Influence of Sodium Chloride (NaCl) Deposition on the Atmospheric Corrosion of Galvanized Steel Roofing

By

Muhammad Zakwan bin Amran

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

DECEMBER 2010

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

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(MECHANICAL ENGINEERING)

Approved by,

____

(Mr. Kamal Ariff bin Zainal Abidin)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

December 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(MUHAMMAD ZAKWAN BIN AMRAN)

ABSTRACT

This paper is a report on the research and study of the atmospheric corrosion behavior of galvanized steel roofing under the influence of Sodium Chloride (NaCl) deposition. This research focus on the atmospheric corrosion behavior of galvanized steel roofing under the application in the marine environment which exposed directly to the extreme environment of sea weather with high exposure to Sodium Chloride deposition. ASTM B 117 Salt Spray (Fog) Test and Mass Loss Method are introduced to study the corrosion behavior of galvanized steel under different concentration of Sodium Chloride (NaCl) concentration. The exposure time was set to four weeks for each concentration. The result from the experiments was gathered in a table and graph was plotted to show the influence of the NaCl deposition on the atmospheric corrosion of galvanized steel roofing.

The results show that Sodium Chloride can accelerate the atmospheric corrosion of the galvanized steel roofing. After 4 weeks of exposure, the corrosion rate increase as the NaCl concentration increase. However, the corrosion rate decrease as the time of exposure elapses from week 1 to week 4. This behavior is due to the electrochemical process that takes place on the surface of the galvanized steel as discussed in chapter 4 of this report.

ACKNOWLEDGEMENT

First and foremost, I would like to praise the God the Almighty for His guidance. With His guidance and blessings bestowed upon me, I managed to overcome all obstacles in completing this project. Here, I would like to use this special opportunity to express my heartfelt gratitude to everyone that has contributed to the success of the project.

My deepest appreciation and gratitude goes to my Final Year Project Supervisor, **Mr Kamal Ariff bin Zainal Abidin** for his supervision, commitment, professionalism, advice and guidance throughout the completion of my project.

I also would like to extend my deepest appreciation to all Mechanical Engineering technicians especially to **Mr. Faisal** who has given full cooperation and guidance to me in completing my project and experiments.

Last but not least, special thanks to those who have helped me directly or indirectly in undertaking this project throughout the year. The contributions and insights are highly appreciated.

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CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Metal roofing has been widely used in Malaysia especially in the rural areas. One of the major advantages of using this kind of roofing is due to its light weight, and therefore portable. There are many types of metal roofing used in the applications. One of the metal roofing used in the applications is galvanized steel roofing. Atmospheric corrosion is a major source of concern in the application of metal roofing. This is due to its application that is directly exposed to the outdoor environment. This project attempts to evaluate the corrosion behaviour of galvanized steel roofing in the influence of Sodium Chloride (NaCl) deposition. The analysis will provide a prediction on the behavior of the atmospheric corrosion of the galvanized steel roofing under the influence of Sodium Chloride (NaCl) deposition. ASTM B 117 Salt Spray (Fog) Test and Mass Loss Method will be used to analyze the behavior of atmospheric corrosion under this condition.

1.2 PROBLEM STATEMENT

The application of galvanized steel roofing in the coastal area has exposed it to the extreme environment of sea weather with high exposure to Sodium Chloride (NaCl) deposition. Therefore in order to understand the mechanism of the atmospheric corrosion of the galvanized steel roofing under this condition, experiment to be conducted to understand the corrosion behavior of galvanized steel roofing under this environment. The data gathered would help to further predict the lifespan of the galvanized steel roofing.

1.3 OBJECTIVES

As a main accelerator of atmospheric corrosion of galvanized steel roofing in marine environment, Sodium Chloride (NaCl) can attract water vapor from humid air to form thin water film on the metal surface. The role of this water layer is to provide a medium for mobilization of ions. NaCl dissolved in the layer also raises the conductivity of the electrolyte. This will greatly increase the electrochemical corrosion and affect the composition of the corrosion products. It is therefore a great interest to study the influence of NaCl deposition on the atmospheric corrosion of galvanized steel roofing.

The main objectives of this project are:

- To provide a reliable prediction on the behavior of atmospheric corrosion rate on galvanized steel roofing under the influence of NaCl deposition.
- To conduct laboratory experiment on galvanized steel roofing and understand the effect of different concentration of NaCl to the atmospheric corrosion of galvanized steel.

1.4 SCOPE OF WORK

As stated earlier, the main approach that will be used in this project is through the experiment to understand the corrosion behavior of galvanized steel roofing under the influence of Sodium Chloride (NaCl) deposition. This project will cover the following scope of work:

- Application of engineering principles in term of corrosion engineering and engineering materials.
- A study and application of ASTM B 117 Salt Spray (Fog) to evaluate the corrosion behavior of galvanized steel under the influence of Sodium Chloride (NaCl) deposition.
- A study and application of Mass Loss Method to determine the corrosion rate.
- A thorough analysis and interpretation of the results gain from the experiments.

CHAPTER 2

LITERATURE REVIEW

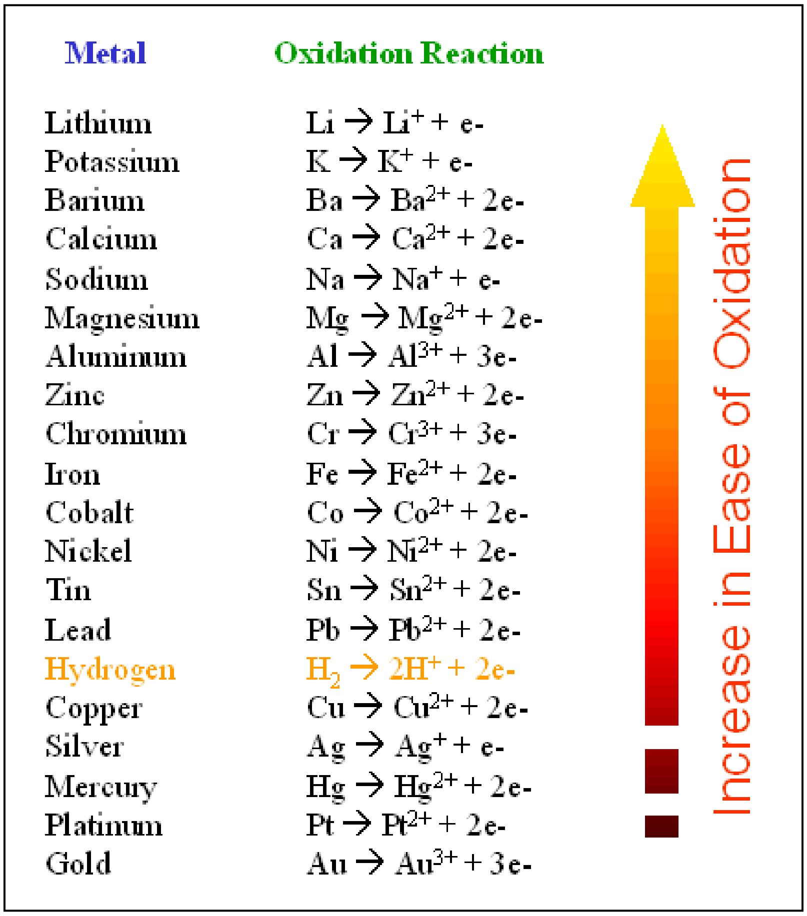
2.1 GALVANIZED STEEL ROOFING BACKGROUND

A metal roof is a roofing system made from metal pieces or tiles (Wikipedia, Metal Roofing, 2010). It can be used on residential, commercial, industrial or agricultural buildings. It is not only used in roofing applications, but also may be used as a wall covering. There are many different profiles and styles available to fit most every building situation. The use of metal roofing is increasing from years to years. In 1985 the number of metal roofing systems being specified was far lower than in 1995 (Steve Hard, 1998, p 148).

Corrugated galvanized steel roofing sheet is the original product of the metal roofing, which consist of mild steel as the base metal but coated with zinc by either hot dip galvanizing process or metallic coating process. Zinc coatings prevent corrosion of the protected metal by forming a physical barrier and by acting as a sacrificial anode if this barrier is damaged. When exposed to the atmosphere, zinc reacts with oxygen to form zinc oxide, which further reacts with water molecules in the air to form zinc hydroxide. Finally zinc hydroxide reacts with carbon dioxide in the atmosphere to yield a thin, impermeable, tenacious and quite insoluble dull grey layer of zinc carbonate which adheres extremely well to the underlying zinc, so protecting it from further corrosion, in a way similar to the protection afforded to aluminium and stainless steels by their oxide layers (Wikipedia, Hot-dip Galvanizing, 2010). The density of Galvanized Iron is no different from other Steels, and is generally taken as 7850 kg/m^3.

The application of a metallic coating to a metal surface affects the type of electrolytic action that takes place. Generally, if two metals are in contact in the presence of an electrolyte, a current will flow from the metal that is more reactive to the one that is lower as shown in the Standard EMF series in **Figure 1**. Hence, if zinc and steel are in contact in the presence of electrolyte, current will flow from the steel to the zinc, so that the zinc becomes an anodic electron-producing area while the steel is cathodic and consumes electrons. The zinc therefore corrodes in preference to the steel and will protect the underlying steel. This type of cathodic protection occurs when zinc coatings on steel subjected to mechanical damage such as scratches and cut edges on which the zinc coating is broken and the steel surface is exposed. The cathodic protection offered by zinc coatings depends largely on (Porter, 1994, pg 84):

- The dimensions of scratches, cut edges, and impact damaged.
- The coating thickness of the zinc layer.



Metal	Oxidation Reaction
Lithium	$\mathrm{Li} \rightarrow \mathrm{Li}^{+} + e-$
Potassium	$\mathrm{K} \rightarrow \mathrm{K}^{+} + e-$
Barium	$\mathrm{Ba} \rightarrow \mathrm{Ba}^{2+} + 2e-$
Calcium	$\mathrm{Ca} \rightarrow \mathrm{Ca}^{2+} + 2e-$
Sodium	$\mathrm{Na} \rightarrow \mathrm{Na}^{+} + e-$
Magnesium	$\mathrm{Mg} \rightarrow \mathrm{Mg}^{2+} + 2e-$
Aluminum	$\mathrm{Al} \rightarrow \mathrm{Al}^{3+} + 3e-$
Zinc	$\mathrm{Zn} \rightarrow \mathrm{Zn}^{2+} + 2e-$
Chromium	$\mathrm{Cr} \rightarrow \mathrm{Cr}^{3+} + 3e-$
Iron	$\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2e-$
Cobalt	$\mathrm{Co} \rightarrow \mathrm{Co}^{2+} + 2e-$
Nickel	$\mathrm{Ni} \rightarrow \mathrm{Ni}^{2+} + 2e-$
Tin	$\mathrm{Sn} \rightarrow \mathrm{Sn}^{2+} + 2e-$
Lead	$\mathrm{Pb} \rightarrow \mathrm{Pb}^{2+} + 2e-$
Hydrogen	$\mathrm{H}_2 \rightarrow 2\mathrm{H}^{+} + 2e-$
Copper	$\mathrm{Cu} \rightarrow \mathrm{Cu}^{2+} + 2e-$
Silver	$\mathrm{Ag} \rightarrow \mathrm{Ag}^{+} + e-$
Mercury	$\mathrm{Hg} \rightarrow \mathrm{Hg}^{2+} + 2e-$
Platinum	$\mathrm{Pt} \rightarrow \mathrm{Pt}^{2+} + 2e-$
Gold	$\mathrm{Au} \rightarrow \mathrm{Au}^{3+} + 3e-$

Figure 1: Standard EMF series

The galvanized coating is tightly bonded to the underlying steel, at approximately 3,600 pounds per square inch (psi) (American Galvanizers Association, 2010). **Table 1** shows the total theoretical thickness for coating mass according to Malaysian Standard (MS 1196, 2004, pg 21) and **Table 2** shows the nominal thickness and coating designation together with its application in accordance with Malaysian Standard (MS 1196, 2004, pg 22).

Table 1: Total theoretical thickness for coating mass

Coating Designation	Equivalent Thickness (mm)
AZ070	0.021
AZ090	0.027
AZ100	0.030
AZ150	0.045
AZ200	0.060

Table 2: Nominal thickness and coating designation

Use	Nominal Thickness (mm)	Coating Designation
For roofing	Up to and include 0.42	AZ090, AZ100, AZ 150
	0.42 and over	AZ150, AZ200
For architectural siding	Up to and include to 0.42	AZ090, AZ100, AZ 150
	0.42 and over	AZ150, AZ200
For internal application or components	0.25 and over	AZ070, AZ090, AZ100, AZ150

Figure 2: Crystalline surface of a hot-dip galvanized surface

Although galvanising inhibits corrosion of the underlying steel, rusting will be inevitable, especially if the local rainfall is at all acidic in nature. So for example, corrugated iron sheet roofing will start to degrade within a few years despite the protective action of the zinc coating in corroding preferentially. Other environments which lower the lifetime of galvanised steel roofs and similar products includes marine locations, where the high electrical conductivity of sea water will encourage and increase the rate of attack (Wikipedia, Corrugated Galvanized Steel Roofing, 2010).

The choice of zinc as coating materials often depends on factors other than corrosion resistance (Porter, 1994, pg 96):

- **Abrasion resistance**
  With respect to abrasion resistance, hot dipped galvanized coatings are at least four to five times as good as pure zinc.
- **Frictional characteristics**
  Zinc, unlike most paints can be left in place on the faying surfaces of a bolted joint. This property, together with the use of zinc-coated steel fasteners, ensures the joint is fully protected. The initial lubricity of the coating is also useful and can be enhanced for metal working operations by phosphate coating.
- **Antisparking**
  The characteristic means that the material will not ignite hazardous gas mixture, vapors, or particulate matter when struck by rusted ferrous materials.

Figure 3: Corrosion of Metal Roofing in one of the rumah panjang in Sarawak

2.2 CORROSION

2.2.1 Corrosion Definition and Background

Corrosion is destruction of metal by chemical or electrochemical reaction with its environment (Herbert H. Uhlig, 2001, pg 1). It is estimated that corrosion destroys one quarter of the world's annual steel production, which corresponds to about 150 million tons per year or 5 tons per second (Dieter Landolt, 2006, pg 1). Examples of corrosion phenomena include:

- Transformation of steel into rust
- Cracking of brass in the presence of ammonia
- Oxidation of an electrical contact made of copper
- Weakening of high resistance steal by hydrogen
- Hot corrosion of super alloy in Gas Turbine
- Chemical attack of mineral glass by an alkaline solution

According to Dieter Landolt (2006)

> Corrosion affects all areas of economy, from the integrated circuit to the bridge made of reinforced concrete. The cost of corrosion has been estimated to represent 4% of the gross national product of America (ASM Metal Handbook, 1987, p1415).
>
> These numbers include:
>
> - Direct losses: Replacement of corroded materials and equipment ruined by corrosion.
> - Indirect loses: Cost of repair and loss of production.
> - Cost of corrosion protection: Use of more expensive corrosion-resistant materials, application of surface coatings and cathodic protection systems.
> - Cost of corrosion prevention: Maintenance, inspection, corrosion prevention by design.

2.2.2 General Corrosion Properties of Zinc and Iron

Zinc and its alloys are some of the most corrosion resistance materials. This is due to their ability to form protective layers that cover the metal surface. These protective layers are typically oxide, hydroxide or carbonate films that are very adherent to the metal surface and can be insoluble in solution. Corrosion of zinc increases from immersion in hard water, then in sea water and soft water is the most corrosive (Ken Yu-Jen Su, 2008, pg 16).

Upon contact with water or immersed in solution, zinc dissolves readily and forms a film of corrosion products on the surface. The corrosion film is particularly stable in near neutral pH solutions but will dissolve in strong acidic or alkaline solutions (Slunder and Boyd, 1983). In addition, the corrosion rate of zinc is especially low in near neutral pH values but can increase in either acidic or alkaline environments (Porter, 1991). Under atmospheric conditions, high moisture content or condensation on the metal surface may cause zinc hydroxide to form. This film is then likely to react with carbon dioxide to form insoluble zinc carbonate that shields zinc from the outside environment. Thus, zinc carbonate is very protective and is responsible for the excellent corrosion resistance of zinc in the atmosphere (Porter, 1991).

In general, the stability, adherence, and compactness of the corrosion products can affect the corrosion resistance thereby influence the corrosion rate of zinc coatings (Zhang, 1996, pg 178).

The corrosion of zinc in most atmospheric environments is usually general corrosion that is corrosion occurs uniformly across the zinc surface. The corroded surface after years of exposure may be covered with dimples, for which the ratio of depth to diameter is small. The dimple size can be a few millimeters in a marine environment and much smaller in a rural environment. Another common corrosion form of zinc is galvanic corrosion. On galvanized steel at places where coating is damaged, the exposed steels are cathodically protected while the zinc coating is galvanically corroded. Although a common form of corrosion, galvanic corrosion is not a major contributor to the corrosion of zinc coatings because the exposed areas of bare steel are usually too small to cause significant corrosion. Usually the atmospheric corrosion rate of galvanized steel is essentially the same as that of zinc (Zhang, 1996, pg 262).

2.2.3 Atmospheric Corrosion

Atmospheric corrosion is the oldest types of corrosion recognized. Atmosphere is the environment to which metals are most frequently exposed (D. Fyfe, 1976, pg 226).

Atmospheric corrosion is the result of interaction between a material and its atmospheric environment. When exposed to atmosphere at room temperature with virtually no humidity present, most metal spontaneously form a solid oxide film. If the oxide is stable, the growth rate ceases and the oxide reach a minimum thickness of 1 nanometer to 5 nanometer (Phillipe Marcus, 2002, pg 529).

Atmospheric corrosion is an electrochemical process, requiring the presence of an electrolyte. Thin film "invisible" electrolytes tend to form on metallic surfaces under atmospheric corrosion conditions, when a certain critical humidity level is reached. For iron, this level is around 60%, in unpolluted atmospheres. The critical humidity level is not a constant - it depends on the corroding material, the hygroscopic nature of corrosion products and surface deposits and the presence of atmospheric pollutants (corrosionsource, Atmospheric corrosion, 2010).

In the presence of thin film electrolytes, atmospheric corrosion proceeds by balancing anodic and cathodic reactions. The anodic oxidation reaction involves the dissolution of the metal in the electrolyte, while the cathodic reaction is often assumed to be the oxygen reduction reaction. Oxygen from the atmosphere is readily supplied to the electrolyte, under thin film corrosion conditions (corrosionsource, Atmospheric corrosion, 2010).

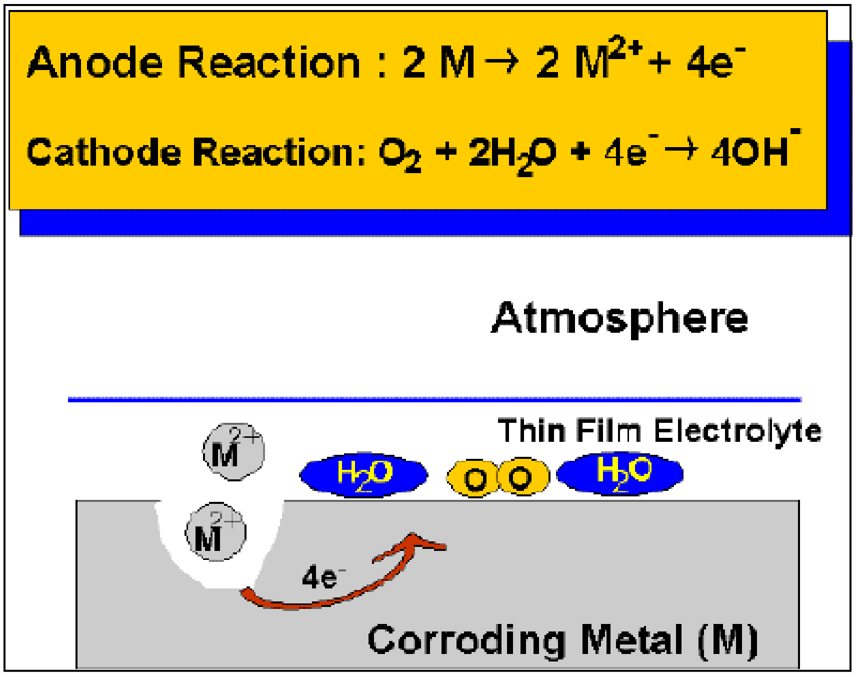


Figure 4: Atmospheric corrosion mechanism

Atmospheric corrosion is a complicated electrochemical process taking place in corrosion cells consist of base metal, metallic corrosion products, surface electrolyte and the atmosphere. (Philip A. Scheweitzer, 2007, pg 39).

2.2.3.1 Factors Affecting Atmosphere Corrosion

There are several factors that will affect the atmospheric corrosion rate. Important factors that affect the atmospheric corrosion include (Philip A. Scheweitzer, 2007, pg 42):

1. **Time of wetness:** The length of time on which the metal surface is covered by a film of water that renders significant atmospheric corrosion possible. It depends on the relative humidity of the atmosphere, the temperature of the air and the duration of rain, fog, dew and melting snow, as well as the hours of sunshine and wind speed.
2. **Composition of surface electrolyte:** The electrolyte film on the surface will contain various species deposited from atmosphere or originating from the corroded metal. The composition of the electrolyte is the determining factor of the corrosion process.
3. **Temperature:** As the temperature increase, the rate of corrosive attack will increase as a result of an increase in the rate of electrochemical and chemical reactions as well as the diffusion rate.
4. **Wind velocity:** Wind speed and type of wind flow have a pronounced effect on the atmospheric corrosion rate by the dry deposition velocity that is defined as the ratio of deposition rate of any gaseous compound and the concentration of that compound in the atmosphere.
5. **Pollutants present:** The presence of atmospheric pollutants such as the various oxides of nitrogen, sulfur-containing compounds and chlorine-containing compounds will stimulate and increase the rate of corrosion.

2.3 SODIUM CHLORIDE (NaCl) COMPOSITION COMPARISON BETWEEN COASTAL AREA AND NON-COASTAL AREA

Table 3 shows the Sodium Chloride Composition in rain water in Mersing (coastal) and Petaling Jaya (non-coastal) based on the annual report from Malaysia Meteorology Department (MMD) from 2004 to 2008. From the table, Sodium Chloride composition in Mersing which is a coastal area is more than 20 mg/L for the five years compared to Petaling Jaya which is not a coastal area.

Table 3: Sodium Chloride (NaCl) composition in Rain Water Mersing and Petaling Jaya

YEAR	MERSING	PETALING JAYA
	NaCl composition (mg/L)	NaCl composition (mg/L)
2004	26.89	19.57
2005	23.61	19.34
2006	25.82	18.86
2007	24.81	19.04
2008	22.01	18.62

2.4 CORROSION RATE METHOD OF ANALYSIS

2.4.1 Salt Spray (Fog) Test

Salt spray (fog) test is the most commonly used cabinet corrosion test. It is used with reference to the ASTM B 117 Salt Spray (Fog) Test. It is performed by placing samples in a test cabinet that has been designed and operated in accordance with ASTM B 117. **Figure 5** shows the typical components of a corrosion chamber (Ascott, 2010)

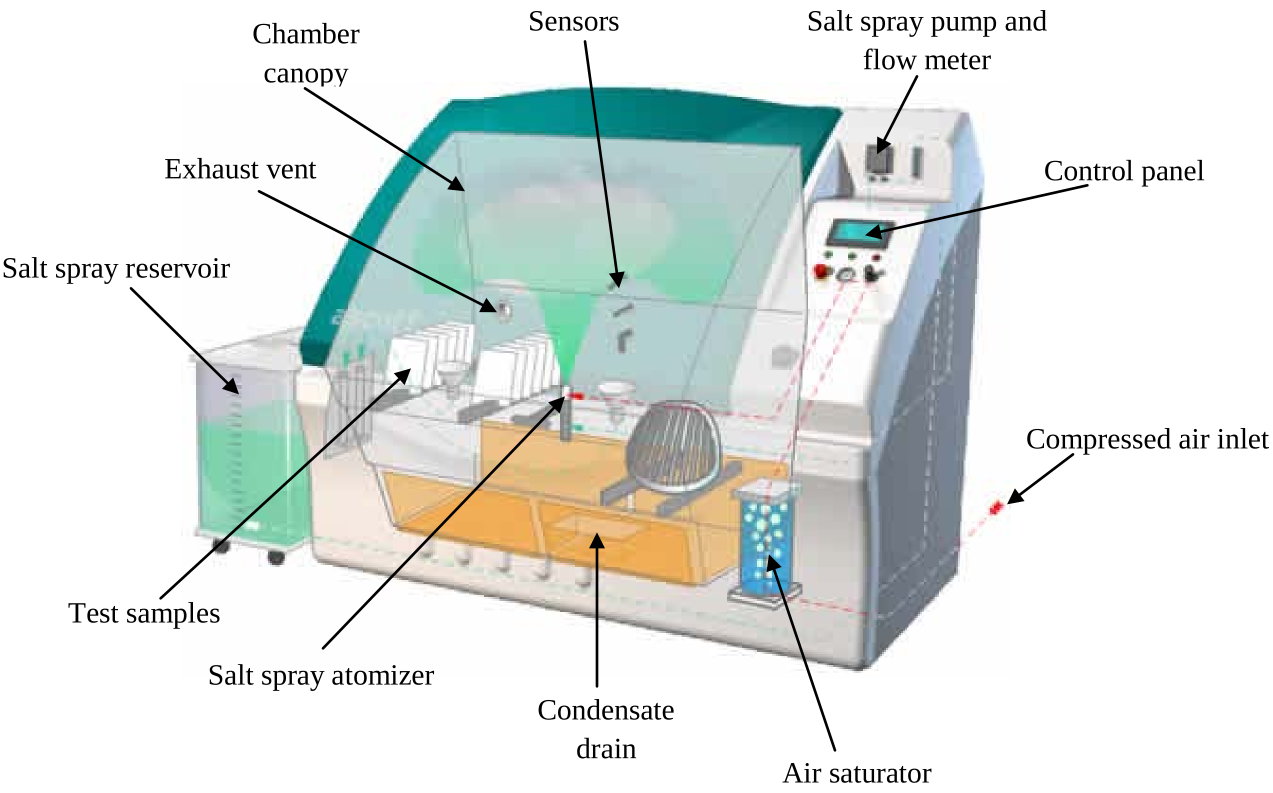


Figure 5: Corrosion chamber and its components

Compressed air inlet

- Compressed air from a separate compressed air supply is required for the chamber. The primary use of this is to atomize salt water into spray at the salt spray atomizer, located inside the chamber, during salt spray testing. The compressed air supply should be clean, dry and oil free, pressurized to within the limits 1.4 to 6.0 bar (20 to 87 P.S.I.). Between these pressures the air supply should be capable of delivering a flow rate of at least 75 Liters (2.6 cubic feet) per minute, which equates to a free flow at atmospheric pressure of approximately 102 standard liters (3.6 standard cubic feet) per minute.

Air Saturator

- During salt spray testing, the compressed air utilized to generate the salt spray is bubbled through the air saturator (also referred to as a bubble tower or humidifier) in order to raise its humidity to c.100%RH at the point that it leaves the salt spray atomizer. This ensures a 'wet' and 'dense' salt spray is created.

Salt solution reservoir

- A separate salt solution reservoir is provided for ease of filling and cleaning. During salt spray testing, the salt solution (brine) is drawn from this reservoir by the chamber peristaltic pump, via a primary filter unit which removes any large undissolved salt crystals or other debris.

Salt solution pump and flow meter

- During salt spray testing, the salt solution pump positively draws salt water into the chamber from the separate salt solution reservoir, by peristaltic action, so avoiding the need for a gravity fed system and the consequent difficulties in maintaining a constant 'head' of salt solution to be sprayed. This salt water is delivered, via a graduated flow meter, to the salt spray atomizer inside the chamber.

Salt spray atomizer

- During salt spray testing, it is here that the compressed air, delivered via the air saturator, meets the salt water, delivered via the salt solution pump and flow meter, to create a finely divided salt spray (also referred to as 'salt mist' or 'salt fog').

Control panel

- Forming the centre-piece of the ergonomically designed control panel is a state of the art Human Machine Interface (HMI). This incorporates alpha-numeric text messaging and digital displays of chamber variables such as temperature and time (see chamber data sheets for the type of HMI fitted). It is here that the user controls and monitors the various chamber functions. In addition, all chamber control panels incorporate an emergency stop and other safety facilities.

Chamber canopy

- An automatic purge facility is incorporated to minimise the risk of corrosive salt spray escaping into the laboratory when the chamber is opened. The chamber canopy is effortlessly opened/closed using pneumatic cylinders, which are activated at the touch of a button on the control panel.

Sensors

- Strategically located sensors, mounted inside the chamber and air saturator, monitor the climate continuously and convey this information to the Human Machine Interface (HMI), where it is displayed digitally at the control panel.

Condensate drain

- A floor level drain is required to remove to waste the excess salt fog condensate etc. which accumulates over the internal base of the chamber interior.

2.4.2 Mass Loss Method

In Salt Spray Test and Immersion Test, the mass loss of the samples exposed to corrosive environments will be determine in order to measure the corrosion rate of the specimens. The corrosion rate is determined from the Corrosion Penetration Rate (CPR) Expression:

$$CPR = \frac{KW}{DAT}$$

K = constant (534 for mill/yr and 87.6 for mm/yr)

W= Weight Loss (mg)

D= Density (g/cm^3)

A= Area (in^2 or cm^2)

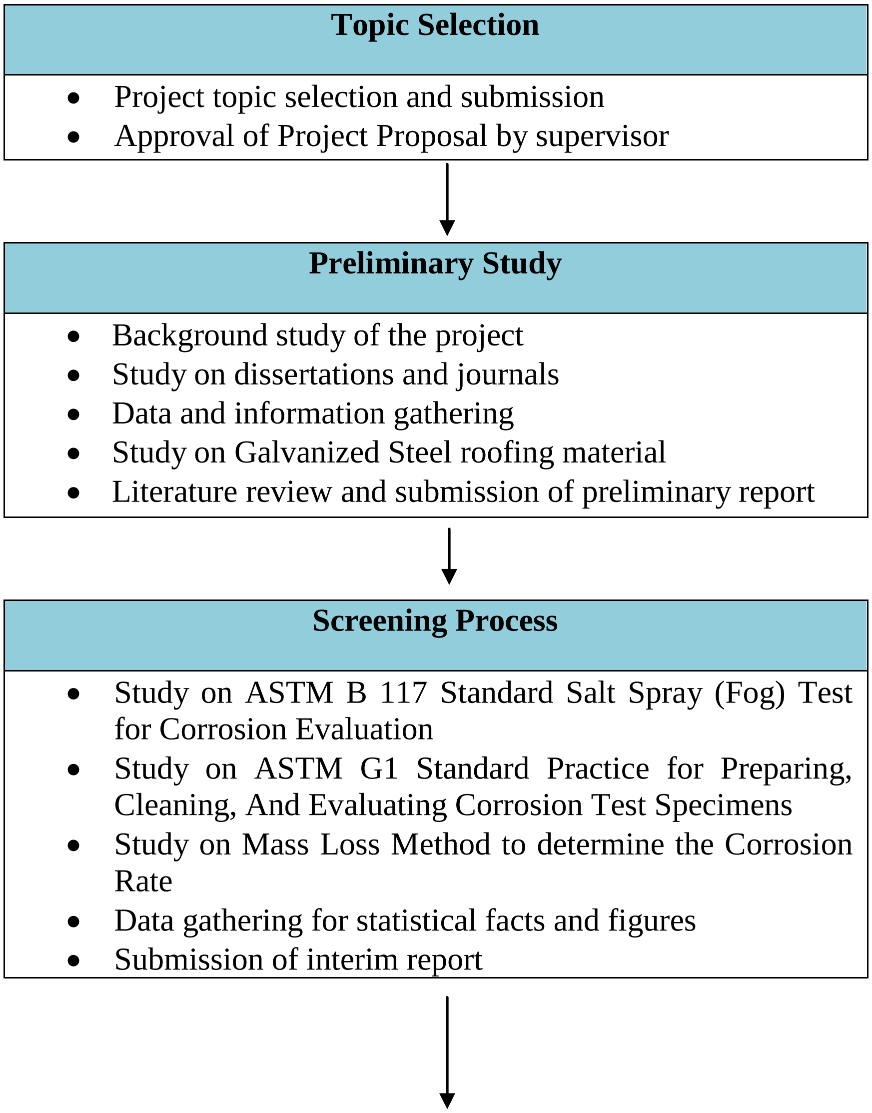
T= Time (Hour)

CHAPTER 3

METHODOLOGY

3.1 PROJECT FLOW

Methodology plays an important role in completing a project. It is an abstract representation of each system process. The purpose of having methodology is to make sure that the system is developed within the scope planned and also to ensure the consistency of each process. The project flow is shown in **Figure 6**.



Topic Selection

- Project topic selection and submission
- Approval of Project Proposal by supervisor

Preliminary Study

- Background study of the project
- Study on dissertations and journals
- Data and information gathering
- Study on Galvanized Steel roofing material
- Literature review and submission of preliminary report

Screening Process

- Study on ASTM B 117 Standard Salt Spray (Fog) Test for Corrosion Evaluation
- Study on ASTM G1 Standard Practice for Preparing, Cleaning, And Evaluating Corrosion Test Specimens
- Study on Mass Loss Method to determine the Corrosion Rate
- Data gathering for statistical facts and figures
- Submission of interim report

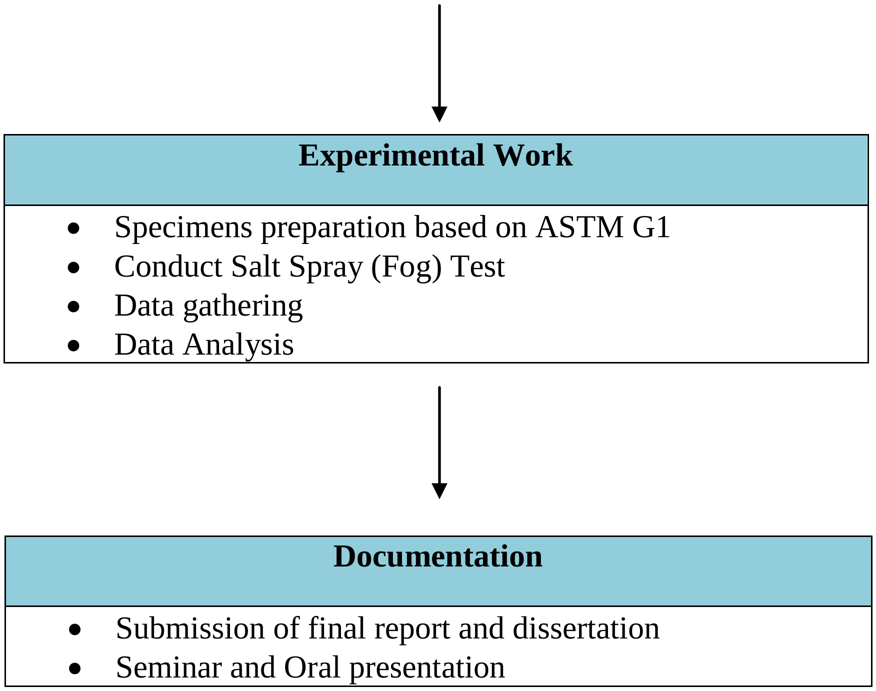


Figure 6: Project Flow Diagram

3.2 PROJECT PROCEDURES

1. Prepare samples as per needed according to ASTM G1 Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens. Twelve samples need to be prepared. Before weighing and exposure, test specimens must be cleaned from any contaminants and dirt. The samples were polished on Silicon Carbon (SiC) paper with 60, 120 and 220 grit size and then washed in ultrasonic bath containing acetone for 10 minutes. After that, the samples are dried with hair dryer and store in desiccators with silica gel to remove water. The dimensions of the sample prepared are as follow:

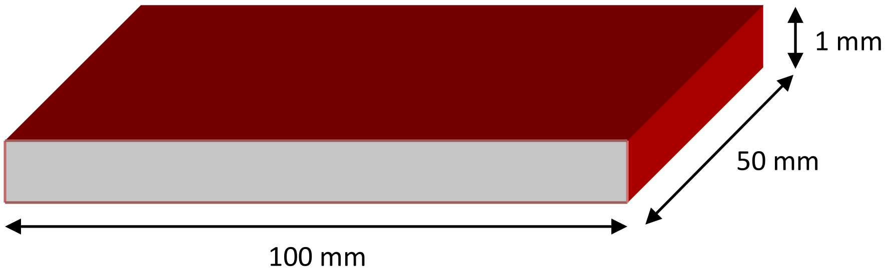


Figure 7: Specimens Dimensions

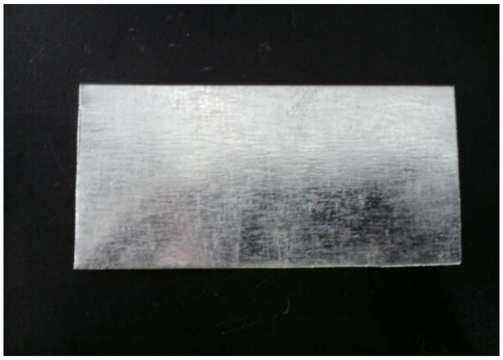


Figure 8: Specimen before the cleaning process

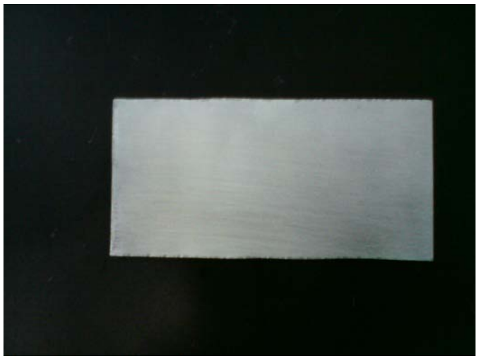


Figure 9: Specimen after the cleaning process

2. Four samples are used under each of the concentration of the Sodium Chloride (NaCl) solution. Sodium Chloride (NaCl) concentrations used in this project are 5%, 10% and 20% concentration.
3. The initial weight of each of the sample is measured before it is exposed to the respected Sodium Chloride (NaCl) solution.
4. The experiment is conducted for 4 weeks for each concentration of Sodium Chloride (NaCl) solution. Each week, one sample is taken out from the corrosion chamber and the sample is cleaned according to ASTM G1 Standard Practice for Preparing, Cleaning and Evaluating Corrosion Test Specimens. After the cleaning process, the final weight of the sample is measured.
5. Corrosion rate of the sample is then measured by using Mass Loss Method.
6. After the experiment finished, the overall result is analyzed and interpreted.

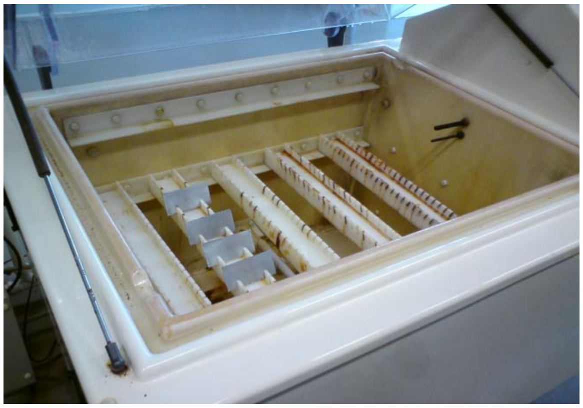


Figure 10: Specimens in the corrosion chamber before the exposure

3.2.1 Salt Solution Preparation

The salt solutions used in this experiment are prepared by dissolving crystallized Sodium Chloride (NaCl) in distilled water.

For 5% concentration of NaCl:

- *The solution consists of 95% of water and 5% of NaCl.*
- *The mass of water is 1g for 1mL of water, so the mass for 1 L of water is 1000 g.*
- *Since the total mass of the solution (water + NaCl) is only 95% of the total mixture by mass, the total mass of the solution is: 1000 / 0.95 = 1053 g*
- *Mass of NaCl = 1053 g – 1000 g = 53 g*
- *Multiplier of NaCl = 53 g /1000 g = 0.053*
- *So, the equation for 5% NaCl solution is: 0.053 x Mass of water (g) = Mass of NaCl required (g).*

The 10% and 20% concentration of NaCl solution is prepared by using the same concept as above. The pH of the salt solution must be measured by using the pH meter to make sure that it is maintained between 6.5-7.2 pH in accordance to ASTM B 117 Salt Spray (Fog) Test.

3.2.2 Experiment Parameters

Table 4: Experiment Parameters

Parameter	Value
NaCl concentration	5%, 10%, 20%
pH	6.5-7.2
Temparature	27°C
Time of Exposure	1 week, 2 weeks, 3 weeks, 4 weeks
Position of specimen during exposure	15° - 30° from vertical

3.3 TOOLS AND EQUIPMENT

1. Salt Spray (Fog) Test equipment (Corrosion chamber)

Figure 11: Salt Spray (Fog) Test equipment

2. Digital Electronic Weighing

Figure 12: Digital electronic weighing

3. Ultrasonic Cleaner

Figure 13: Ultrasonic Cleaner

3. Dryer

Figure 14: Dryer

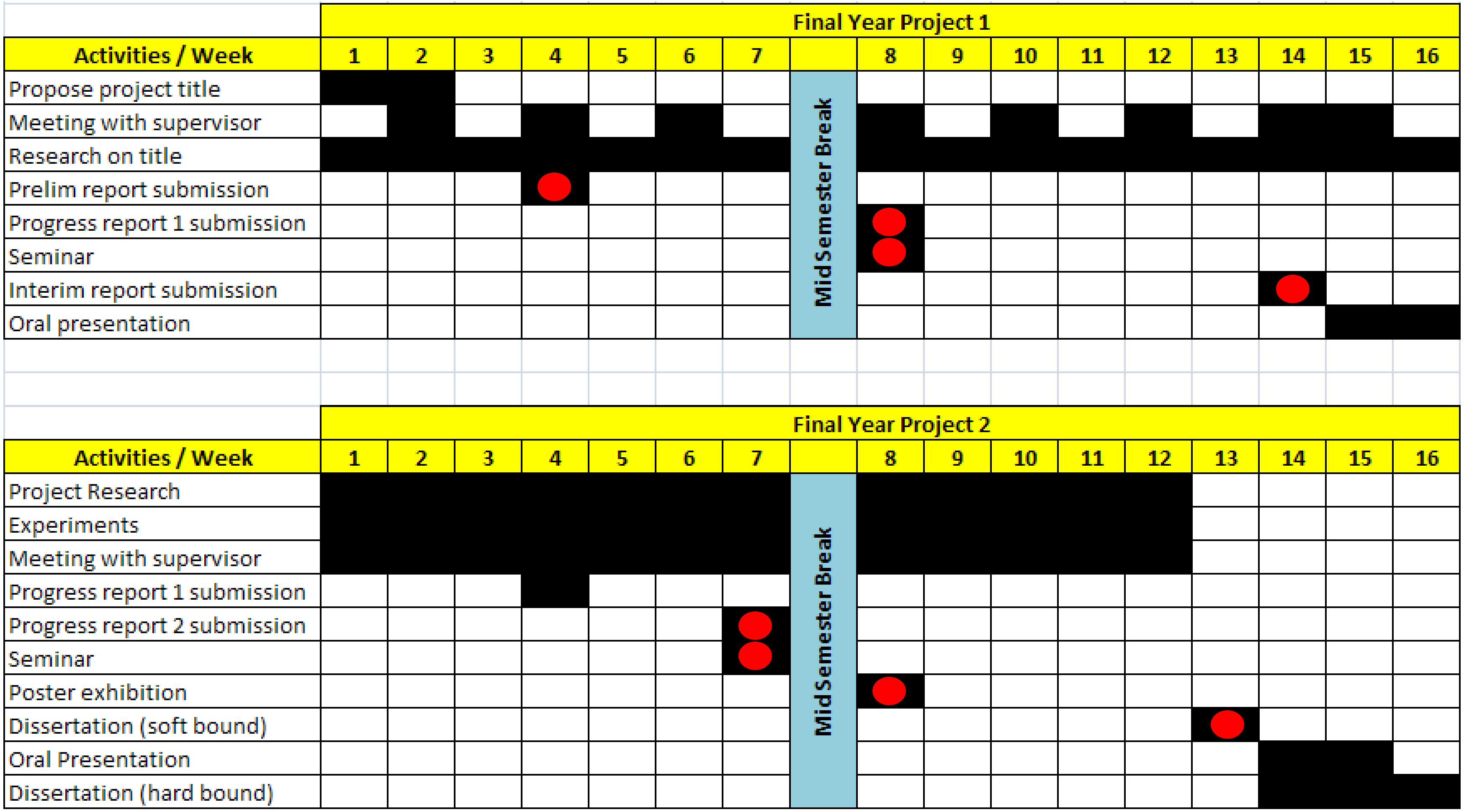
4. pH meter

Figure 15: pH meter

5. Silicon Carbide paper (sand paper)

Figure 16: Silicon carbide paper with 60, 120 and 220 grit size

3.4 GANTT CHART



	Final Year Project 1																
Activities / Week	**1**	**2**	**3**	**4**	**5**	**6**	**7**		**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Propose project title	■	■						Mid Semester Break									
Meeting with supervisor		■		■		■			■		■		■		■	■	
Research on title	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■
Prelim report submission				●													
Progress report 1 submission									●								
Seminar									●								
Interim report submission															●		
Oral presentation																■	■

	Final Year Project 2																
Activities / Week	**1**	**2**	**3**	**4**	**5**	**6**	**7**		**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Project Research	■	■	■	■	■	■	■	Mid Semester Break	■	■	■	■	■				
Experiments	■	■	■	■	■	■	■		■	■	■	■	■				
Meeting with supervisor	■	■	■	■	■	■	■		■	■	■	■	■				
Progress report 1 submission				■													
Progress report 2 submission							●										
Seminar							●										
Poster exhibition									●								
Dissertation (soft bound)														●			
Oral Presentation															■	■	
Dissertation (hard bound)															■	■	■

● Milestone

■ Process

CHAPTER 4

RESULTS AND DISCUSSION

4.1 DATA GATHERING

The dry mass losses of the exposed samples have been recorded from this experiment after the exposure period as stated in chapter 3. The following table shows the result of the experiment after the four weeks exposure in the corrosion chamber.

Table 5: Weight loss of samples

Experiment	NaCl Concentration (%)	Exposure time (Week)	Initial Weight (mg)	Final Weight (mg)	Weight Loss (mg)
1	5	1	13687.60	13686.1	1.5
		2	13588.70	13586.5	2.2
		3	13846.60	13844.3	2.3
		4	13966.80	13694.1	2.7
2	10	1	13688.60	13685.10	3.5
		2	13660.20	13656.00	4.2
		3	13546.40	13541.70	4.7
		4	13842.20	13837.10	5.1
3	20	1	13587.40	13580.20	7.2
		2	13742.40	13733.90	8.5
		3	13689.40	13680.20	9.2
		4	13952.60	13942.70	9.9

From **Table 5**, the graph of Weight Loss versus Exposure Time is plotted as follows:

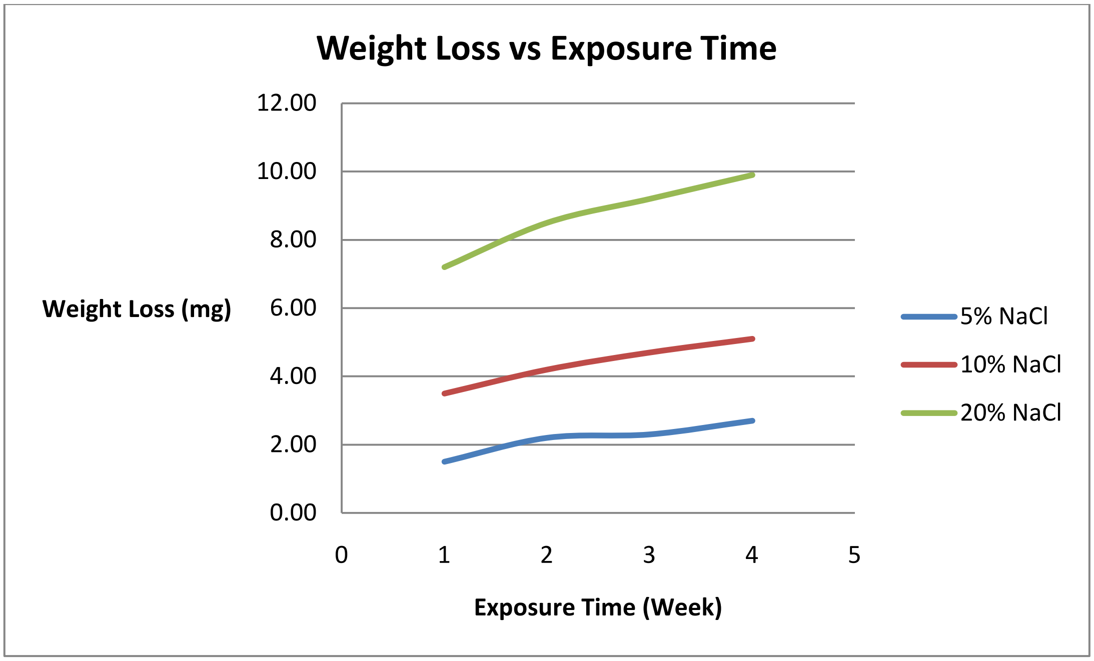


Figure 17: Graph of Weight Loss (mg) versus Exposure Time (week)

From the weight loss measured in **Table 5**, the corrosion rate of the samples is calculated by using Corrosion Penetration Rate (CPR) formula. The following example shows the calculation of corrosion rate for the sample exposed in 5% Sodium Chloride (NaCl) concentration solution after one week exposure in the corrosion chamber.

$$\boxed{CPR = \frac{KW}{DAT}}$$

K= 87.6 (constant)

Density of galvanized steel = 7.85 g/cm³

Weight Loss = 1.5 mg

Sample surface area= (10 cm x 5cm)(2) + (10 cm x 0.1 cm)(2) + (5cm x 0.1 cm)(2)

= 103 cm²

Exposure time = 1 week = 168 hours

CPR = (87.6)(1.5 mg) / (7.85 g/cm³)(103 cm²)(168 hours)

= 0.00096734 mm/yr = 0.967340124 µm/yr

Table 6 shows the corrosion rate calculated for the remaining samples in different concentrations of Sodium Chloride (NaCl) solutions.

Table 6: Corrosion Rate after four weeks of exposure in different concentration of Sodium Chloride solutions

Experiment	NaCl Concentration (%)	Exposure Time (week)	Corrosion Rate (µm/year)
1	5	1	0.96734
		2	0.70938
		3	0.49441
		4	0.43530
2	10	1	2.25712
		2	1.35427
		3	1.010333
		4	0.822239
3	20	1	4.643232
		2	2.740797
		3	1.977673
		4	1.596111

From **Table 6,** the graph of Corrosion Rate versus Exposure Time is plotted as follows:

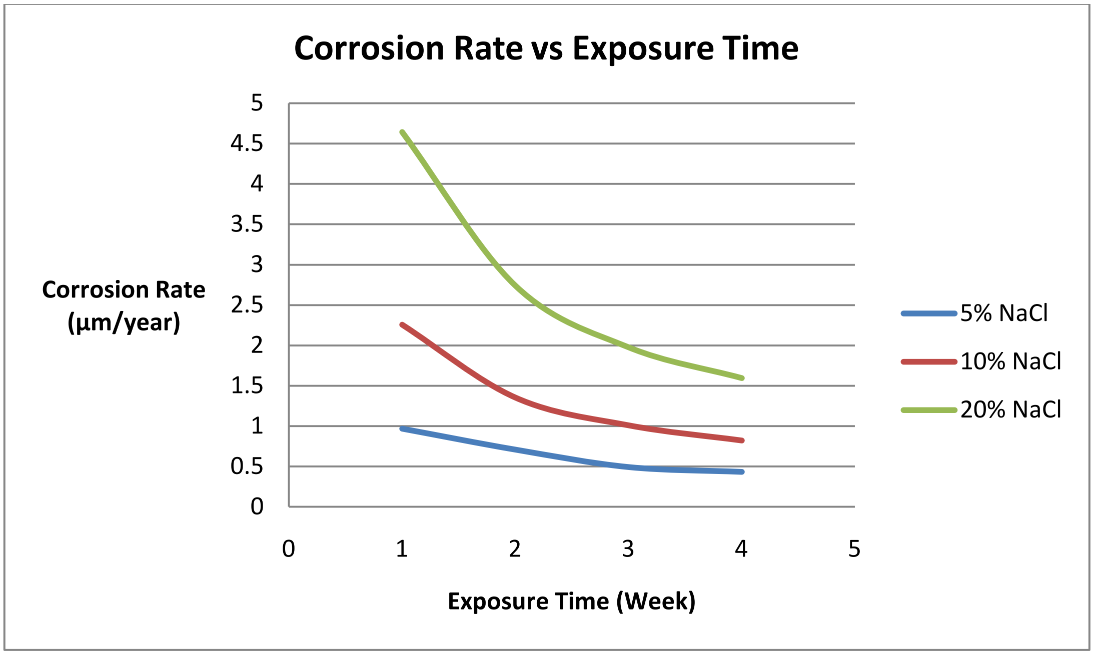


Figure 18: Graph of Corrosion Rate (µm/year) versus Exposure Time (week)

4.2 DISCUSSION

From **Figure 17**, it is observed that the corrosion rate is increased as the Sodium Chloride (NaCl) concentration increase from 5% to 20% concentration. It means that the weight loss is increased when the concentration of Sodium Chloride (NaCl) solutions increase. This can be explained from the chemical reaction that takes place between the galvanized steel surface and the environment. In order for the corrosion reaction to occur, there must be electrons transfer from the surface of the galvanized steel to the environment allowing the protective zinc to form dissolved zinc species (Zn^{2+}) in the solution. With the existence of dissolved Sodium Chloride (NaCl), the Sodium Chloride will break up in the solution to form Sodium Ions (Na+) and Chloride Ions (Cl-) which will then help to carry the electrons back and forth during the corrosion reaction. Thus, with the increasing of NaCl concentration, more ions will involve in the reactions and cause the corrosion rate to increase.

However, it is observed that the corrosion rate is decreasing with the increasing of the exposure time from week one to week four. In the environment of 5% of NaCl concentration, the corrosion rate for week 1 is 0.96734 µm/year while for week 2, the corrosion rate is 0.70938 µm/year. The corrosion rate continues to decrease in week 3 to 0.49441 µm/year and further decrease in week 4 to 0.43530 µm/year. The corrosion rate also shows the same trend and behavior in other environments which are in 10% and 20% NaCl concentration.

The decreasing of corrosion rate with the increasing of exposure time can be explained by the electrochemical reaction that takes place on the surface of the galvanized steel. From literature review, zinc layer plays an important role in the corrosion resistance of the galvanized steel. In general, the anodic reaction of the zinc when it is exposed to the corrosive environment is as follows:

$$Zn \longrightarrow Zn^{2+} + 2e^- \qquad \text{(Eq 4.1)}$$

If the environment or solution is neutral or alkaline, the cathodic reaction that takes place is generally as follows:

$$2H_2O + O_2 + 4e^- \longrightarrow 4OH^- \qquad \text{(Eq 4.2)}$$

However, the atmospheric corrosion is often divided into different types of environment that are rural, urban, industrial and marine. Each type of atmospheric environment can cause zinc to form different compounds. In general, oxides, hydroxides, and carbonates are the most common corrosion products of zinc and have a very low solubility in water (Ken Yu-Jen Su, 2008, p 22). Initially, zinc hydroxides are formed when dissolved zinc species (Zn^{2+}) react with hydroxyls ions (OH^-) in the solutions.

$$Zn^{2+} + 2OH^- \longrightarrow Zn(OH)_2 \qquad \text{(Eq 4.3)}$$

Zinc Hydroxide formed will then gradually transform into zinc oxides by the reaction as follow:

$$Zn(OH)_2 \longrightarrow ZnO + H_2O \qquad \text{(Eq 4.4)}$$

When the environment contains chlorides, the corrosion process generally leads to the formation of zinc hydroxyl chlorides (ZHC), also known as simonkolleite by the equation below:

$$Zn^{2+} + Cl^{-} \longrightarrow ZnCl_2 \qquad \text{(Eq 4.5)}$$

$$4Zn^{2+} + 8OH^{-} + ZnCl_2\,(aq) \longrightarrow ZnCl_2\,[Zn(OH)_2]_4 \qquad \text{(Eq 4.6)}$$

According to Kawafuku *et al.* zinc hydroxyls chloride, $ZnCl_2$ $[Zn(OH)_2]_4$ has compact nature of structure. The compact nature of the corrosion product prevents the permeation and retention of oxygen and water. This is the main reason for the decreasing of corrosion rate as the exposure time increase.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the result and analysis done in chapter 4, several conclusions can be done:

- The corrosion rate of the galvanized steel roofing sheet increase as the concentration of the Sodium Chloride (NaCl) increase
- The corrosion rate of the galvanized steel roofing sheet decrease as the time of exposure increase
- The formation of zinc compound will slow down the rate of corrosion
- It is predicted that the lifespan of the galvanized steel roofing sheet in the marine environment is shorter compared to its application in the normal environment.

5.2 Recommendations

There are few recommendations for future work for expansions:

- Do the analysis of the surface and cross-section of the samples by using Scanning Electron Microscope (SEM) before and after the experiments to see the severity of the atmospheric corrosion as the Sodium Chloride (NaCl) concentration increase from 5% to 20% concentrations.
- The corrosion products from the experiment should be characterized by using X-Ray Diffraction (XRD) technique in order to know the actual composition of the corrosion product and to determine the existence of the Zinc Hydroxyl Chloride (ZHC).
- For recommendation for future experiment, other parameters that influence the atmospheric corrosion such as temperature, wind velocity and time of wetness should be tested in various combinations to determine the optimum condition for the atmospheric corrosion of galvanized steel roofing sheet to occur at optimum rate.

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