure time, as demonstrated in the results presented in Table 4.10. The inhibitor efficiency percentages of specimen in three different medium: river water, 5M HCl and 3.5 wt.% NaCl. We can observed the differences in these three mediums on day 35, the inhibitor efficiency percentage of specimen in river water is 7.6%, specimen in 5M HCl is 57.5% and specimen in 3.5 wt.% NaCl is 24.9%.

Table 4.10 Inhibitor Efficiency of each specimen

Days	**Types of solutions**	**Weight loss of sample in the absence of inhibitor (g) (W_0)**	**Weight loss of sample in the presence inhibitor (g) (W_1)**	**Inhibitor efficiency (%)**
7	River water	0.367	0.243	33.78
	5M HCl	0.658	0.467	29.03
	3.5wt.% NaCl	0.421	0.306	27.32
14	River water	0.483	0.364	24.64
	5M HCl	0.762	0.534	29.92
	3.5wt.% NaCl	0.582	0.431	25.95
21	River water	0.567	0.489	13.76
	5M HCl	0.884	0.641	27.49
	3.5wt.% NaCl	0.697	0.569	18.36
28	River water	0.594	0.514	8.00
	5M HCl	1.053	0.693	34.18
	3.5wt.% NaCl	0.804	0.615	23.51
35	River water	0.672	0.596	7.6
	5M HCl	1.297	0.722	57.5
	3.5wt.% NaCl	0.923	0.674	24.9

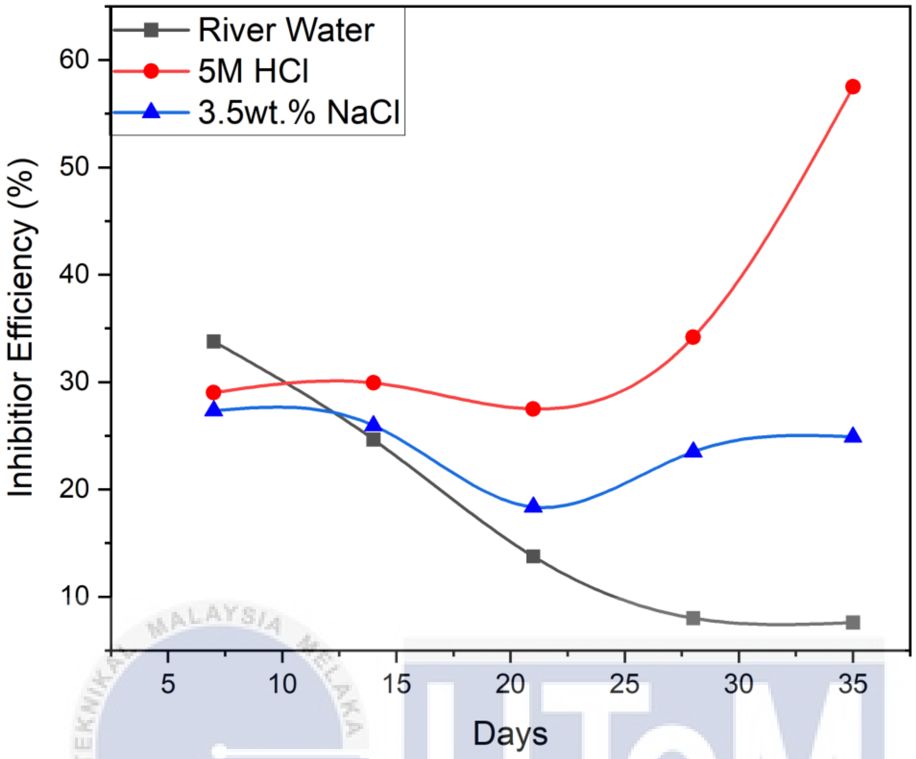


Figure 4.9 Inhibitor efficiency graph of each specimen

4.5 Surface Study by SEM and EDX

Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDX) is a powerful combination that provides detailed information about the morphology, composition, and elemental analysis of materials. It is the most commonly used for surface study.

4.5.1 Scanning Electron Microscopy (SEM)

To investigate the surface of the specimen after the immersion test within days 7, 21, and 35 with the presence of aloe vera extract and the absence of aloe vera extract. We used Scanning Electron Microscopy (SEM) with different magnifications to determine whether the inhibitor had greater efficiency with less corrosion on the specimen surface. As present in Figures 4.11, Figure 4.12, and Figure 4.13, shows SEM morphology for different specimens: (a) specimen in river water with the presence of aloe vera extract, (c) specimen in 5M HCl with the presence of aloe vera extract, (e) specimen in 3.5wt.% NaCl with the presence of aloe vera extract and (g) specimen in 5M HCl with the absence of aloe vera extract. It shows that (a) specimen in river water with the presence of aloe vera extract and (c) specimen in 3.5wt.% NaCl with the presence of aloe vera extract has the least corroded surface and pitting, while (b) specimen in 5M HCl with the presence of aloe vera extract has more corroded and pitting than (a) and (b), but specimens in 5M HCl with the absence of aloe vera extract has the most corroded surface and pitting. Furthermore, as the number of immersion days increases, so does the surface corrosion and more pitting can be seen.

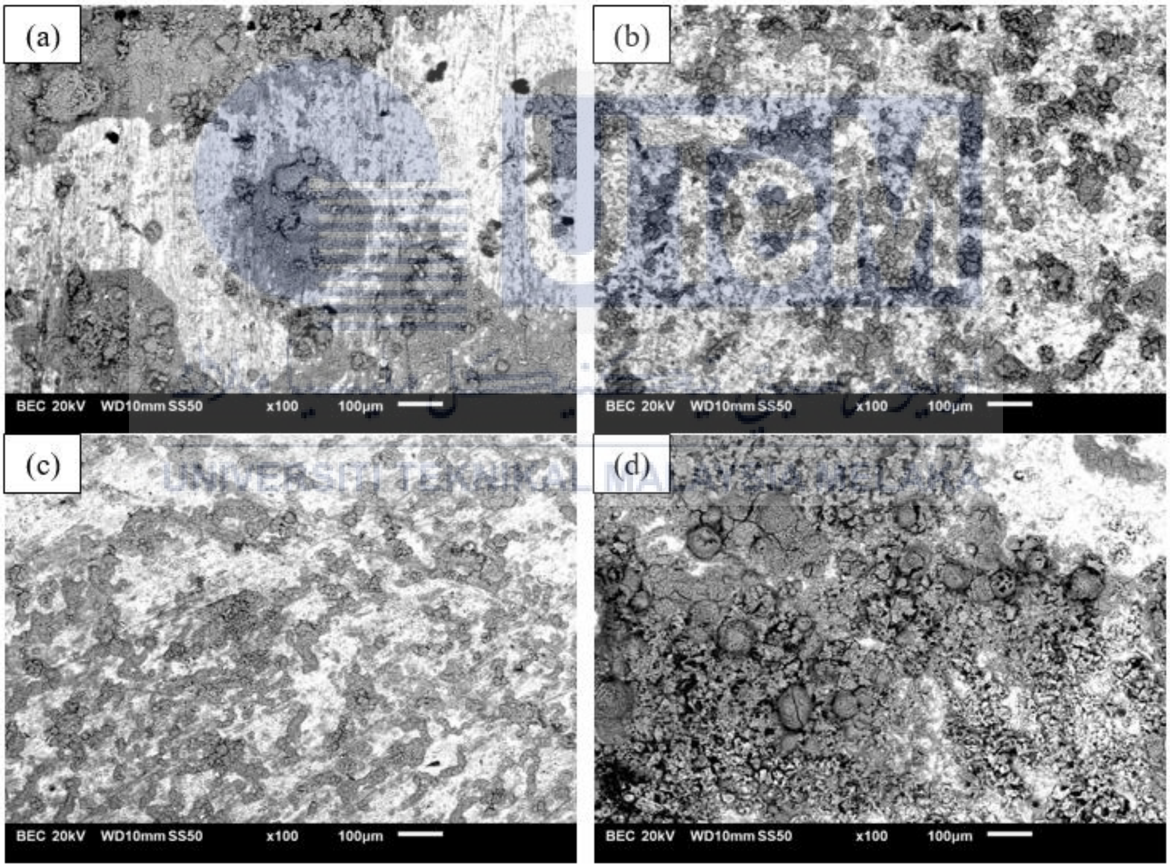


Figure 4.10 SEM morphology of specimen (a) in river water with the presence of aloe vera extract, (b) in 5M HCl with the presence of aloe vera extract, (c) in 3.5wt.% NaCl with the presence of aloe vera extract and (d) in 5M HCl with the absence of aloe vera extract in 7 days.

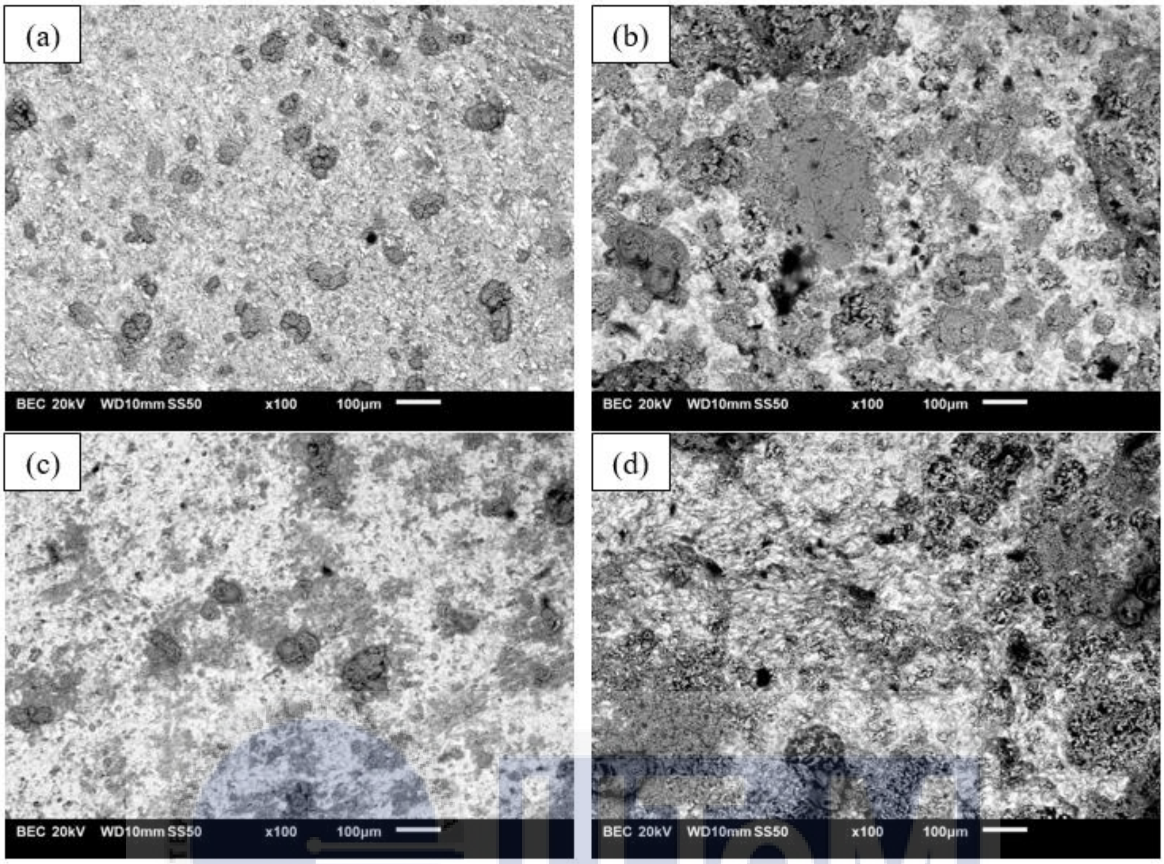


Figure 4.11 SEM morphology of specimen (a) in river water with the presence of aloe vera extract, (b) in 5M HCl with the presence of aloe vera extract, (c) in 3.5wt.% NaCl with the presence of aloe vera extract and (d) in 5M HCl with the absence of aloe vera extract in 21 days.

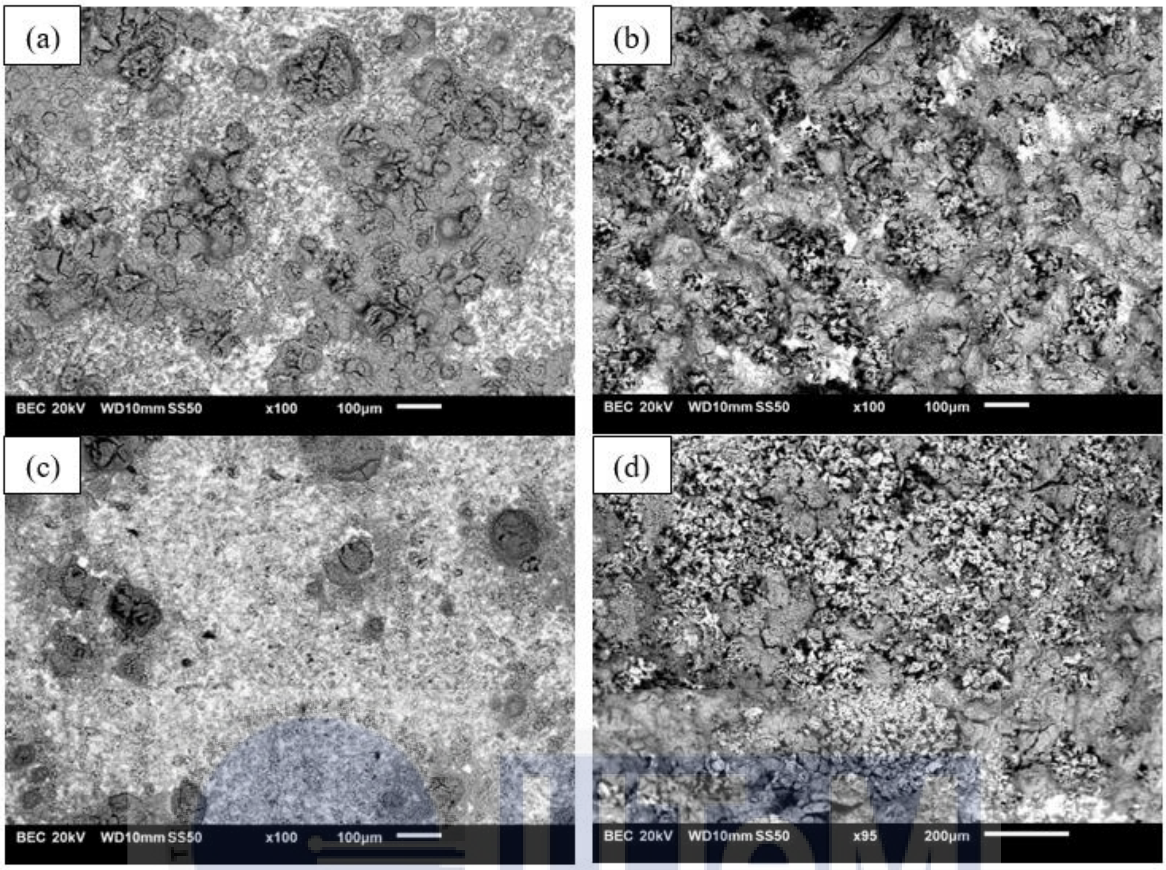
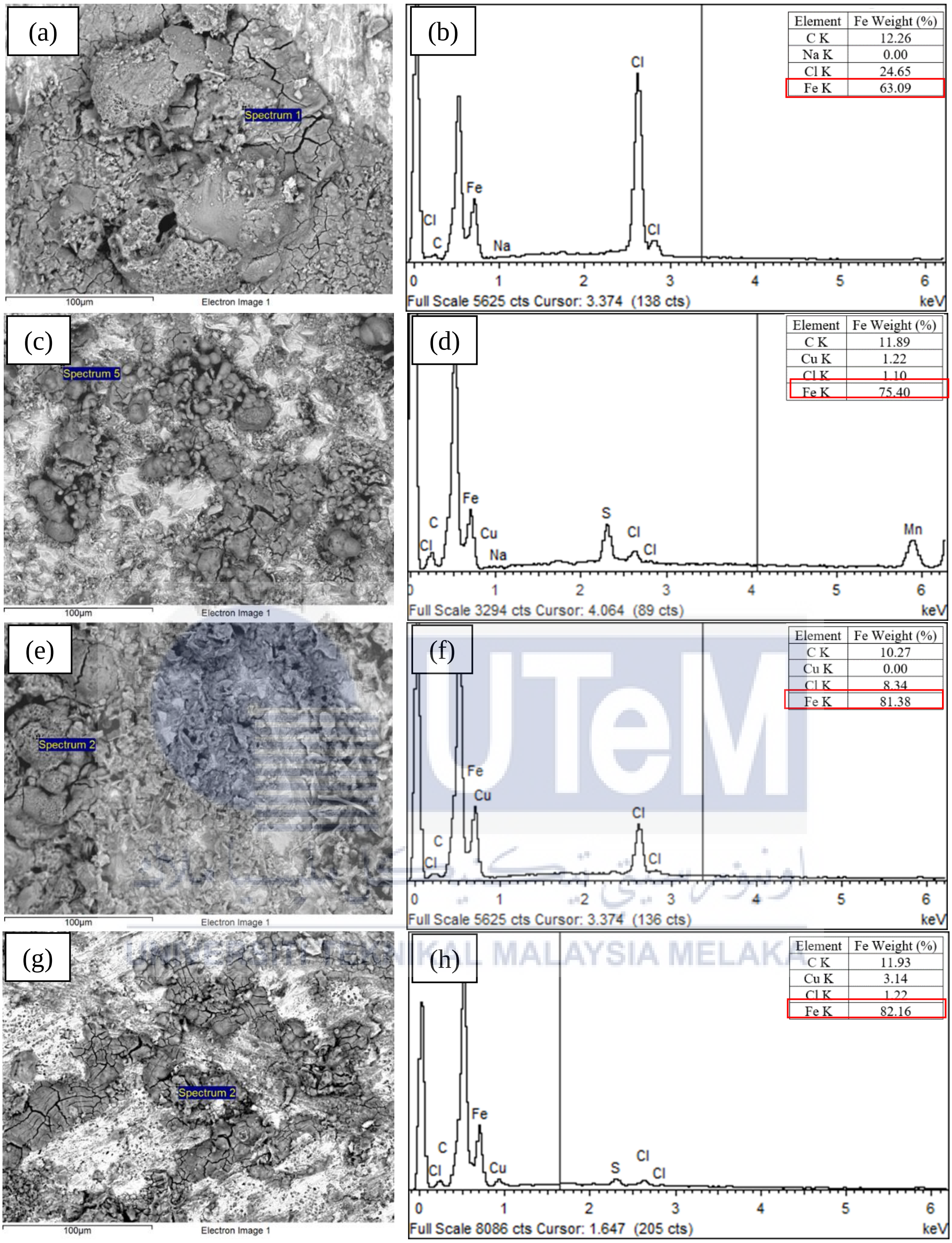


Figure 4.12 SEM morphology of specimen (a) in river water with the presence of aloe vera extract, (b) in 5M HCl with the presence of aloe vera extract, (c) in 3.5wt.% NaCl with the presence of aloe vera extract and (d) in 5M HCl with the absence of aloe vera extract in 35 days.

4.5.2 Energy Dispersive X-ray (EDX)

The Energy Dispersive X-ray (EDX) machine was used to investigate the element composition in the inhibitor that supported the adsorption on the low carbon steel in the immersion test, preventing the specimen from corroding. The observations were made on days 7, 21, and 35. Figure 4.14 shows the morphology of the SEM and the graph of EDX on low carbon steel in shows the SEM and EDX morphology for different specimen for day 7: (a) specimen in river water with the presence of aloe vera extract, (c) specimen in 5M HCl with the presence of aloe vera extract, (e) specimen in 3.5wt.% NaCl with the presence of aloe vera extract and (g) specimen in 5M HCl with the absence of aloe vera extract. It shows that the amount of iron for specimen in river water with the presence of aloe vera extract is 63.09%, the amount of iron for specimen in 5M HCl with the presence of aloe vera extract is 75.40%, the amount of iron for specimen in 3.5wt.% NaCl with the presence of aloe vera extract is 81.38% and the amount of iron for specimen in 5M HCl with the absence of aloe vera extract is 82.16%. The lowest percentage is 63.09%, which is specimen in river water with the presence of aloe vera extract and the highest percentage is 82.16%, which is specimen in 5M HCl with the absence of aloe vera extract.



(b)

Element	Fe Weight (%)
C K	12.26
Na K	0.00
Cl K	24.65
Fe K	63.09

(d)

Element	Fe Weight (%)
C K	11.89
Cu K	1.22
Cl K	1.10
Fe K	75.40

(f)

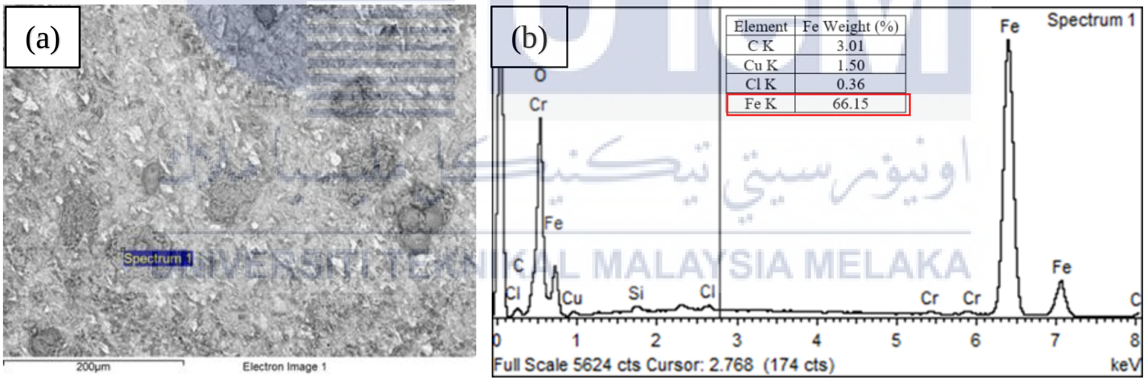
Element	Fe Weight (%)
C K	10.27
Cu K	0.00
Cl K	8.34
Fe K	81.38

(h)

Element	Fe Weight (%)
C K	11.93
Cu K	3.14
Cl K	1.22
Fe K	82.16

Figure 4.13 EDX analysis of the specimen (a) in river water with the presence of aloe vera extract, (c) in 5M HCl with the presence of aloe vera extract, (e) in 3.5wt.% NaCl with the presence of aloe vera extract and (g) in 5M HCl with the absence of aloe vera extract in 7 days.

Figure 4.15 shows the morphology of the SEM and the graph of EDX on low carbon steel shows the SEM and EDX morphology for different specimens for day 21: (a) specimen in river water with the presence of aloe vera extract, (c) specimen in 5M HCl with the presence of aloe vera extract, (e) specimen in 3.5wt.% NaCl with the presence of aloe vera extract and (g) specimen in 5M HCl with the absence of aloe vera extract. It shows that the amount of iron for specimen in river water with the presence of aloe vera extract is 66.15%, the amount of iron for specimen in 5M HCl with the presence of aloe vera extract is 65.31%, the amount of iron for specimen in 3.5wt.% NaCl with the presence of aloe vera extract is 68.18% and the amount of iron for specimen in 5M HCl with the absence of aloe vera extract is 71.26%. The lowest percentage is 65.31%, which is specimen in 3.5wt.% NaCl with the presence of aloe vera extract and the highest percentage is 71.26%, which is specimen in 5M HCl with the absence of aloe vera extract.



Element	Fe Weight (%)
C K	3.01
Cu K	1.50
Cl K	0.36
Fe K	66.15

Figure 4.14 EDX analysis of the specimen (a) in river water with the presence of aloe vera extract, (c) in 5M HCl with the presence of aloe vera extract, (e) in 3.5wt.% NaCl with the presence of aloe vera extract and (g) in 5M HCl with the absence of aloe vera extract in 21 days

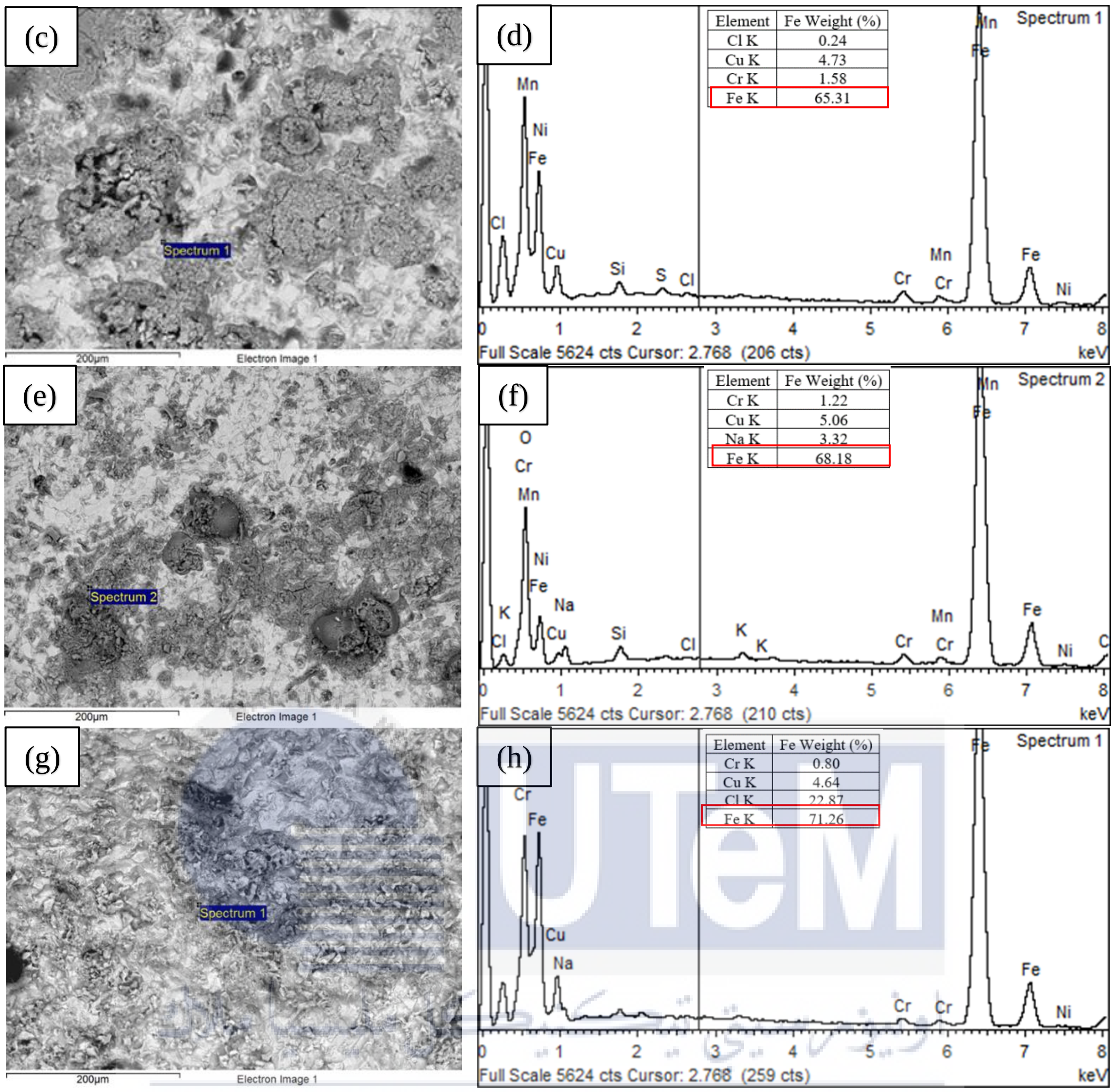
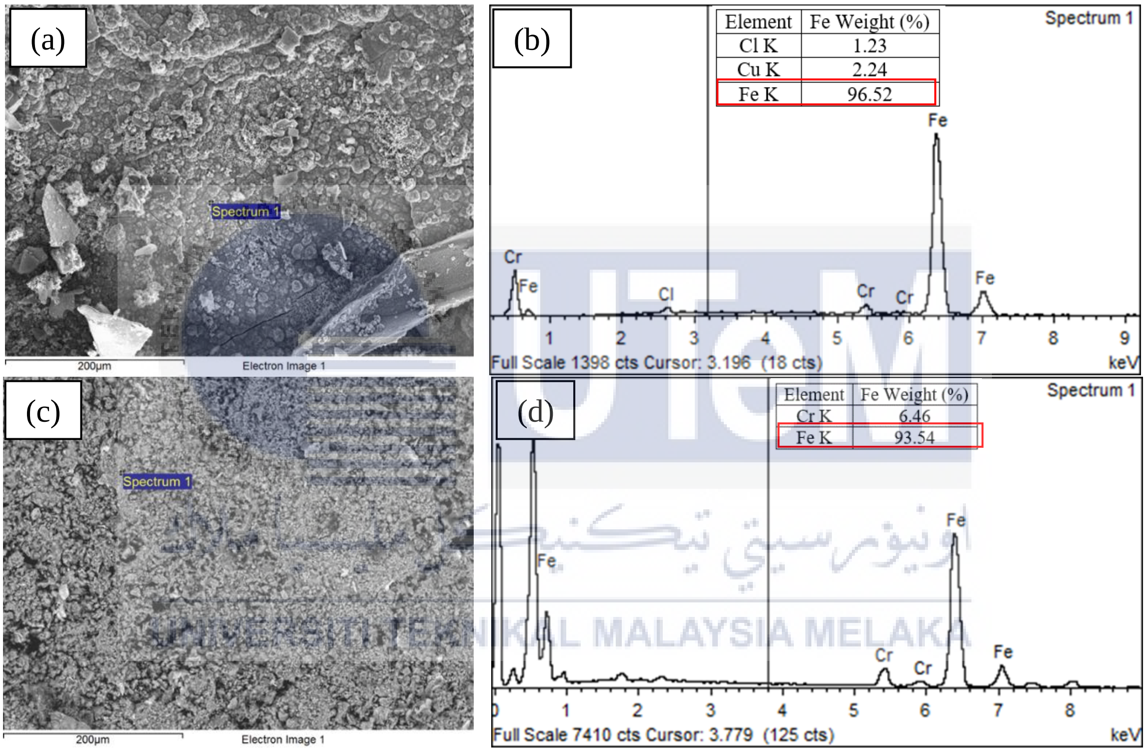


Figure 4.15 EDX analysis of the specimen (a) in river water with the presence of aloe vera extract, (c) in 5M HCl with the presence of aloe vera extract, (e) in 3.5wt.% NaCl with the presence of aloe vera extract and (g) in 5M HCl with the absence of aloe vera extract in 21 days

Figure 4.16 shows the morphology of the SEM and the graph of EDX on low carbon steel in shows the SEM and EDX morphology for different specimen for day 35: (a) specimen in river water with the presence of aloe vera extract, (c) specimen in 5M HCl with the presence of aloe vera extract, (e) specimen in 3.5wt.% NaCl with the presence of aloe vera extract and (g) specimen in 5M HCl with the absence of aloe vera extract. It shows that the amount of iron for specimen in river water with the presence of aloe vera extract is 96.52%, the amount of iron for specimen in 5M HCl with the presence of aloe vera extract is 93.54%, the amount of iron for specimen in 3.5wt.% NaCl with the presence of aloe vera extract is 80.65% and the amount of iron for specimen in 5M HCl with the absence of aloe vera extract is 96.92%. The lowest percentage is 80.65%, which is specimen in 3.5wt.% NaCl with the presence of aloe vera extract and the highest percentage is 96.92%, which is specimen in 5M HCl with the absence of aloe vera extract.



Element	Fe Weight (%)
Cl K	1.23
Cu K	2.24
Fe K	96.52

Element	Fe Weight (%)
Cr K	6.46
Fe K	93.54

Figure 4.16 EDX analysis of the specimen (a) in river water with the presence of aloe vera extract, (c) in 5M HCl with the presence of aloe vera extract, (e) in 3.5wt.% NaCl with the presence of aloe vera extract and (g) in 5M HCl with the absence of aloe vera extract in 35 days

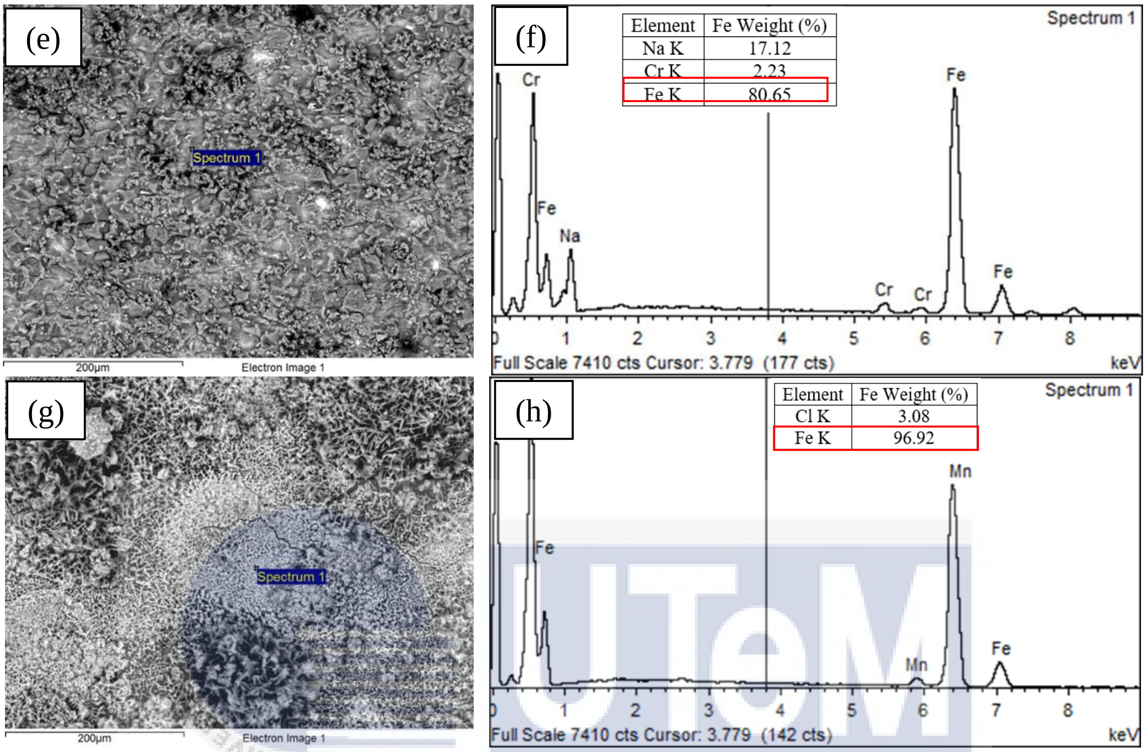


Figure 4.17 EDX analysis of the specimen (a) in river water with the presence of aloe vera extract, (c) in 5M HCl with the presence of aloe vera extract, (e) in 3.5wt.% NaCl with the presence of aloe vera extract and (g) in 5M HCl with the absence of aloe vera extract in 35 days

4.5.3 Green Inhibitor Mechanism

The mechanism of green inhibitors involves the adsorption of their molecules on the metal or alloy surface to form a protective layer. The inhibiting properties of these compounds result from the adsorption ability of their molecules. The polar group serves as the reaction center for the adsorption process, which blocks active corrosion sites and forms a film that protects the surface, hindering corrosion. This inhibition process is demonstrated in Figure 4.17. Furthermore, the corrosion rate can be reduced by using an inhibitor that forms a long-lasting barrier layer. This layer effectively prevents corrosion of low carbon steel in river water, 5M HCl, and 3.5wt.% NaCl, without altering the concentration of the corrosive agent. This ensures the appropriate concentration and inhibits the corrosive agent from reaching the metal surface.

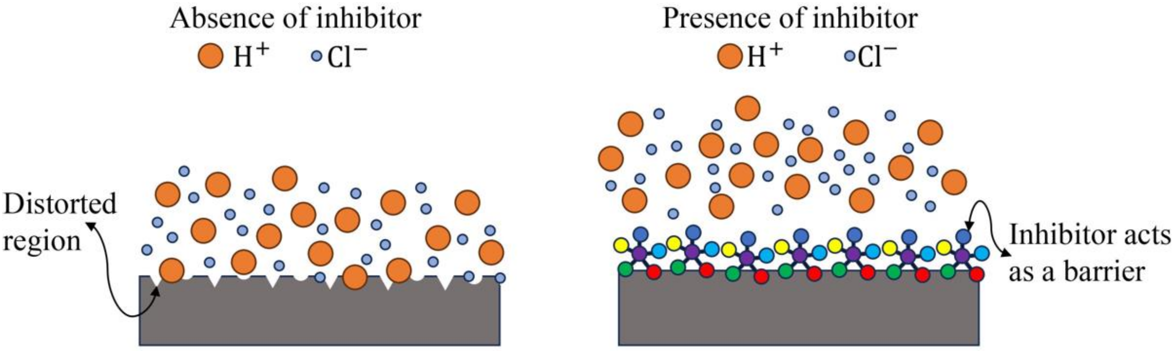
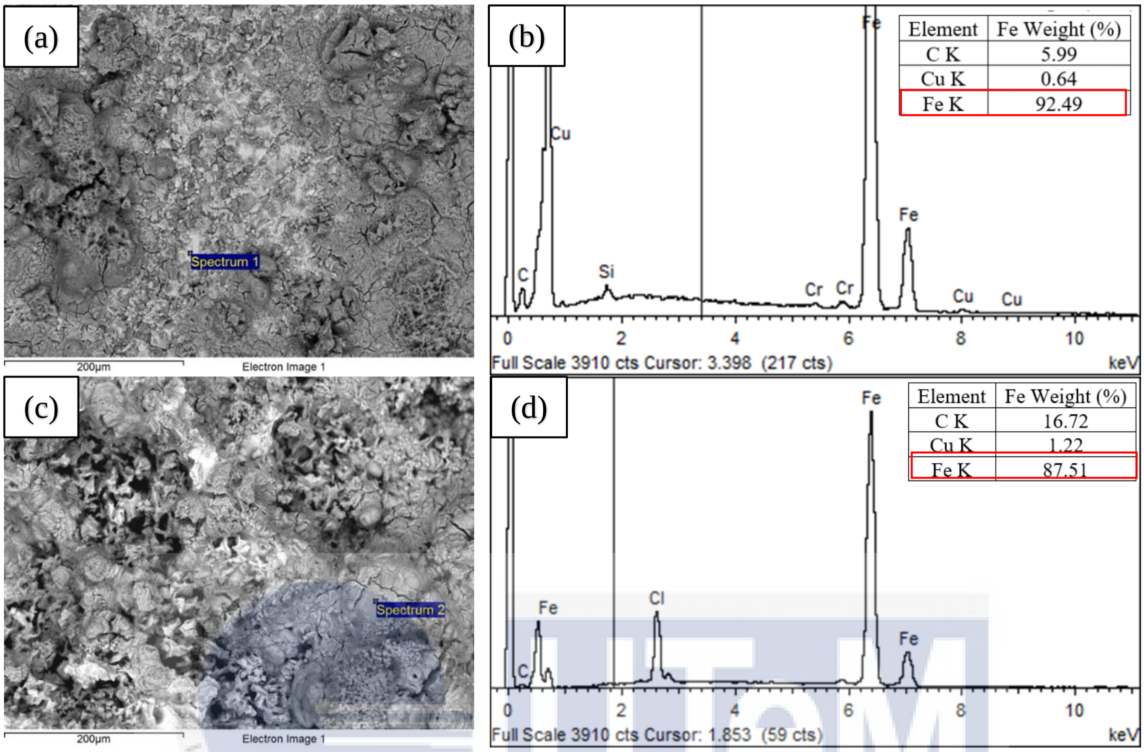


Figure 4.18 Green inhibitor mechanism

Energy Dispersive X-ray analysis (EDX), also known as Energy Dispersive X-ray Spectroscopy (EDS), is an analytical technique used for the elemental analysis or chemical characterization of a sample. It has various applications, including materials and product research, troubleshooting, and deformulation. In this study, we examined the chemical composition of aloe vera leaf extracts on the surface of low carbon steel, forming a protective layer. Figure 4.18 shows the SEM and EDX morphology for different specimen: (a) specimen in river water with the presence of aloe vera extract, (c) specimen in 5M HCl with the presence of aloe vera extract, (e) specimen in 3.5wt.% NaCl with the presence of aloe vera extract and (g) specimen in 5M HCl with the absence of aloe vera extract. It shows that the amount of iron for specimen in river water with the presence of aloe vera extract is 92.49%, the amount of iron for specimen in 5M HCl with the presence of aloe vera extract is 87.51%, the amount of iron for specimen in 3.5wt.% NaCl with the presence of aloe vera extract is 83.66% and the amount of iron for specimen in 5M HCl with the absence of aloe vera extract is 97.11%. The lowest percentage is 87.51%, which is specimen in 3.5wt.%

NaCl with the presence of aloe vera extract and the highest percentage is 97.11%, which is specimen in 5M HCl with the absence of aloe vera extract.



Element	Fe Weight (%)
C K	5.99
Cu K	0.64
Fe K	92.49

Element	Fe Weight (%)
C K	16.72
Cu K	1.22
Fe K	87.51

Figure 4.19 EDX analysis of specimen (a) in river water with the presence of aloe vera extract, (c) in 5M HCl with the presence of aloe vera extract, (c) in 3.5wt.% NaCl with the presence of aloe vera extract and (g) in 5M HCl with the absence of aloe vera extract.

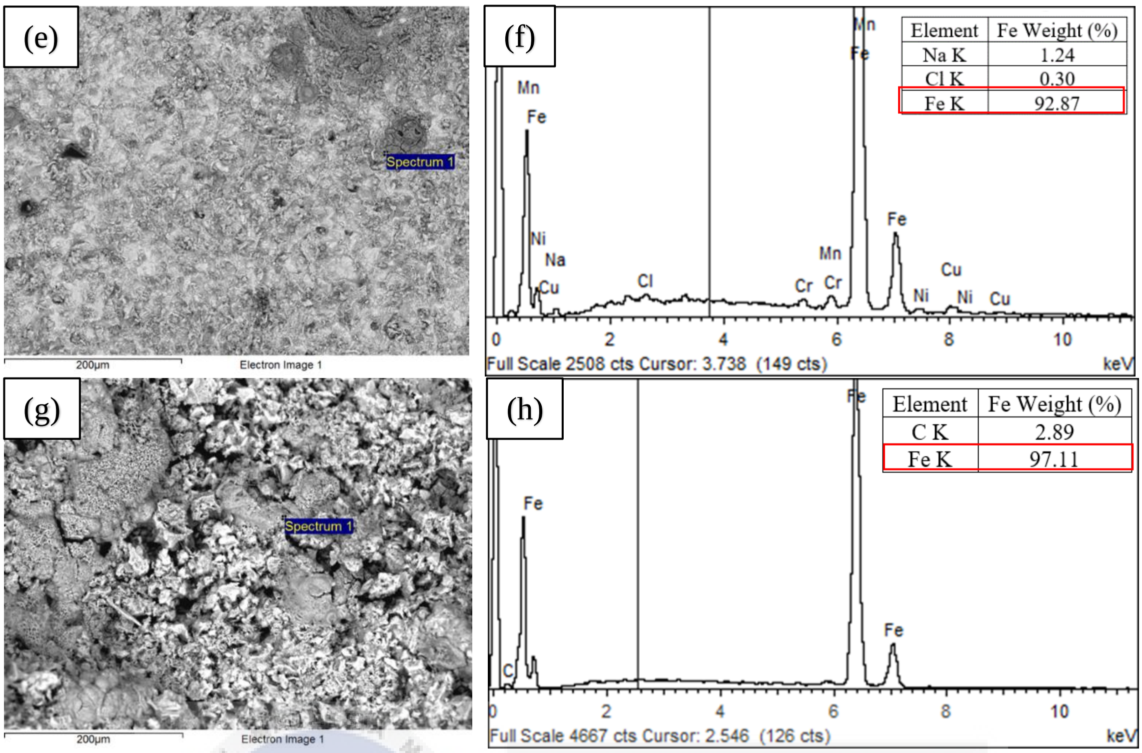


Figure 4.20 EDX analysis of specimen (a) in river water with the presence of aloe vera extract, (c) in 5M HCl with the presence of aloe vera extract, (e) in 3.5wt.% NaCl with the presence of aloe vera extract and (g) in 5M HCl with the absence of aloe vera extract.

Table 4.11 shows the difference in weight percentage of Ferum (Fe) between three mechanisms. The specimen without immersion, which is low carbon steel, has the highest value compared to the other two green inhibitors.

Table 4.11 Fe weight % value

Mechanism	Fe Weight %
Specimen in river water with the presence of aloe vera extract	92.49
Specimen in 5M HCl with the presence of aloe vera extract	83.66
Specimen in 3.5wt.% NaCl with the presence of aloe vera extract	87.51
Specimen in 5M HCl with the absence of aloe vera extract	97.11

4.6 Summary of Results and Discussion

Basically, as determined in this chapter from the hardness testing results, which are microstructure testing and microhardness testing until the green inhibitor mechanism, it can be summarized that specimens with the presence of inhibitor it is more efficient than with the absence of inhibitor. In addition, we can observe the weight loss measurements from day 7 until day 35 that the specimen with the presence of aloe vera extract proved to have the least weight loss than specimen with the absence of aloe vera extract. The corrosion rate and inhibitor efficiency results also justify the specimen with the presence of aloe vera extract is lower than specimen with the absence of aloe vera extract.

Equally important, both the morphology of SEM and EDX on the substrate surfaces found that the Ferum (Fe) percent for specimen with the presence of aloe vera extract was lower than specimen with the absence of aloe vera extract. The green inhibitor mechanism represents a corrosion inhibitor mechanism of low carbon steel immersed in river water, 5M HCl and 3.5wt.% NaCl with and without the presence of aloe vera. At the same time, it can be demonstrated that the chemical molecules in aloe vera leaves extract may form coordination bonds. As a result, this corrosion protection diagram will be performed on the basis of the testing findings. Furthermore, the experiments may show the establishment of adsorption on the low carbon steel substrate surface.

INFOGRAPHIC OF THE EVALUATION OF ALOE VERA EXTRACT AS AN ECO-FRIENDLY COROSSION INHIBITOR FOR CARBON STEEL IN 5M HCl, RIVER WATER AND 3.5wt.% NaCl MEDIUM

Figure 4.21 Infographic of this study

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Conclusion

In a nutshell, from this research we can identify:

i. The use of environmentally friendly inhibitors, such as Aloe Vera leaves, can effectively reduce corrosion on low carbon steel. This is due to their excellent adsorption properties. The composition of the low carbon steel is a crucial factor in this process.

ii. The microstructure of low carbon steel was found to consist of both ferrite and pearlite through mechanical testing. The strength properties of low carbon steel can be determined by conducting a hardness test, which yielded an average value of 75.88 HRB.

iii. During the immersion test, differences in the surfaces of the specimens were observed through visual inspection. To ensure clarity, the specimens were cleaned with acetone. As a result, differences in the surfaces of the specimens with and without the presence of aloe vera extract in the three solutions were observed before and after cleaning. Specifically, the surface of the specimen with the presence of aloe vera was smoother than that the specimen without the presence of aloe vera extract.

iv. The ATR – FTIR graph of aloe vera extracts indicates the graph pattern with the peak pattern over the wavenumber and also the transmittance levels.

v. The weight loss of low carbon steel was calculated. It was observed that the specimen with the presence of aloe vera extract experienced the least weight loss compared to the specimen with the absence of aloe vera extract.

vi. The corrosion rate of low carbon steel proved to be greater with the presence of aloe vera extract compared to with the absence of aloe vera extract, as shown by the graph. the corrosion rate of specimens with the presence of green inhibitor performs significantly better than specimens with the absence of aloe vera extract.

vii. The inhibitor efficiency percentages of specimen in river water is 7.6%, specimen in 5M HCl is 57.5% and specimen in 3.5 wt.% NaCl is 24.9%. It shows that specimen in 5M HCl has the most inhibitor efficiency percentages and river water has the least inhibitor efficiency percentages.

viii. The morphology of SEM and EDX analysis demonstrates and proves pitting or corroding occurred more on the specimen with the presence of aloe vera extract rather than in the absence of aloe vera extract. It can be proved from the amount of Ferum (Fe) atomic percent and weight percent content.

ix. Green inhibitor mechanism and EDX result proved that specimen with the presence of aloe vera leaves extract has a lower Ferum Fe weight percent compared to specimen with the absence of aloe vera extract

5.2 Recommendation

The recommendations to improve this final year project are:

i. Thoroughly extract Aloe Vera gel to ensure maximum yield of bioactive compounds. The Aloe Vera leaf extract should be boiled longer and filtered in the rotary evaporator to reduce the water content in the solution before being placed in the oven.

ii. Different application methods, such as coating, immersion, or spraying, should be explored to determine the most practical and effective way to apply Aloe Vera extract as a corrosion inhibitor.

iii. To determine the most effective dosage for corrosion inhibition using Aloe Vera gel, experiments with varying concentrations should be conducted. Factors such as the type of metal, environmental conditions, and the severity of corrosion should be considered when determining the concentration.

5.3 Project Potential

In general, this project has a several potential market which are:

i. Aloe vera extract can be used as a green inhibitor in the oil and gas industry, providing an environmentally friendly alternative to traditional corrosion inhibitors. Corrosion is a significant challenge in this sector, where metal components are exposed to harsh conditions, including corrosive environments and high temperatures. Traditional corrosion inhibitors often contain chemicals that may be harmful to the environment or pose safety concerns.

ii. Aloe vera extract as a green inhibitor also can be used for piping systems, offering an environmentally friendly alternative for corrosion protection. Green inhibitors are substances that are derived from natural sources, are biodegradable, and are considered environmentally sustainable. These inhibitors are gaining attention as industries, including those using piping systems, seek more eco-friendly and sustainable practices.

iii. Aloe vera extract can be used as a green inhibitor for corrosion protection in metal structures. This eco-friendly alternative helps prevent steel corrosion, which can cause structural damage over time.

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APPENDICES

APPENDIX A ASTM G1

Designation: G1 – 03

Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens[1]

This standard is issued under the fixed designation G1; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers suggested procedures for preparing bare, solid metal specimens for tests, for removing corrosion products after the test has been completed, and for evaluating the corrosion damage that has occurred. Emphasis is placed on procedures related to the evaluation of corrosion by mass loss and pitting measurements. (**Warning**—In many cases the corrosion product on the reactive metals titanium and zirconium is a hard and tightly bonded oxide that defies removal by chemical or ordinary mechanical means. In many such cases, corrosion rates are established by mass gain rather than mass loss.)

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* For specific precautionary statements, see 1 and 7.2.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

A262 Practices for Detecting Susceptibility to Intergranular Attack in Austenitic Stainless Steels

D1193 Specification for Reagent Water

D1384 Test Method for Corrosion Test for Engine Coolants in Glassware

D2776 Test Methods for Corrosivity of Water in the Absence of Heat Transfer (Electrical Methods)

G15 Terminology Relating to Corrosion and Corrosion Testing

G16 Guide for Applying Statistics to Analysis of Corrosion Data

G31 Practice for Laboratory Immersion Corrosion Testing of Metals

G33 Practice for Recording Data from Atmospheric Corrosion Tests of Metallic-Coated Steel Specimens

G46 Guide for Examination and Evaluation of Pitting Corrosion

G50 Practice for Conducting Atmospheric Corrosion Tests on Metals

G78 Guide for Crevice Corrosion Testing of Iron-Base and Nickel-Base Stainless Alloys in Seawater and Other Chloride-Containing Aqueous Environments

3. Terminology

3.1 See Terminology G15 for terms used in this practice.

4. Significance and Use

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

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

5. Reagents and Materials

5.1 *Purity of Reagents*—Reagent grade chemicals shall be used in all tests. Unless otherwise indicated, it is intended that all reagents conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society where such specifications are available.[3] Other grades may be used, provided it is first ascertained that the reagent is of sufficiently high purity to permit its use without lessening the accuracy of the determination.

5.2 *Purity of Water*—Unless otherwise indicated, references to water shall be understood to mean reagent water as defined by Type IV of Specification D1193.

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

Current edition approved October 1, 2003. Published October 2003. Originally approved in 1967. Last previous edition approved in 1999 as G1 – 90 (1999)$^{\varepsilon1}$. DOI: 10.1520/G0001-03.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

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

1

APPENDIX B ASTM G31

Designation: NACE TM0169/G31 – 12a

Standard Guide for Laboratory Immersion Corrosion Testing of Metals[1]

This standard is issued under the fixed designation NACE TM0169/G31; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers and describes the factors that influence laboratory immersion corrosion tests, particularly mass loss tests. These factors include apparatus, sampling, test specimen, test conditions (test solution composition, temperature, gas sparging, fluid motion, solution volume, method of supporting test specimens, duration of test), methods of cleaning test specimens, interpretation of results, and calculation of corrosion rates. This guide also emphasizes the importance of recording all pertinent data and provides a checklist for reporting test data.

1.2 The specific evaluation of localized attack, environmentally assisted cracking, and effects of solution flow are not within the scope of this guide.

1.3 This guide is intended to be used by those designing laboratory immersion tests who may not be familiar with all of the variables to consider and the pitfalls that could be encountered when designing and conducting this kind of testing. It should be used as a reference to ensure that the test will allow generation of data relevant to the application with the minimum of interferences.

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

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

2. Referenced Documents

2.1 *ASTM Standards:*[2]

A262 Practices for Detecting Susceptibility to Intergranular Attack in Austenitic Stainless Steels
D1193 Specification for Reagent Water
E8 Test Methods for Tension Testing of Metallic Materials
E300 Practice for Sampling Industrial Chemicals
G1 Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens
G28 Test Methods for Detecting Susceptibility to Intergranular Corrosion in Wrought, Nickel-Rich, Chromium-Bearing Alloys
G34 Test Method for Exfoliation Corrosion Susceptibility in 2XXX and 7XXX Series Aluminum Alloys (EXCO Test)
G46 Guide for Examination and Evaluation of Pitting Corrosion
G48 Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride Solution
G66 Test Method for Visual Assessment of Exfoliation Corrosion Susceptibility of 5XXX Series Aluminum Alloys (ASSET Test)
G67 Test Method for Determining the Susceptibility to Intergranular Corrosion of 5XXX Series Aluminum Alloys by Mass Loss After Exposure to Nitric Acid (NAMLT Test)
G71 Guide for Conducting and Evaluating Galvanic Corrosion Tests in Electrolytes
G78 Guide for Crevice Corrosion Testing of Iron-Base and Nickel-Base Stainless Alloys in Seawater and Other Chloride-Containing Aqueous Environments
G82 Guide for Development and Use of a Galvanic Series for Predicting Galvanic Corrosion Performance
G107 Guide for Formats for Collection and Compilation of Corrosion Data for Metals for Computerized Database Input
G108 Test Method for Electrochemical Reactivation (EPR) for Detecting Sensitization of AISI Type 304 and 304L Stainless Steels

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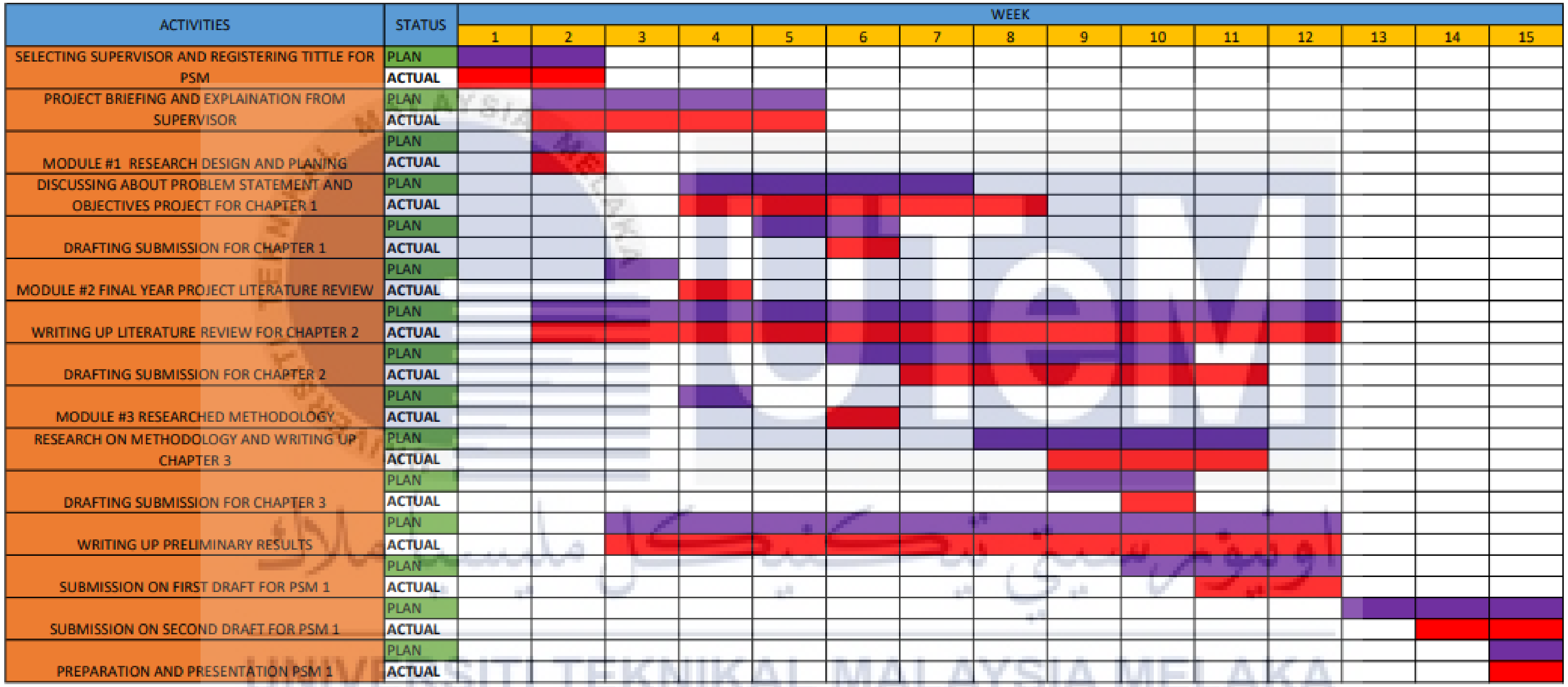
[1] This guide is under the jurisdiction of NACE/ASTM Committee J01, Joint Committee on Corrosion, and is the direct responsibility of Subcommittee J01.01, Working Group on Laboratory Immersion Tests.

Current edition approved July 1, 2012. Published October 2012. Originally approved in 1972. Last previous ASTM edition approved in 2012 as G31–12. NACE edition originally approved in 1969. Last previous NACE edition approved in 2000 as TM0169-2000. DOI: 10.1520/G0031-12A.

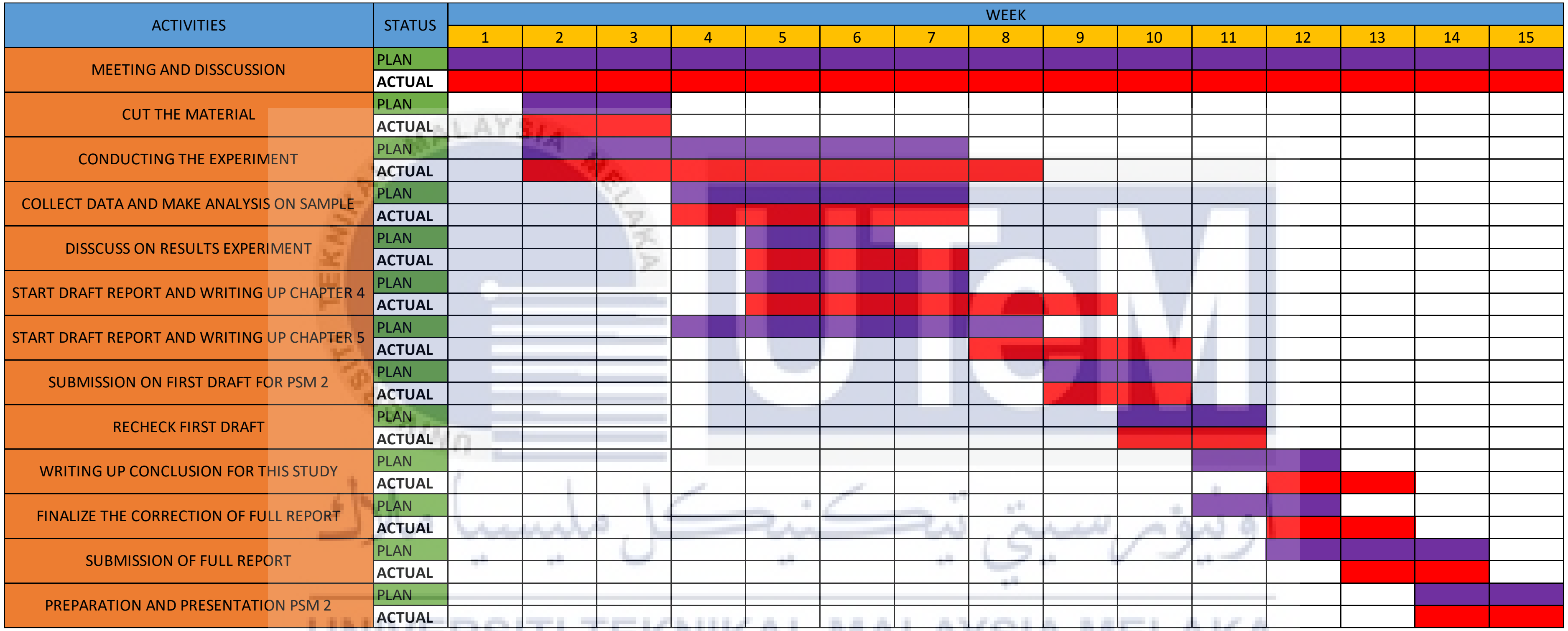
[2] For referenced ASTM standards, visit the ASTM Web site, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM Web site. For NACE standards, visit the NACE Web site, www.nace.org, or contact NACE *FirstService* at firstservice@nace.org.

APPENDIX C Gantt Chart of Study for PSM 1



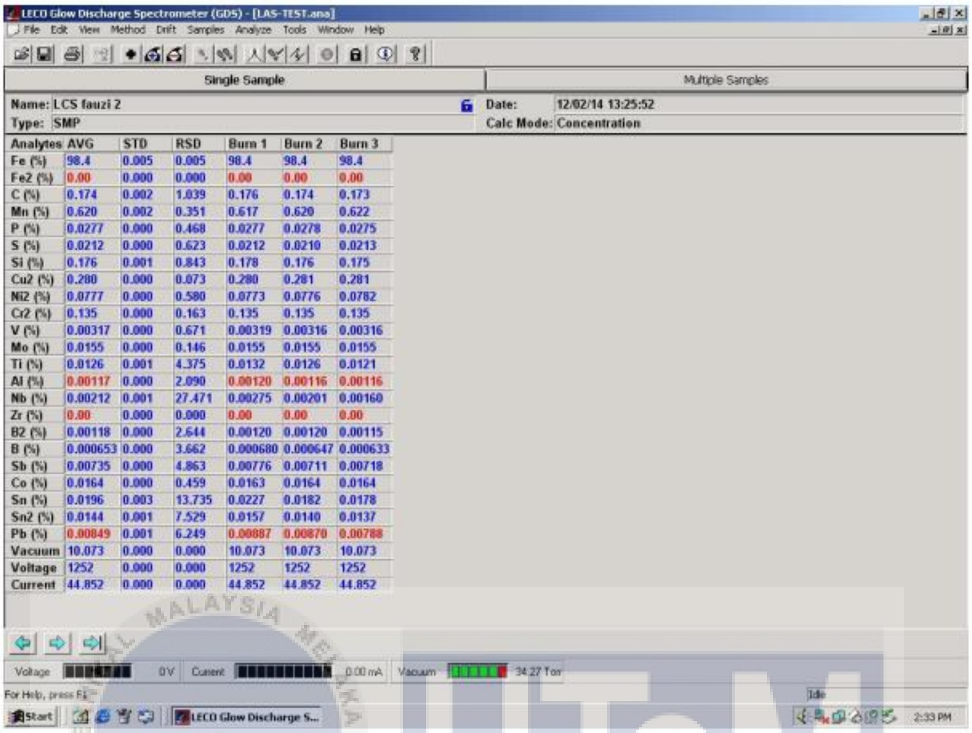
ACTIVITIES	STATUS	WEEK														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SELECTING SUPERVISOR AND REGISTERING TITTLE FOR PSM	PLAN	🟪	🟪													
	ACTUAL	🟥	🟥													
PROJECT BRIEFING AND EXPLAINATION FROM SUPERVISOR	PLAN		🟪	🟪	🟪	🟪										
	ACTUAL		🟥	🟥	🟥	🟥										
MODULE #1 RESEARCH DESIGN AND PLANING	PLAN		🟪													
	ACTUAL		🟥													
DISCUSSING ABOUT PROBLEM STATEMENT AND OBJECTIVES PROJECT FOR CHAPTER 1	PLAN				🟪	🟪	🟪	🟪								
	ACTUAL				🟥	🟥	🟥	🟥	🟥							
DRAFTING SUBMISSION FOR CHAPTER 1	PLAN					🟪	🟪									
	ACTUAL						🟥									
MODULE #2 FINAL YEAR PROJECT LITERATURE REVIEW	PLAN			🟪												
	ACTUAL				🟥											
WRITING UP LITERATURE REVIEW FOR CHAPTER 2	PLAN		🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪			
	ACTUAL		🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥			
DRAFTING SUBMISSION FOR CHAPTER 2	PLAN						🟪	🟪	🟪	🟪	🟪					
	ACTUAL							🟥	🟥	🟥	🟥	🟥				
MODULE #3 RESEARCHED METHODOLOGY	PLAN				🟪											
	ACTUAL						🟥									
RESEARCH ON METHODOLOGY AND WRITING UP CHAPTER 3	PLAN								🟪	🟪	🟪	🟪				
	ACTUAL									🟥	🟥	🟥				
DRAFTING SUBMISSION FOR CHAPTER 3	PLAN									🟪	🟪					
	ACTUAL										🟥					
WRITING UP PRELIMINARY RESULTS	PLAN			🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪			
	ACTUAL			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥			
SUBMISSION ON FIRST DRAFT FOR PSM 1	PLAN										🟪	🟪	🟪			
	ACTUAL											🟥	🟥			
SUBMISSION ON SECOND DRAFT FOR PSM 1	PLAN													🟪	🟪	🟪
	ACTUAL														🟥	🟥
PREPARATION AND PRESENTATION PSM 1	PLAN															🟪
	ACTUAL															🟥

APPENDIX D Gantt Chart of Study for PSM 2



ACTIVITIES	STATUS	WEEK														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
MEETING AND DISSCUSSION	PLAN	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
	ACTUAL	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
CUT THE MATERIAL	PLAN		🟪	🟪												
	ACTUAL		🟥	🟥												
CONDUCTING THE EXPERIMENT	PLAN		🟪	🟪	🟪	🟪	🟪	🟪								
	ACTUAL		🟥	🟥	🟥	🟥	🟥	🟥	🟥							
COLLECT DATA AND MAKE ANALYSIS ON SAMPLE	PLAN				🟪	🟪	🟪	🟪								
	ACTUAL				🟥	🟥	🟥	🟥								
DISSCUSS ON RESULTS EXPERIMENT	PLAN					🟪	🟪									
	ACTUAL					🟥	🟥	🟥								
START DRAFT REPORT AND WRITING UP CHAPTER 4	PLAN					🟪	🟪	🟪								
	ACTUAL					🟥	🟥	🟥	🟥	🟥						
START DRAFT REPORT AND WRITING UP CHAPTER 5	PLAN				🟪	🟪	🟪	🟪	🟪							
	ACTUAL								🟥	🟥	🟥					
SUBMISSION ON FIRST DRAFT FOR PSM 2	PLAN									🟪	🟪					
	ACTUAL									🟥	🟥					
RECHECK FIRST DRAFT	PLAN										🟪	🟪				
	ACTUAL										🟥	🟥				
WRITING UP CONCLUSION FOR THIS STUDY	PLAN											🟪	🟪			
	ACTUAL												🟥	🟥		
FINALIZE THE CORRECTION OF FULL REPORT	PLAN											🟪	🟪			
	ACTUAL												🟥	🟥		
SUBMISSION OF FULL REPORT	PLAN												🟪	🟪	🟪	
	ACTUAL													🟥	🟥	
PREPARATION AND PRESENTATION PSM 2	PLAN														🟪	🟪
	ACTUAL														🟥	🟥

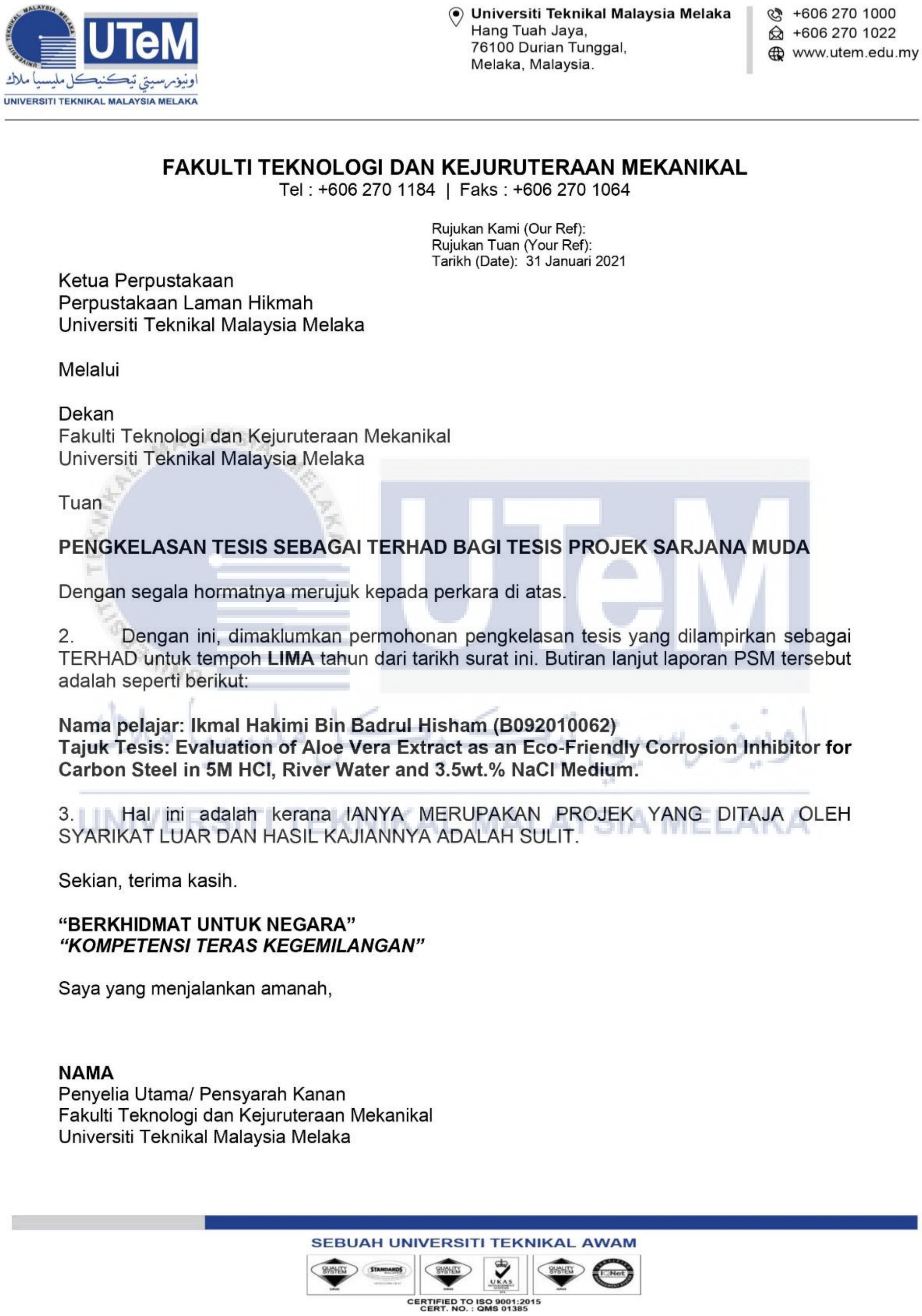
APPENDIX E GDS Result



Name: LCS fauzi 2
Type: SMP
Date: 12/02/14 13:25:52
Calc Mode: Concentration

Analytes	AVG	STD	RSD	Burn 1	Burn 2	Burn 3
Fe (%)	98.4	0.005	0.005	98.4	98.4	98.4
Fe2 (%)	0.00	0.000	0.000	0.00	0.00	0.00
C (%)	0.174	0.002	1.039	0.176	0.174	0.173
Mn (%)	0.620	0.002	0.351	0.617	0.620	0.622
P (%)	0.0277	0.000	0.468	0.0277	0.0278	0.0275
S (%)	0.0212	0.000	0.623	0.0212	0.0210	0.0213
Si (%)	0.176	0.001	0.843	0.178	0.176	0.175
Cu2 (%)	0.280	0.000	0.073	0.280	0.281	0.281
Ni2 (%)	0.0777	0.000	0.580	0.0773	0.0776	0.0782
Cr2 (%)	0.135	0.000	0.163	0.135	0.135	0.135
V (%)	0.00317	0.000	0.671	0.00319	0.00316	0.00316
Mo (%)	0.0155	0.000	0.146	0.0155	0.0155	0.0155
Ti (%)	0.0126	0.001	4.375	0.0132	0.0126	0.0121
Al (%)	0.00117	0.000	2.090	0.00120	0.00116	0.00116
Nb (%)	0.00212	0.001	27.471	0.00275	0.00201	0.00160
Zr (%)	0.00	0.000	0.000	0.00	0.00	0.00
B2 (%)	0.00118	0.000	2.644	0.00120	0.00120	0.00115
B (%)	0.000653	0.000	3.662	0.000680	0.000647	0.000633
Sb (%)	0.00735	0.000	4.863	0.00776	0.00711	0.00718
Co (%)	0.0164	0.000	0.459	0.0163	0.0164	0.0164
Sn (%)	0.0196	0.003	13.735	0.0227	0.0182	0.0178
Sn2 (%)	0.0144	0.001	7.529	0.0157	0.0140	0.0137
Pb (%)	0.00849	0.001	6.249	0.00887	0.00870	0.00788
Vacuum	10.073	0.000	0.000	10.073	10.073	10.073
Voltage	1252	0.000	0.000	1252	1252	1252
Current	44.852	0.000	0.000	44.852	44.852	44.852

APPENDIX F Thesis Report Status Form



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Tuan

PENGKELASAN TESIS SEBAGAI TERHAD BAGI TESIS PROJEK SARJANA MUDA

Dengan segala hormatnya merujuk kepada perkara di atas.

2. Dengan ini, dimaklumkan permohonan pengkelasan tesis yang dilampirkan sebagai TERHAD untuk tempoh **LIMA** tahun dari tarikh surat ini. Butiran lanjut laporan PSM tersebut adalah seperti berikut:

Nama pelajar: Ikmal Hakimi Bin Badrul Hisham (B092010062)
Tajuk Tesis: Evaluation of Aloe Vera Extract as an Eco-Friendly Corrosion Inhibitor for Carbon Steel in 5M HCl, River Water and 3.5wt.% NaCl Medium.

3. Hal ini adalah kerana IANYA MERUPAKAN PROJEK YANG DITAJA OLEH SYARIKAT LUAR DAN HASIL KAJIANNYA ADALAH SULIT.

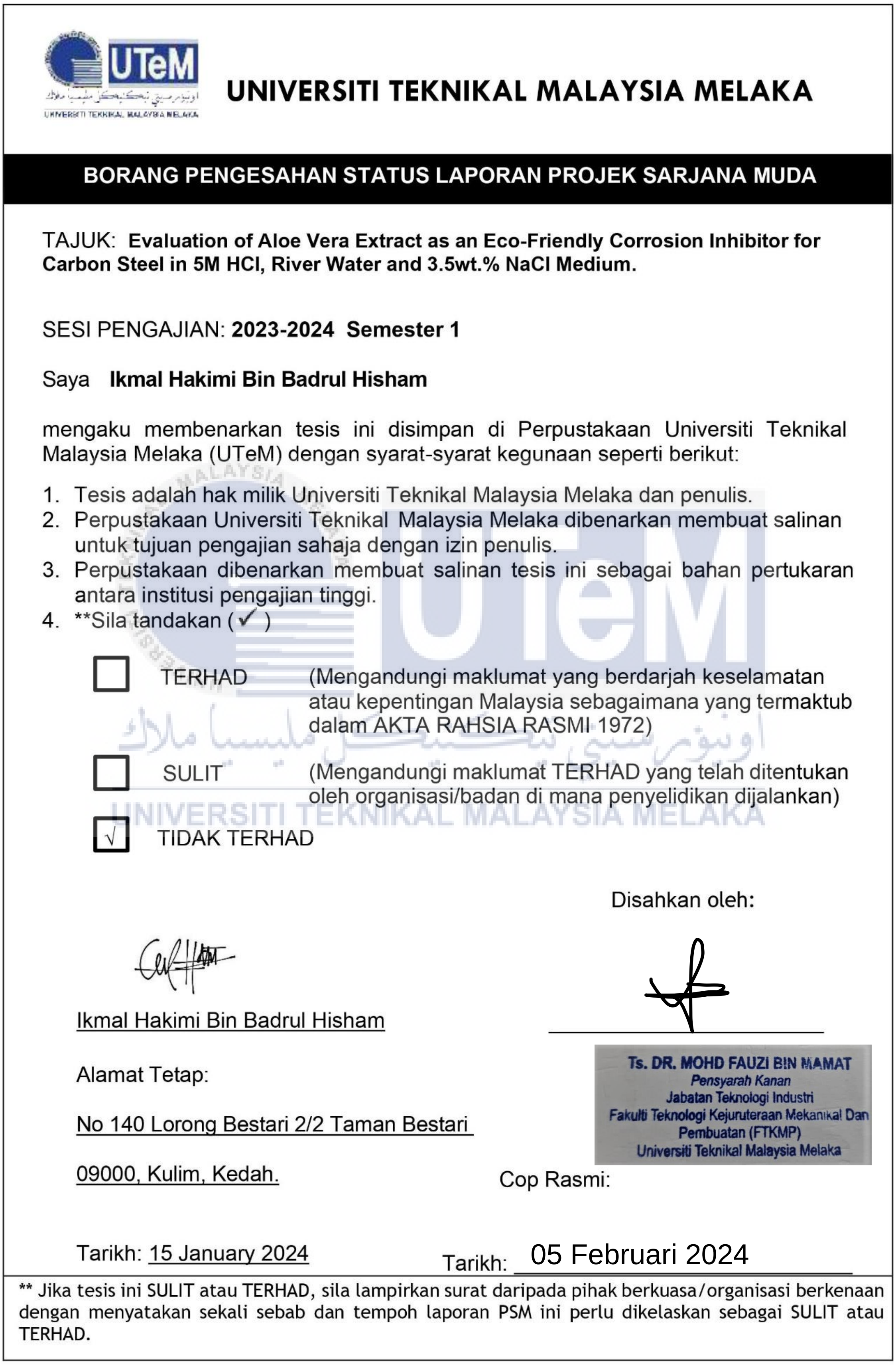
Sekian, terima kasih.

"BERHIDMAT UNTUK NEGARA"
"KOMPETENSI TERAS KEGEMILANGAN"

Saya yang menjalankan amanah,

NAMA
Penyelia Utama/ Pensyarah Kanan
Fakulti Teknologi dan Kejuruteraan Mekanikal
Universiti Teknikal Malaysia Melaka

APPENDIX G Thesis Verification Form



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

BORANG PENGESAHAN STATUS LAPORAN PROJEK SARJANA MUDA

TAJUK: **Evaluation of Aloe Vera Extract as an Eco-Friendly Corrosion Inhibitor for Carbon Steel in 5M HCl, River Water and 3.5wt.% NaCl Medium.**

SESI PENGAJIAN: **2023-2024 Semester 1**

Saya **Ikmal Hakimi Bin Badrul Hisham**

mengaku membenarkan tesis ini disimpan di Perpustakaan Universiti Teknikal Malaysia Melaka (UTeM) dengan syarat-syarat kegunaan seperti berikut:

1. Tesis adalah hak milik Universiti Teknikal Malaysia Melaka dan penulis.
2. Perpustakaan Universiti Teknikal Malaysia Melaka dibenarkan membuat salinan untuk tujuan pengajian sahaja dengan izin penulis.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. **Sila tandakan (✓)

☐ TERHAD (Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia sebagaimana yang termaktub dalam AKTA RAHSIA RASMI 1972)

☐ SULIT (Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)

☑ TIDAK TERHAD

Disahkan oleh:

Ikmal Hakimi Bin Badrul Hisham

Alamat Tetap:

No 140 Lorong Bestari 2/2 Taman Bestari
09000, Kulim, Kedah.

Ts. DR. MOHD FAUZI BIN MAMAT
Pensyarah Kanan
Jabatan Teknologi Industri
Fakulti Teknologi Kejuruteraan Mekanikal Dan Pembuatan (FTKMP)
Universiti Teknikal Malaysia Melaka

Cop Rasmi:

Tarikh: 15 January 2024

Tarikh: 05 Februari 2024

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