
CORROSION OF MILD STEEL

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14th MAY 2019

ABSTRACT

The current project investigated the corrosion of mild steel in various solutions. The chosen salts for this investigation included: Sodium Chloride, Sodium Carbonate and Sodium Sulphate. It has been shown that the corrosion in water after 56 days exposure showed a very minimal reduction in the mass of the sample. However, this scenario was completely different with Sodium Chloride Wherein the corrosion was significant due to the penetration of chlorides into the metal and the high conductivity of the solution. Similarly, the corrosion of the sample in water and Sodium Sulphate was significant due to the high conductivity of the solution and the severity of the salt on the metal. On the contrary, it has been revealed that there was no corrosion of the sample in water and Sodium Carbonate as well as no observed mass loss. This is due to the fact that the Sodium Carbonate is actually a corrosion inhibitor. This is due to the formation of the protective layer on the surface of the metal which protects it from corrosion. The surface roughness measurements have confirmed the obtained outcomes. In other words, the higher the corrosion rate, the larger the amount of material lost from the surface and hence the rougher the surface. The mass loss was highest for the Sodium Sulphate samples when compared to the Sodium Chloride samples. This can be observed in the slope of the measured mass vs. time plots wherein the higher the slope the quicker the corrosion rate.

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CHAPTER 1: INTRODUCTION

1.1 Background

Mild steel is a very well-known material due to its excellent properties and this has attracted the attention to use such steel alloys in the construction and manufacturing industries, Figure 1. The mild steel is readily available and has excellent physical and mechanical properties such as strength, hardness and ductility alongside weldability. Moreover, it is machinable and can be used in marine applications and ship industries. Moreover, it is widely used in pipe fabrication and tidal wind turbines (ACERAR, 2018).



Figure 1: The various steel applications
from construction to automotive industries.

The main disadvantage of the mild steel is the oxidation and corrosion under atmospheric conditions. This means that the material can be easily corroded in acids and in high temperature environments. Moreover, rust can form under normal conditions and this causes weakness of the structure and eventually failure under stress conditions, Figure 2, (Corrosion_Steel, 2018).



Figure 2: The corrosion of steel under various environmental conditions.

Corrosion is defined as a chemical reaction between the material and the environment. This requires the existence of oxygen and water and it can be accelerated by salts such as in seawater. There are many types of corrosion that might affect the steel and this depends on the material, environment and salts. The product of corrosion is what is called 'rust' which is a brownish-coloured material that is normally deposited at the surface of the steel when it corrodes. This rust material is considered a loss of material from the surface and therefore leads to thinning of the material and weakness, Figure 3, (Corrosion_Steel, 2018).

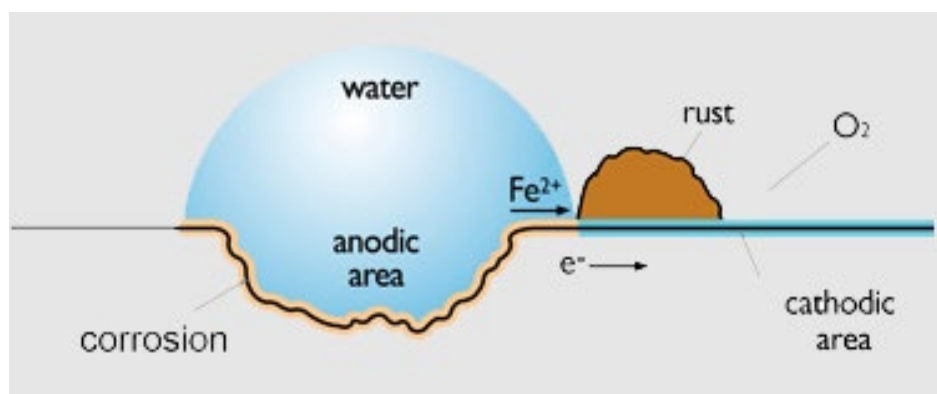


Figure 3: The process of corrosion and formation of rust.

1.2 Objectives

1.2.1 Main objectives

This project aims at studying the effect of different environments on the corrosion rate of mild steel. This will include the use of sodium chloride (NaCl), sodium sulphate (Na_2SO_4) and sodium carbonate (Na_2CO_3). This will simulate the process of corrosion in these environments as well as provide guidance on the effect of corrosion on the mild steel under such corrosive conditions. The weight loss method will be utilised to determine the corrosion rate by measuring the weight of the samples at various periods which can be compared to the original weight of each sample. The corrosion rate will depend on the exposure time, surface area and type of corrosive medium (Metrohm, 2018). The corrosion rate can be expressed in mpy (mils per year) wherein a mil is 0.001 inches (NPL, 2018).

1.2.2 Specific objectives

The above objective can be carried out by following the specific objectives:

1. Corrosive media will be prepared by mixing the chosen salts in water. The percentages will be varied in order to study the effect of salt concentration on the corrosion rate.
2. The weight loss will be measured and recorded at defined periods (every 1 week) for a total of 4 weeks.
3. The surface of the material will be studied before and after in order to define the variation in surface features due to corrosion.
4. A relationship can be derived between the corrosion rate and time from which predictions might be obtained.

1.3 Justification of the Project

The current project has been carried out for various reasons:

1. Steel can corrode in various environments, however, there is no comparative studies that quantifies the amount of corrosion in each corrosive environment.
2. Steel can corrode, however, it is necessary to quantify the amount of metal lost during corrosion as this is considered dangerous on structures.
3. Steel can corrode, however, it is necessary to become aware of the time it takes for the corrosion to take place.
4. When steel corrodes, its mechanical properties will be modified. It is important to know the reduction in hardness, weight and other parameters.

1.4 The Emergency Plan

In any project, there are always risks associated with the various activities. This originates from unforeseen circumstances that might take place during the project. It is always essential to evaluate the project and set up a risk assessment plan for the work. Moreover, this should include an analysis of the consequences of such risks and the best way to mitigate such complications. In the current project, several risks have been identified and a mitigation plan has been proposed.

Risk	Consequences	Mitigation
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The material is expensive	The material can not be purchased. This means no testing will be conducted.	Secure funding and budget for the project.
The material is not available.	This means no testing will be conducted.	The material should be ordered beforehand. In addition, alternative materials should be proposed for testing. It will be helpful to secure more than a single supplier for the chosen material.
Difficulty in making the samples.	Samples can not be made and thus no testing will be conducted.	Training is required and skills need to be available for machining samples.
Machines not available or busy.	There will be a delay in testing, or no testing can be conducted.	It is important to book the machines in advance. Moreover, seek alternative testing houses.
The results are not as expected.	The results are unreliable and cannot be generalised.	It is important to have more samples made beforehand. Also, repeat tests should be carried out.
The duration of the project is short.	The testing will be incomplete.	The number or duration of test should be reduced. Moreover, discuss with supervisor and update.

1.5 The Budget for the Project

The current project is funded by the college of engineering at the University of Wales Trinity Saint David. The materials will be ordered through the workshop and the machines are also available for testing. The university will have a full ownership of the obtained results and the possibility to publish the work in international journals will be a valid option.

CHAPTER 2: LITERATURE REVIEW

2.1 Corrosion

The safety of structures is an important topic that must always be taken into consideration. In this regard, the factor of safety for structures can sometimes be taken as high as 4 in order to ensure safety under loading and environmental conditions (Safety_Factor, 2018). One of the major factors that contribute towards failure of structures and components is 'corrosion'. The effects of corrosion have been found to cause catastrophic failures in automotive structures, bridges and structural applications that are made of steel. The corrosion process is an electro-chemical reaction that takes place between the steel and the environment (oxygen and water). An anode-cathode reaction takes place which is similar to an electric circuit in which electrons move from one electrode to the other Figure 4. This leads to loss of the material from the surface and therefore deterioration of the structure. The corrosion process is influenced by several factors such as the type of material, corrosive medium, temperature and degree and time of exposure (Corrosion_Steel, 2018).

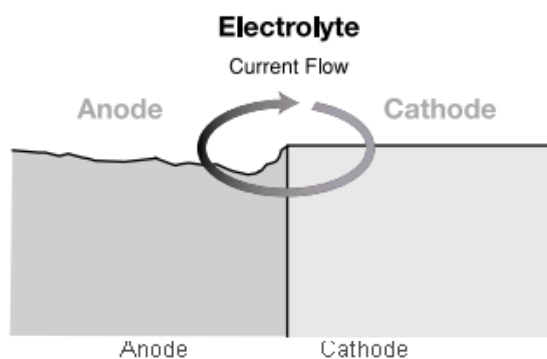
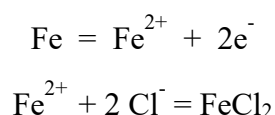
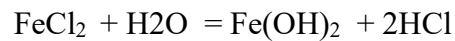


Figure 4: The electro-chemical process of corrosion in metals.

The chemical reaction of the corrosion process in a salty environment is simply given by

(NPL, 1982):





In the above reactions, the iron ions (Fe^{2+}) are lost from the surface of the steel and then combined with chloride ions (Cl^-) to form (FeCl_2). This product then reacts with water to create rust ($\text{Fe}(\text{OH})_2$). The existence of chlorides means that this metal is subjected to salty environments. This speeds up the reaction process and makes corrosion more severe (NPL, 1982).

The corrosion can take several forms and can be localized or uniform. The uniform corrosion can appear along the whole surface and can easily be detected. However, the localized corrosion is more dangerous as it is sometimes undetectable. This includes both microscopic (very small) and macroscopic (larger) corrosion. The microscopic or small-size corrosion includes intergranular, stress-corrosion and corrosion fatigue. Whereas the macroscopic or larger-size corrosion includes galvanic, crevice, pitting and many other types of corrosion. The severity of the resulting corrosion will depend on many factors amongst which is the thickness of the component. The thicker the component the less damaging the corrosion and vice versa. This means that all types of corrosion and influential factors must be studied and taken into consideration. The various types of corrosion that will be discussed are all summarised in Figure 5.

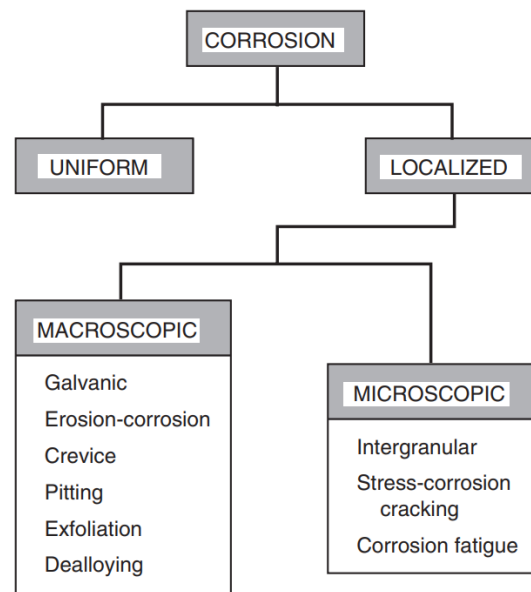


Figure 5: The corrosion

types and categories.

2.2 Corrosion Types

Galvanic Corrosion

This is sometimes call ‘bimetallic’ corrosion which takes place when two dissimilar metals are joined together. This is due to the fact that each metal will have a certain potential which means that one of them will be the anode (negative charge) whereas the other is the cathode (positive charge). This means that the material will flow from/to each dipole leading to loss of material and therefore corrosion (NPL, 1982). This process becomes quicker if the solution is electrolytic such as seawater due to the existence of salts. This type of corrosion might take place in a single material, rather than two dissimilar materials, if it is found that there is a potential difference at the various locations of the same material (Galvanic_Corrosion, 2018). This sometimes takes place in stainless steel materials when the material is joined to another dissimilar material. This might take place in bridges above seawater when screws are used on stainless steel panels. This provides the potential for galvanic corrosion and will be facilitated by salts from the condensate, Figure 6, (Uniform_Corrosion, 2018).

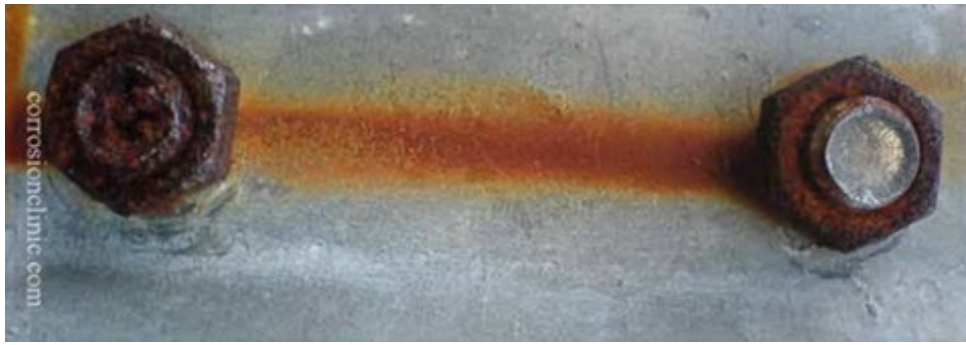


Figure 6: The uniformly distributed galvanic corrosion.

Stress Corrosion Cracking

This type of corrosion requires three basic elements: the material, corrosive environment and external stresses. This is very common in bridges, for instance, which are always subjected to stresses due to loading by vehicles, wind loads and the load from the weight of the material itself. Once this is the case, the loading might cause cracking and corrosion might then take place, hence the name is stress corrosion cracking. With the existence of cracks, the material might eventually fail when the cracks reach a limiting and critical size. The propagation of the corrosion within these cracks leads to internal damage and failure. In order to avoid such scenarios, it is advisable to check for cracks and apply action plans in order to reduce their harmful effects (SCC, 2018).

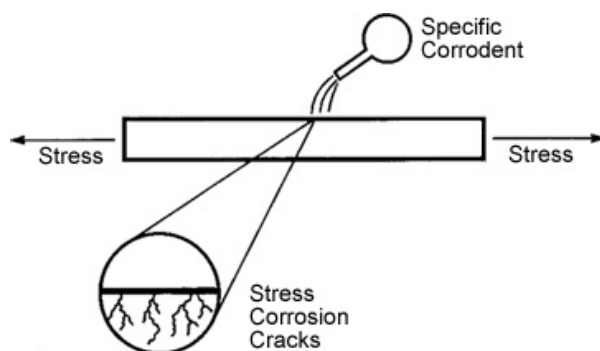


Figure 7: The phenomenon of stress corrosion cracking.

Intergranular Corrosion

This type of corrosion takes place along the grain boundaries of the microstructure inside the materials grains. This takes place due to the loss of a protective element along these boundaries which makes them susceptible to internal corrosion. This means that the material will be lost from the grain boundaries, e.g. the loss of chromium at grain boundaries in stainless steel alloys. Once this happens, the grain boundaries become very weak and internal cracking commences and propagates through the interior regions of the material. This is a very dangerous scenario which can not easily be detected before fracture (Intergranular_Corrosion, 2018).

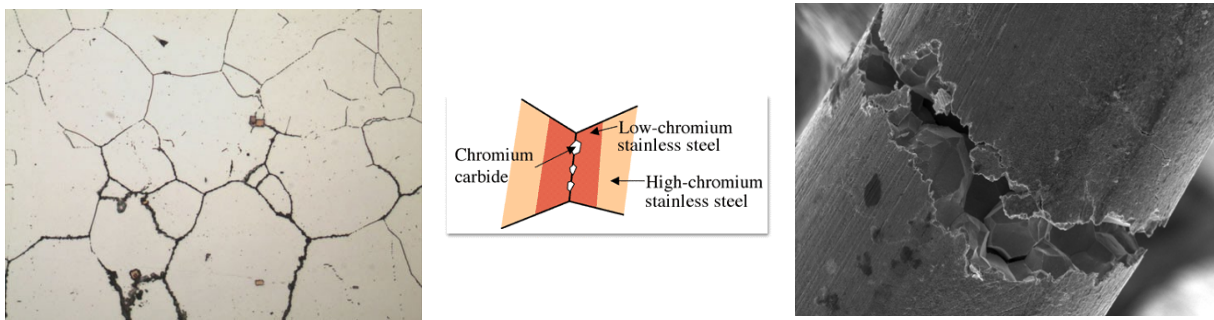


Figure 8: The phenomenon of intergranular corrosion at grain boundaries.

Atmospheric Corrosion

This type of corrosion takes place with the existence of water and oxygen alongside other compounds like sodium chloride salts. This normally takes place in coastal areas which has been found to be 400-500 times greater than corrosion in desert. Moreover, other studies showed that steel that is located 800 feet from coastline (inside the water) corroded 12 times faster than steel located 800 feet from shore (in land). The existence of humidity in coastal areas at the surface of the metal acts like an electrolyte which facilitates the corrosion process when compared to dry surfaces (Galvanic_Corrosion, 2018).

Crevice Corrosion

This type of corrosion takes place in locations where oxygen does not exist such as pockets and underneath shields or seals, gaskets, etc. At these locations, stagnant solution exists, and this initiates the corrosion process. This type of corrosion is accelerated in the presence of chlorides where the reaction takes place underneath such shields and leads to loss of the metal (Kopeliovich, 2018).

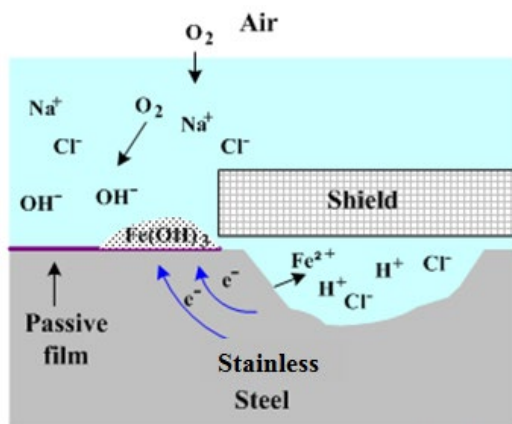


Figure 9: The mechanism of crevice corrosion in metals.

Pitting Corrosion

The process of pitting corrosion takes place as localized holes at the surface of the metal. This type of corrosion is accelerated by chlorides and salts. The process starts with pit initiation due to mechanical damage such as scratches at the surface, pit growth due to the increase in pit depth and width and then material damage in particular when stresses are involved in the process (Pitting_Corrosion, 2018).

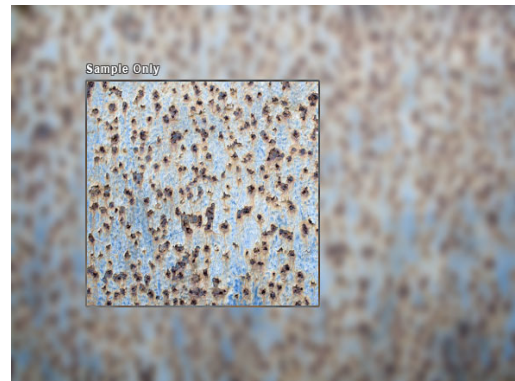
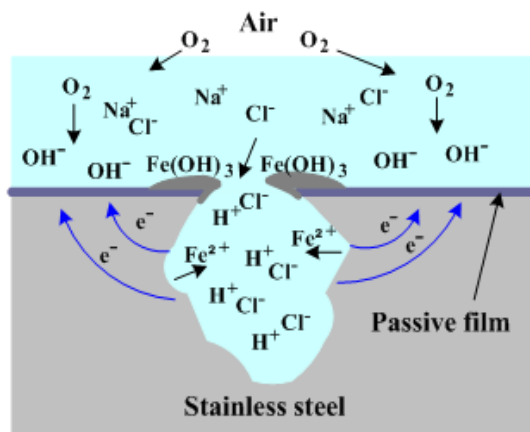


Figure 10: The process of pitting corrosion in steel materials.

2.3 Corrosion Control

In order to reduce the harmful effects of corrosion, various measures can be taken and this includes coatings, material selection and cathodic protection.

a. Coatings

Coating is the process of laying up a thin layer of a material at the surface of the metal in order to provide a barrier against the environment, i.e. oxygen and moisture. The material for coating can be metallic or non-metallic and this depends on the application and the imposed conditions. In the case of steel, for instance, galvanizing is a widely used process in which a Zinc coating is applied to the surface of the steel. This element sacrifice itself to protect the steel which is laid underneath and therefore prevents corrosion (Galvanising, 2018). On the other hand, ceramic materials can be used for coatings, however, these are most suited for high temperature applications (Ceramic_Coatings, 2018).

b. Material Selection

The right selection of materials for a particular application is essential to ensure the integrity of structures. The metals can be active with low corrosion resistance or noble with high

corrosion resistance. Moreover, the resistance to corrosion is dependent on the environmental conditions (HSE, 2018).

c. Cathodic Protection

This method employs a ‘sacrificial’ metal such as magnesium or zinc in order to protect the metallic structure. The sacrificial metal acts as an anode with the electrolytic environment being the cathode. In other words, this metal which is attached to the steel structure protects the component and can periodically be changed when completely corroded (Cathodic_Protection, 2018).

2.4 Effect of Surface Roughness on Corrosion

The surface roughness is defined as the irregularities that can be found at the surface of the metal. This can be a result of manufacturing processes or imposed by the operational conditions. This phenomenon affects the corrosion of materials as well as the mechanical properties of structures (Roughness,

2018),

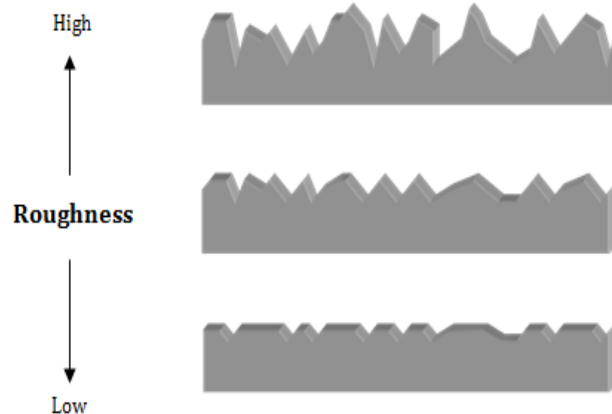


Figure 11.

Figure 11: The surface roughness of materials.

It is a matter of fact that surface roughness affects corrosion of materials. This is due to the fact that the existence of irregularities or grooves at the surface can lead to accumulation of water and salts on the surface and this leads to more corrosion. It has been found that smooth surfaces will not keep water droplets at the surface for a long time when compared to rough surfaces where water particles can be trapped at the surface for much longer times leading to corrosion (Nguyen, 2012). The existence of salts can significantly increase the corrosion of metals when compared to water without salts and dry conditions under mechanical fatigue conditions. In other words, materials will fail faster under fatigue conditions when they are found in salty and humid environments, Figure 12.

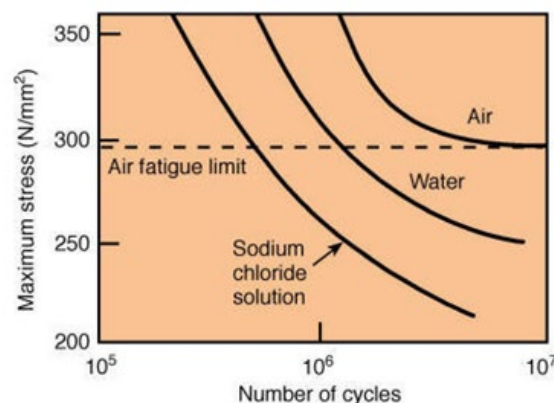


Figure 12: The effect of salts and water on the fatigue life of materials.

In other words, corrosion and surface roughness can affect the mechanical properties of materials as previously discussed. This can be better understood by explaining the effects of surface grooves on the overall thickness of components. In other words, the grooves can act as stress raisers or stress concentration features which means that such regions will be subjected to higher stress due to the reduced thickness. This will then lead to cracking that can propagate under tensile or fatigue conditions until failure, Figure 13, (Deng, 2015).

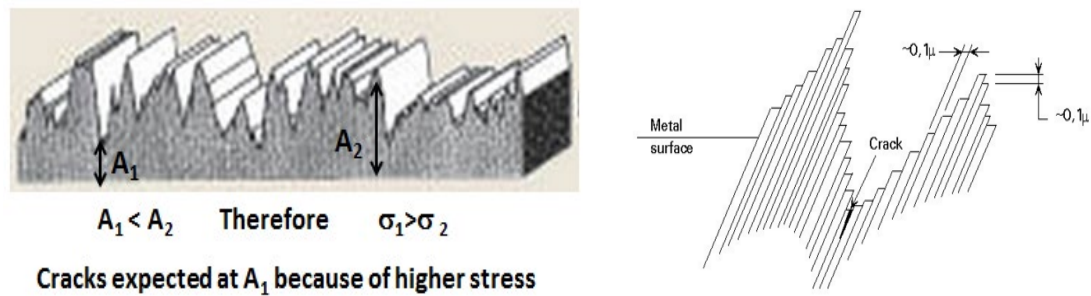


Figure 13: The effect of surface roughness on the mechanical properties.

Some studies showed that surface roughness can lead to reduced tensile strength and fatigue life as shown in Figure 14, (Deng, 2015), (Kılıç, 2009).

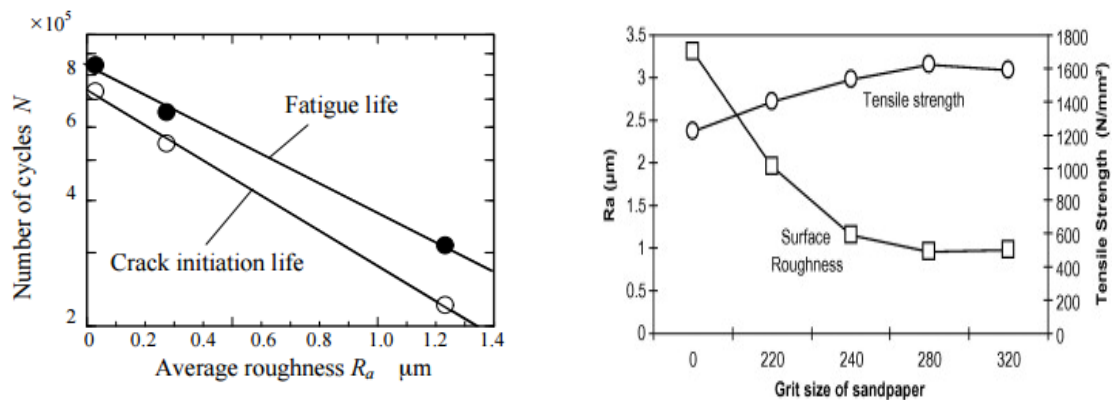


Figure 14: The effects of surface roughness on tensile strength and fatigue life.

2.5 Effect of Salts on Corrosion

Generally speaking, marine environments, wherein the concentration of salts in water is high, can be considered very corrosive when compared to fresh water which contains no salts. These salts originate from rocks erosion by rain and river streams. Moreover, other salts originate from the subsea volcanoes or hydrothermal vents. The most common type of salts that exists in marine environments is sodium chloride (NaCl), (Marine_Water, 2018). In this regard, salinity is the amount of salt (in grams) that is found in 1000g of water. For instance, the salinity of seawater is about 35ppt (parts per thousand, i.e. 35g salt per 1000g water). This amount

might depend on the location, temperature, rate of evaporation and environmental conditions. When the temperature is high, the evaporation of water is high, and this leaves high concentrations of salts in the water. On the contrary, the water from rivers might cause the salinity of seawater becomes less. In general, the salinity of fresh water is 0.5ppt whereas the salinity of brackish water (where fresh and salty water meet) is between 0.5 – 35ppt (Salinity, 2018).

The seawater is considered an excellent electrolyte which means that it conducts electricity at high efficiency. In other words, the movement of ions within seawater is excellent due to the existence of such salts. This means that such environments will have high ability to cause corrosion when compared to fresh water or dry environments. The Chlorine ions are the responsible elements for corrosion of steel and other materials in such environments (FOLEY, 1970). As a matter of fact, it has been found that the intermittent exposure to seawater due to the splash and drying zones can cause more corrosion. This is due to the fact that the steel will be subjected to seawater but when it dries off the chloride ions will be deposited at the surface. This will lead to high concentrations and therefore severe corrosion. It has been found that the splash zone is more corrosive than the submerged zone underneath the seawater level, Figure 15, (Fozan, 2005).

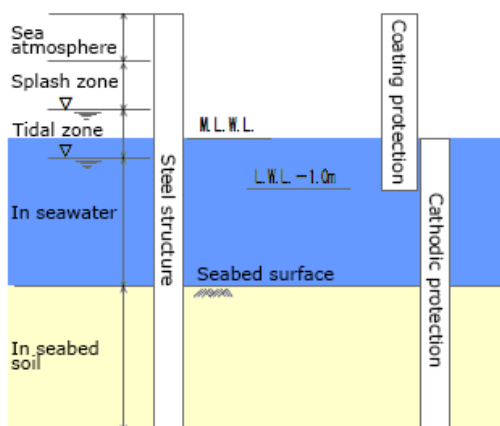


Figure 15: The various seawater zones (left) and the corrosion of steel in the splash zone (right).

2.6 The Economic Impact of Corrosion

The most dangerous corrosion that might take place is the one that affects industrial plants such as electrical power plants or chemical processing plants. This might cause plant shutdowns in order to ensure the safety of operations. This will impact the economic operation of such plants and will require further action plans such as replacement of corroded equipment, preventive maintenance such as painting, contamination of products, loss of efficiency and damage to existing equipment. The health and safety measures are important in such situations due to the possibility of explosions, toxic emissions, collapse of structures, pollution and depletion of resources. This means that the operational life of components will be reduced and affected by corrosion which means that a massive amount of budget will be required to address such consequences. In the United States only, it is estimated that corrosion costs billions of US dollars per year and this is illustrated in Table 1, (ASM_International, 2000).

Table 1: The cost of metallic corrosion in the United States.

Industry	Billions of U.S. dollars	
	1975	1995
All industries		
Total	82.0	296.0
Avoidable	33.0	104.0
Motor vehicles		
Total	31.4	94.0
Avoidable	23.1	65.0
Aircraft		
Total	3.0	13.0
Avoidable	0.6	3.0
Other industries		
Total	47.6	189.0
Avoidable	9.3	36.0

Source: *Economic Effects of Metallic Corrosion in the United States*, Battelle Columbus Laboratories and the National Institute of Standards and Technology (NIST), 1978, and Battelle estimates

CHAPTER 3: EXPERIMENTAL METHODOLOGY

3.1 Experimental Apparatus and Reagents

This part of the report will summarise the various items and procedures that will be required to assess the level of corrosion. This includes the followings:

Material: Mild steel (any chemical composition).

Size of samples: 2cm (length) * 2cm (width) * 0.3cm (thickness)

Number of samples: 7 samples in total.

Preparations: the method for sample preparation is as follows:

- 1) Cut the samples to the above dimensions.
- 2) Mechanically grind using coarse SiC paper (400 grits).
- 3) Wash the sample with water.
- 4) Mechanically grind using finer SiC paper (800 and then 1200 grits).
- 5) Wash the sample with water.
- 6) Polish to mirror-like finish using any available method in the lab (Polishing, 2018).
- 7) Weigh the samples and record the initial mass in grams (this is the baseline mass).
- 8) Store the samples in a desiccator and lubricate with protective oil to avoid any corrosion from the environment.

Corrosive solutions: The experiment will include 7 containers each of which contains:

- 1) 500ml distilled water
- 2) 500 ml distilled water with 10g sodium chloride
- 3) 500 ml distilled water with 20g sodium chloride
- 4) 500 ml distilled water with 10g sodium carbonate chloride
- 5) 500 ml distilled water with 20g sodium carbonate chloride
- 6) 500 ml distilled water with 10g sodium sulphate chloride
- 7) 500 ml distilled water with 20g sodium sulphate chloride

3.2 Duration and Data Sampling

The samples will be left in the relevant solution for 4 weeks (in total). It is essential to measure the weight of samples every 7 days and record in the following table. The procedure is as follows:

- 1) Take sample out of the container.
- 2) Wash by tap water for 1 minute during which use a plastic brush (tooth brush) to remove any oxidized or corroded layer from the surface.
- 3) Wash in acetone for 1 minute
- 4) Dry the sample using a hair dryer (or any available method) to completely remove any water from the surface.
- 5) Weigh the sample
- 6) Put back in the container
- 7) Repeat steps from 1-6 every 7 days and for all samples
- 8) Record the results in Table 2.

Table 2: The data required during the experiment.

Solution	concentration (g)	Sample ID	Mass (g)					35 days	42 days	49 days	56 days
			0 days	7 days	14 days	21 days	28 days				
Water (only)	N/A	W									
Sodium chloride + water	10	WSC10									
	20	WSC20									
Sodium carbonate + water	10	WSCR10									
	20	WSCR10									
Sodium sulphate + water	10	WSS10									
	20	WSS20									

3.3 Investigation Methods

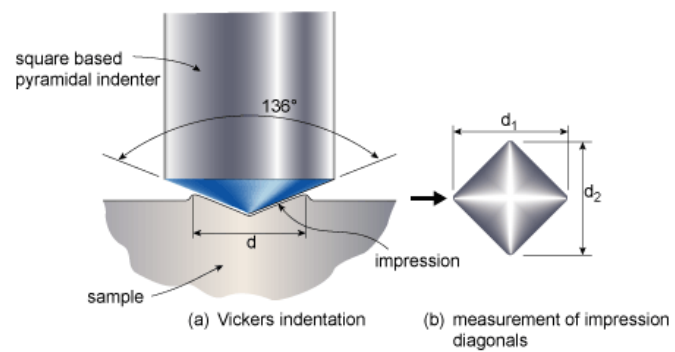
In addition to measuring the weight loss due to corrosion, it will be helpful (but NOT essential) to carry out all/some of the followings:

3.3.1 Hardness Testing

This is only carried out at day 0 and day 28. This means to measure the hardness while the sample is fresh (at 0 days) and after 4 weeks (28 days). Only these measurements at the start and end of corrosion for each sample, Figure 16.



Figure 16: The hardness measurement



device.

3.3.2 Microscope Testing

This is only carried out at day 0 and day 28. This means to study the surface while the sample is fresh (at 0 days) and after 8 weeks (56 days). Only these measurements at the start and end of corrosion for each sample, Figure 17.

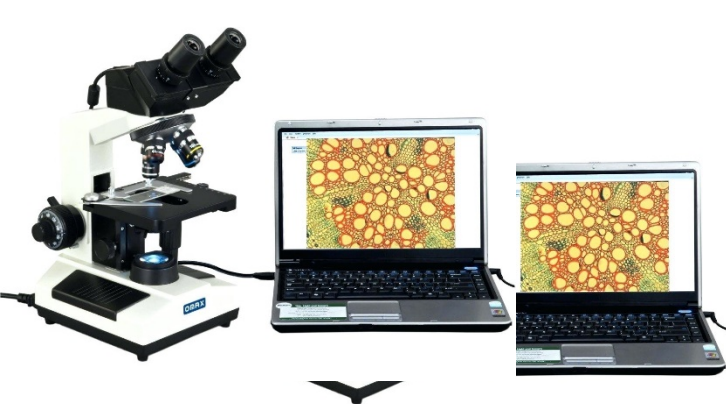


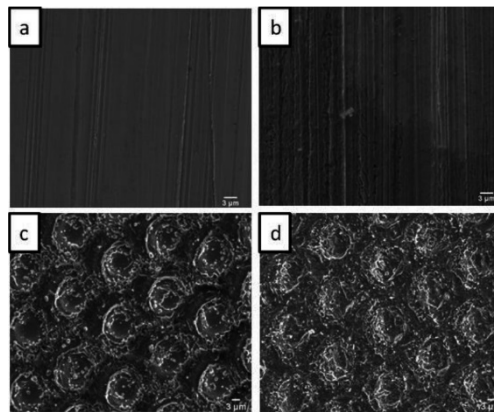
Figure 17: The optical microscopy device.

3.3.3 Surface Roughness Testing

This is only carried out at day 0 and day 28. This means to measure the roughness while the sample is fresh (at 0 days) and after 8 weeks (56 days). Only these measurements at the start and end of corrosion for each sample, Figure 18.



Figure 18: The roughness device.



surface measurement

The requirements for the previously discussed testing methods and the timing is summarised in Table 3.

Table 3: The requirements for testing methods and the timing required.

Solution	concentration (g)	Sample ID	Mass (g)					35 days	42 days	49 days	56 days
			0 days	7 days	14 days	21 days	28 days				
Water (only)	N/A	W									
Sodium chloride + water	10	WSC10									
	20	WSC20									
Sodium carbonate + water	10	WSCR10									
	20	WSCR10									
Sodium sulphate + water	10	WSS10									
	20	WSS20									

Carry out **Microscopy, surface roughness and microscopy**
only here and nothing in between!

3.4 The Items to Purchase

The List of Items to purchase are as follows:

- (1) Mild **steel plate** (30cm*30cm*0.3cm) – the mild steel can be of any type.
- (2) Grinding paper (**silicone carbides, SiC**) – grit size of **400, 800 and 1200**. It is recommended to by two sheets per grit.
- (3) Polishing pastes (Polishing_Metals, 2018)
 - Grey 523LBZ** compound with a sisal polishing mop
 - Green 439T** compound with a white close stitched polishing mop
 - Blue P164** Compound or **Rose P126** Compound with a Loose G quality
 - P175** for super finishing with a Loose WDR quality mop
- (4) 100grams of ach of the followings:
 - Sodium chloride**
 - Sodium carbonate chloride**
 - Sodium sulphate chloride**

CHAPTER 4: RESULTS AND DISCUSSION

4.1 The Overall Results

The obtained results for all samples immersed in water for the test duration are shown in Table 4. It can be seen that there is a reduction in mostly all samples after the completion of the test and this will be quantified.

Table 4: The mass reduction results recorded for all samples under investigation.

Solution	concentration (g)	Sample ID	Mass (g)								
			0 days	7 days	14 days	21 days	28 days	35 days	42 days	49 days	56 days
Water (only)	N/A	W	28.957	28.956	28.96	28.954	28.952	28.952	28.949	28.948	28.943
Sodium chloride + water	10	WSC10	28.674	28.663	28.66	28.644	28.64	28.6	28.593	28.588	28.584
	20	WSC20	30.139	30.131	30.13	30.119	30.11	30.098	30.088	30.072	30.055
Sodium carbonate + water	10	WSCR10	30.092	30.092	30.09	30.092	30.092	30.092	30.092	30.092	30.092
	20	WSCR10	30.899	30.899	30.90	30.899	30.899	30.899	30.899	30.899	30.899
Sodium sulphate + water	10	WSS10	30.211	30.208	30.20	30.192	30.186	30.171	30.163	30.155	30.143
	20	WSS20	27.265	27.259	27.256	27.248	27.236	27.201	27.162	27.14	27.111

In order to facilitate the analysis of results, the percentage of mass reductions for all samples has been evaluated using the equation:

$$\% \text{ mass reduction} = \frac{\text{final mass} - \text{initial mass}}{\text{initial mass}}$$

The obtained percentages once this equation is applied is shown in Table 5. It is evident that mostly all samples have lost weight, however, no weight loss was observed for the Sodium Carbonate when mixed with water as shown in the results. This has to be closely investigated in order to justify the results and possibly obtain a conclusion regarding this behaviour of the samples under corrosion.

Table 5: The percentage of mass reduction results recorded for all samples under investigation.

Solution	concentration (g)	Sample ID	Mass (g)								
			0 days	7 days	14 days	21 days	28 days	35 days	42 days	49 days	56 days
Water (only)	N/A	W	28.957	-0.00345	-0.00345	-0.01036	-0.01727	-0.01727	-0.02763	-0.03108	-0.04835
Sodium chloride + water	10	WSC10	28.674	-0.03836	-0.04534	-0.10462	-0.11857	-0.25807	-0.28249	-0.29992	-0.31387
	20	WSC20	30.139	-0.02654	-0.04645	-0.06636	-0.09622	-0.13604	-0.16922	-0.2223	-0.27871
Sodium carbonate + water	10	WSCR10	30.092	0	0	0	0	0	0	0	0
	20	WSCR10	30.899	0	0	0	0	0	0	0	0
Sodium sulphate + water	10	WSS10	30.211	-0.00993	-0.03972	-0.06289	-0.08275	-0.1324	-0.15888	-0.18536	-0.22508
	20	WSS20	27.265	-0.02201	-0.03301	-0.06235	-0.10636	-0.23473	-0.37777	-0.45846	-0.56483

4.2 The Water (Only) Sample Results

The obtained results for the water only samples are shown in Figure 19. It can be seen that there is an observed reduction in the mass of samples under this condition. The trend looks linear which means that a relation between time and mass loss can be established as derived from the equation of the trendline. In other words, the mass (m) after time (t) can be estimated (predicted) using the equation of the trendline that is given by:

$$\text{mass} = -0.0002 t + 28.958$$

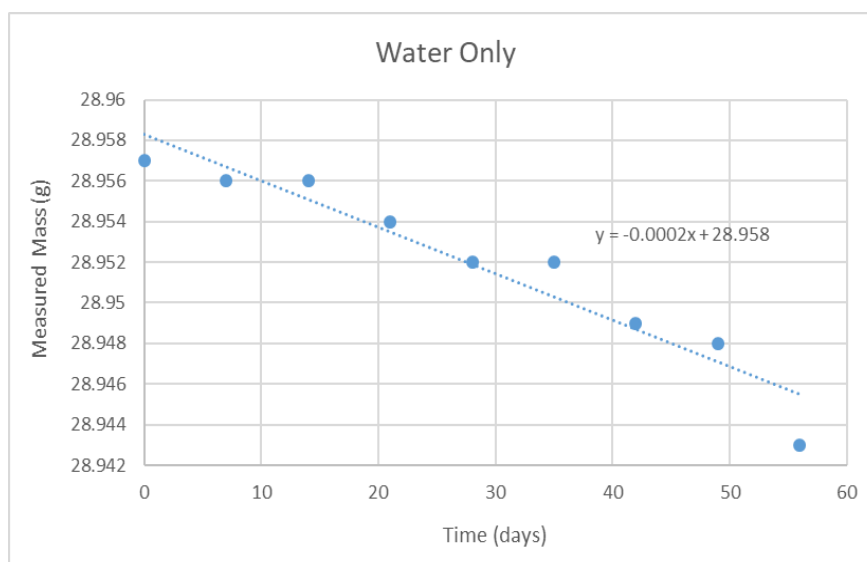


Figure 19:
the mass

the water (only) samples.

The results of
reduction for

To make the results easier to understand, the percentage reduction in mass of the same samples has been evaluated as previously discussed. The obtained results for the percentage reductions

are shown in Figure 20. From this figure, it can be seen that the maximum mass reduction after the completion of the test was about -0.05% of the original mass which is considered minimal.

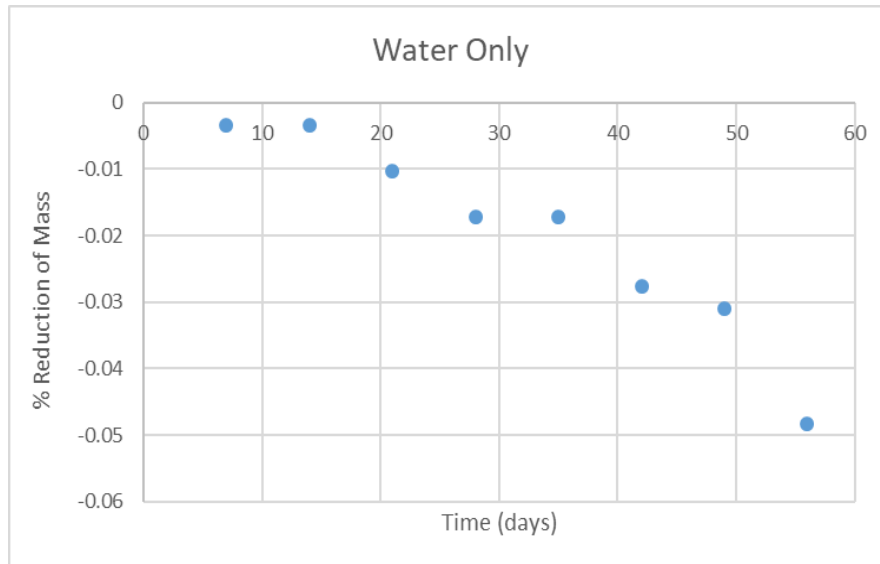


Figure 20:
the

mass reduction for the water (only) samples.

The results of
percentage

4.3 The Water (Sodium Chloride) Sample Results

The obtained results for the water (Sodium Chloride) samples (10 and 20g of salt) are shown in Figure 21 and Figure 22, respectively. It can be seen that there is an observed reduction in the mass of samples under this condition. The trend looks linear which means that a relation between time and mass loss can be established as derived from the equation of the trendline. In other words, the mass (m) after time (t) can be estimated (predicted) using the equation of the trendline that is given by:

For 10g samples: $mass = -0.0018 t + 28.678$

For 20g samples: $mass = -0.0014 t + 30.145$

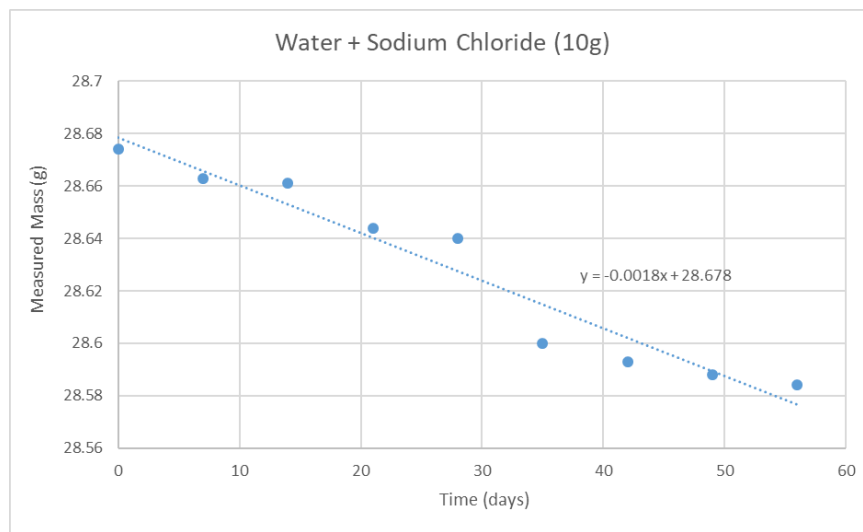


Figure 21: The mass

the water (10g Sodium Chloride) samples.

results of the reduction for

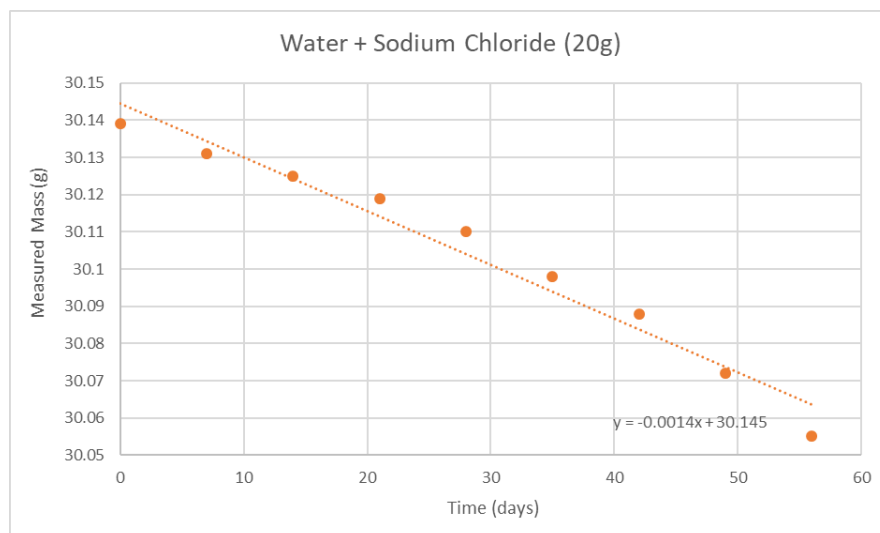


Figure 22: The results of the mass reduction for the water (20g Sodium Chloride) samples.

To make the results easier to understand, the percentage reduction in mass of the same samples has been evaluated as previously discussed. The obtained results for the percentage reductions are shown in Figure 23 and Figure 24 for the 10 and 20g samples, respectively. From this figure, it can be seen that for both salt samples the maximum mass reduction after the completion of the test was about -0.3% of the original mass which is considered much higher than that recorded for the water (only) samples. This means that the existence of salt has increased the level of corrosion and therefore the amount of mass loss from the samples.

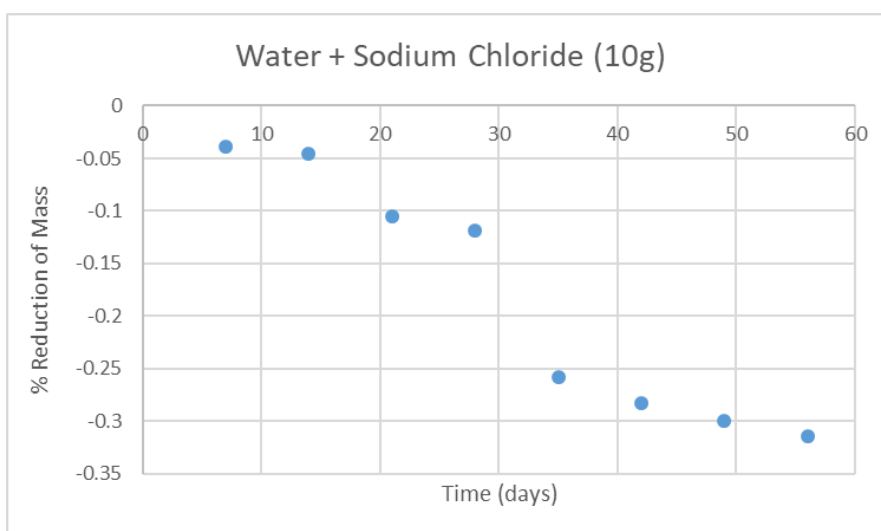


Figure 23:

the percentage mass reduction for the water (10g Sodium Chloride) samples.

The results of

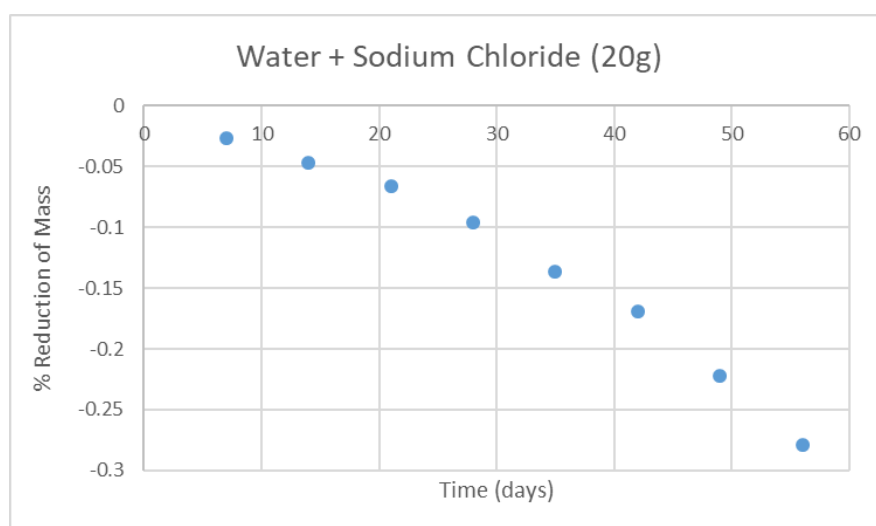


Figure 24: The results of the percentage mass reduction for the water (20g Sodium Chloride) samples.

4.4 The Water (Sodium Carbonate) Sample Results

The obtained results for the water (Sodium Carbonate) samples (10 and 20g of salt) are shown in Figure 25 and Figure 26 respectively. It can be seen that there is no observed reduction in the mass of samples under this condition. In other words, it seems that the existence of the Sodium Carbonate has prevented corrosion, and this is evident when comparing these results with those from the water (only) samples. In other words, the samples in water (only) have corroded while those in water (Sodium Carbonate) have not corroded which means that the solution acted as a 'corrosion' inhibitor in this case.

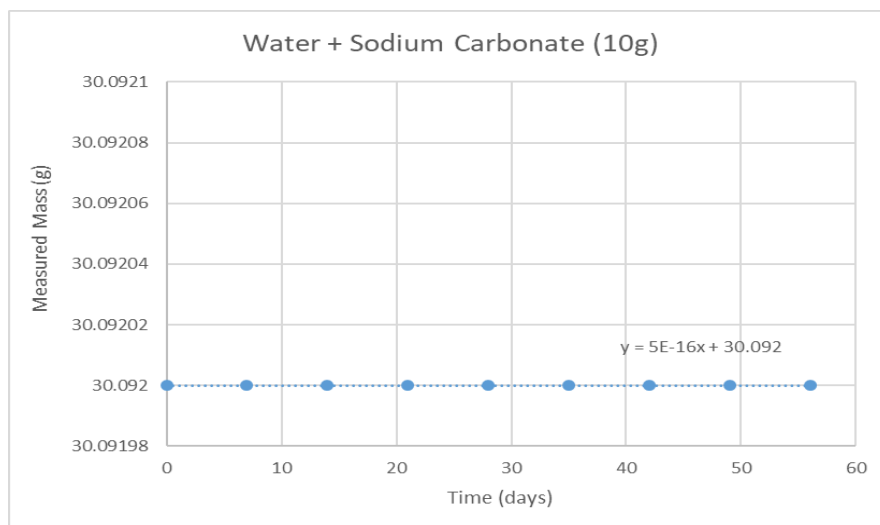


Figure 25:
the mass

the water (10g Sodium Carbonate) samples.

The results of
reduction for

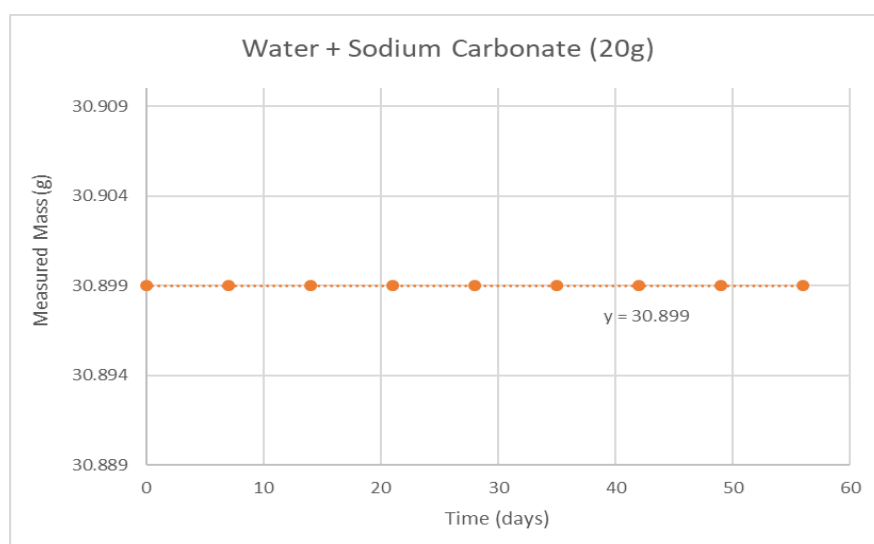


Figure 26: The results of the mass reduction for the water (20g Sodium Carbonate) samples.

To make the results easier to understand, the percentage reduction in mass of the same samples has been evaluated as previously discussed. The obtained results for the percentage reductions are shown in Figure 27 and Figure 28 for the 10 and 20g samples, respectively. It can be seen that there is no observed reduction in mass as it is almost 0% reduction recorded. This confirms the previous outcomes regarding these samples which means that the Sodium Carbonate might have inhibited the corrosion process and prevented any mass loss from the samples.

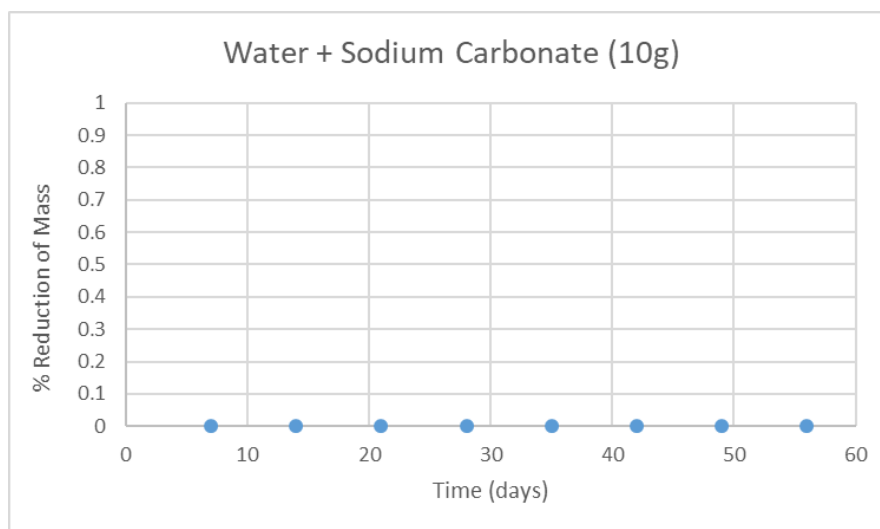


Figure 27:
of the

mass reduction for the water (10g Sodium Carbonate) samples.

The results
percentage

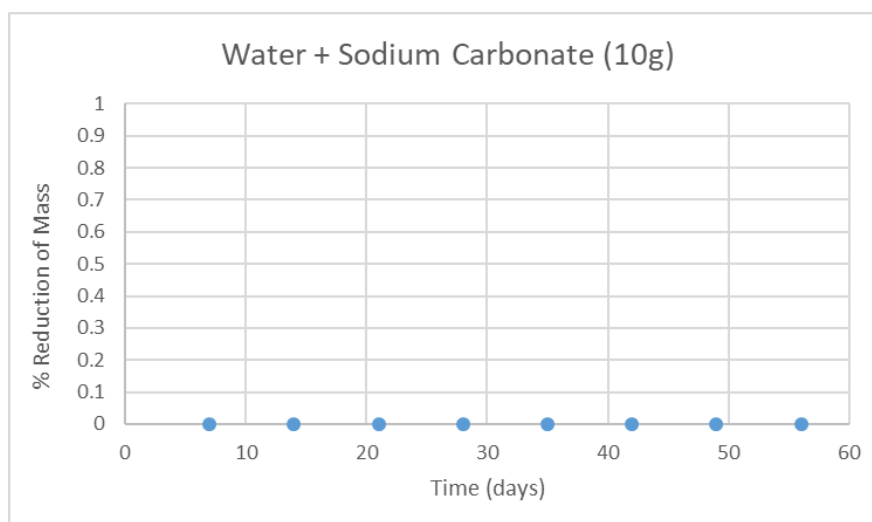


Figure 28: The results of the percentage mass reduction for the water (20g Sodium Carbonate) samples.

4.5 The Water (Sodium Sulphate) Sample Results

The obtained results for the water (Sodium Sulphate) samples (10 and 20g of salt) are shown in Figure 29 and Figure 30, respectively. It can be seen that there is an observed reduction in the mass of samples under this condition. The trend looks linear which means that a relation between time and mass loss can be established as derived from the equation of the trendline. In other words, the mass (m) after time (t) can be estimated (predicted) using the equation of the trendline that is given by:

For 10g samples: $mass = -0.0012 t + 30.216$

For 20g samples: $mass = -0.0029 t + 27.289$

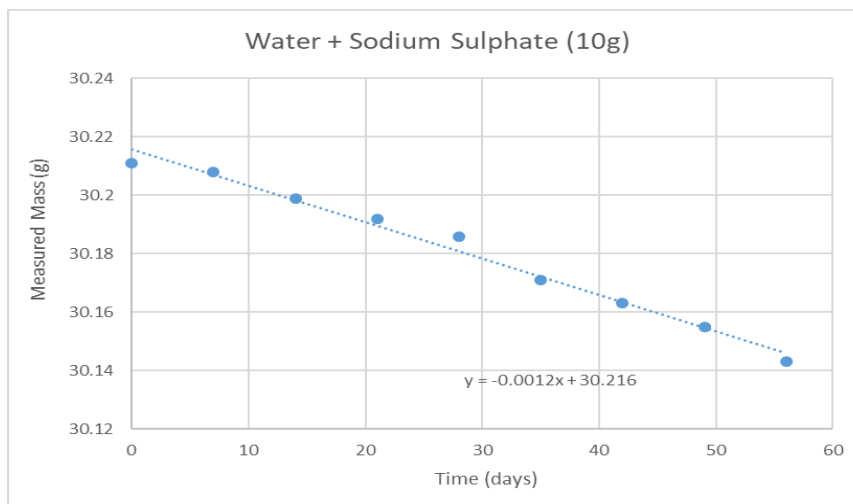


Figure 29: The results of the mass reduction for the water (10g Sodium Sulphate) samples.

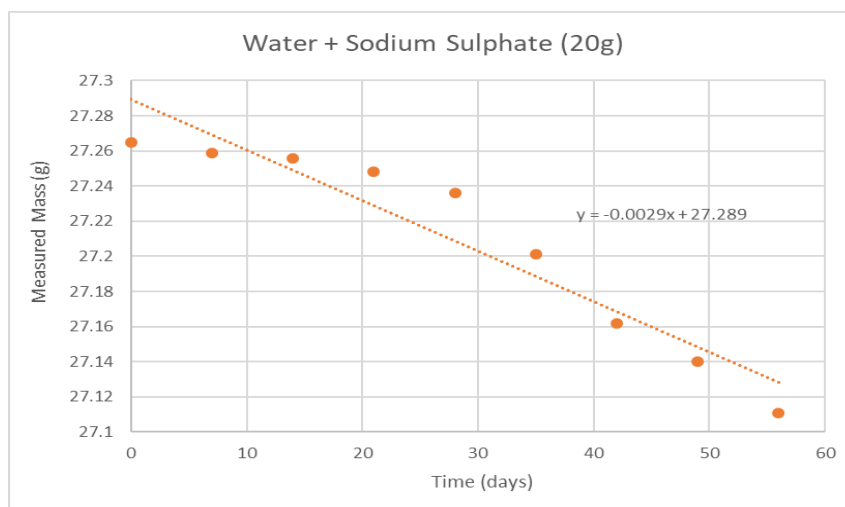


Figure 30: The

mass reduction for the water (10g Sodium Sulphate) samples.

results of the

To make the results easier to understand, the percentage reduction in mass of the same samples has been evaluated as previously discussed. The obtained results for the percentage reductions are shown in Figure 31 and Figure 32 for the 10 and 20g samples, respectively. From this figure, it can be seen that for both salt samples the maximum mass reduction after the completion of the test for the 10g samples was about -0.23% of the original mass which is considered much higher than that recorded for the water (only) samples. Moreover, at the 20g

salt samples, this percentage reduction has increased to -0.58% of the initial mass which is considered an increase by a factor of 2.5 when compared to the 10g sample. This means that the existence of salt has increased the level of corrosion and therefore the amount of mass loss from the samples

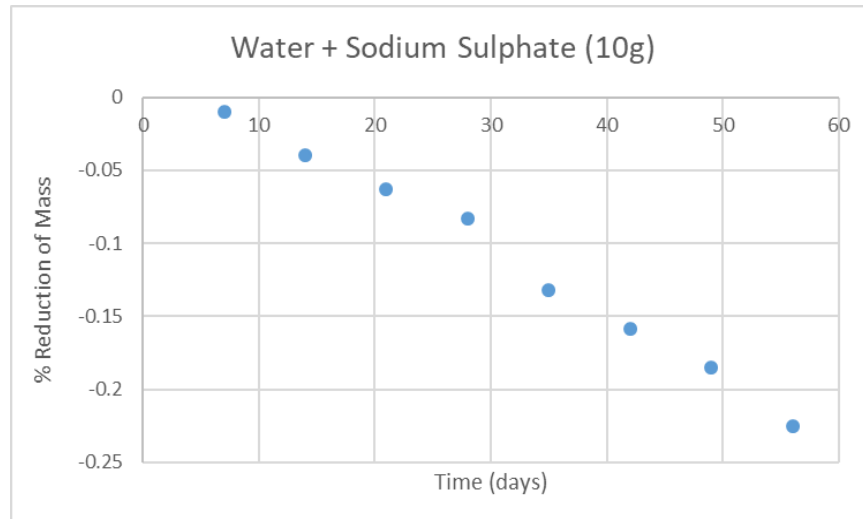


Figure 31: The results of the percentage mass reduction for the water (10g Sodium Sulphate) samples.

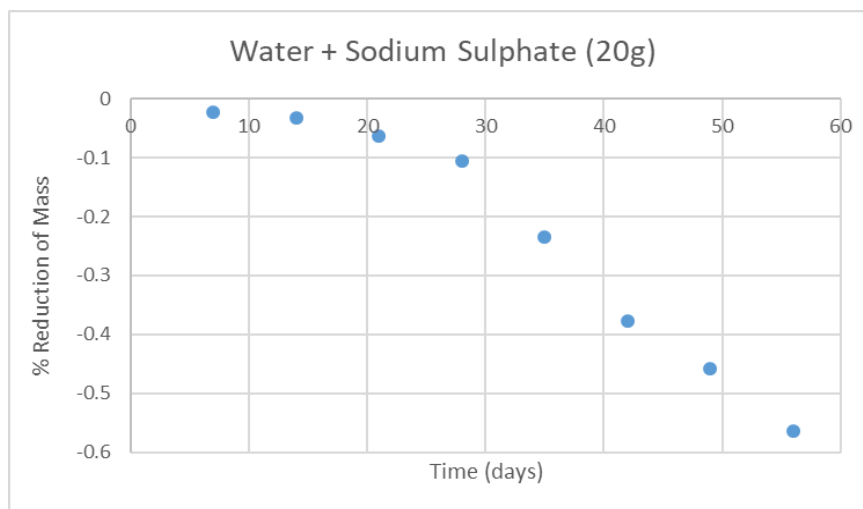


Figure 32: The results of the percentage mass reduction for the water (20g Sodium Sulphate) samples.

4.6 Discussion of Immersion Results

The overall results of all tests carried out in the project are summarised in Table 6. It has been observed that the samples in water (only) showed a minimal amount of corrosion, almost -0.05% reduction in mass after 56 days. On the contrary, the Sodium Chloride solution has shown a higher degree of corrosion between -0.28 and -0.31% reduction in mass after 56 days.

This is considered higher than that observed in water (only) and confirms the fact that salts lead to a higher degree of corrosion. On the other hand, the Sodium Carbonate solution has had no effect whatsoever on the mass reduction, and hence on corrosion. The Sodium Sulphate solution results showed a mass reduction between -0.22 and -0.56% which is considered the highest of all results. This means that the type of salt involved might affect the material and corrosion and therefore should be considered in engineering applications.

Table 6: The summary of all mass reduction testing results in the project after 56 days.

Medium	Mass Reduction (%)		
	0g salt	10g salt	20g salt
Water (only)	-0.05		
Sodium chloride + water		-0.31	-0.28
Sodium carbonate + water		0.00	0.00
Sodium sulphate + water		-0.22	-0.56

4.7 The Surface Roughness Results

In terms of surface roughness, it has been observed that there is a change in surface roughness before and after immersion in the various solutions. In this regard, the surface roughness results after 56 days are summarised in Table 7. It is evident that the samples which lost mass have shown a change in surface roughness and this is expected. In other words, the loss of mass means that there are grooves which have been generated into the surface where the material is lost. This leads to a change in the surface roughness and it is proportional to the amount of mass lost. When comparing the proportionality in Table 6 and Table 7, there is an agreement, however, there are values which are not proportional to each other. This might be due to the fact that the mass lost is not necessarily from the surface where the roughness measurement was taken. In other words, if the surface roughness is taken at the top surface, there might be a minimal amount of mass loss from this surface when compared to the sides or bottom of the sample. This, therefore, might provide misleading results and this should be taken into consideration when analysis and discussing these results. Overall, it is a matter of fact that when the material is lost, grooves are generated and therefore the surface roughness is modified.

Table 7: The summary of all surface roughness testing results in the project after 56 days.

Original surface roughness = 0.19 μ m			
Medium	Surface roughness after testing (μ m)		
	0g salt	10g salt	20g salt
Water (only)	1.51		
Sodium chloride + water		1.047	0.597
Sodium carbonate + water		0.19	0.33
Sodium sulphate + water		2.241	0.533

4.8 Discussion of Results

From the obtained outcomes, it is evident that water (only) has resulted in minimal corrosion when compared to the water with salt samples. This is due to the fact that the water molecules can cause corrosion, however, the lack of salts make this process slower. In other words, salts work as ‘carriers’ of corrosion products and therefore they speed up the corrosion process when compared to water which contains no ‘carriers’. This result has also been observed in other studies wherein the weight loss with 0% salt was very minimal and comparable with the results obtained in the current project (Aramide, 2019), Figure 33.

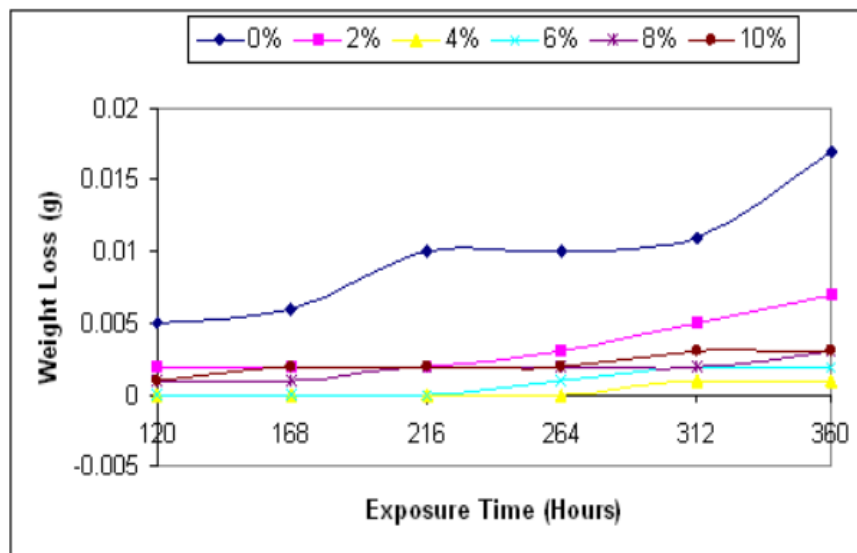


Figure 33: The corrosion rate with water

salts obtained from other studies (Aramide, 2019).

corrosion rate (only) and

On the other hand, the corrosion with Sodium Chloride is very critical and dangerous as can be seen from the mass loss and surface roughness measurements. In another study by May (May, 2016) on corrosion with Sodium Chloride, they investigated corrosion for 28 days and under varying amounts of salts from 1 to 10%. It has been observed that a continuous increase in corrosion and hence, mass reduction, has been observed with increasing the amount of salts. This has been attributed to the increase in conductivity of the solution molecules with increasing the amount of salt and the penetrating power of the chloride ion through surface films on a metal (Oloruntoba, 2016). The obtained figures from this experiment were comparable with these obtained in the current project, which is something desirable, Figure 34.

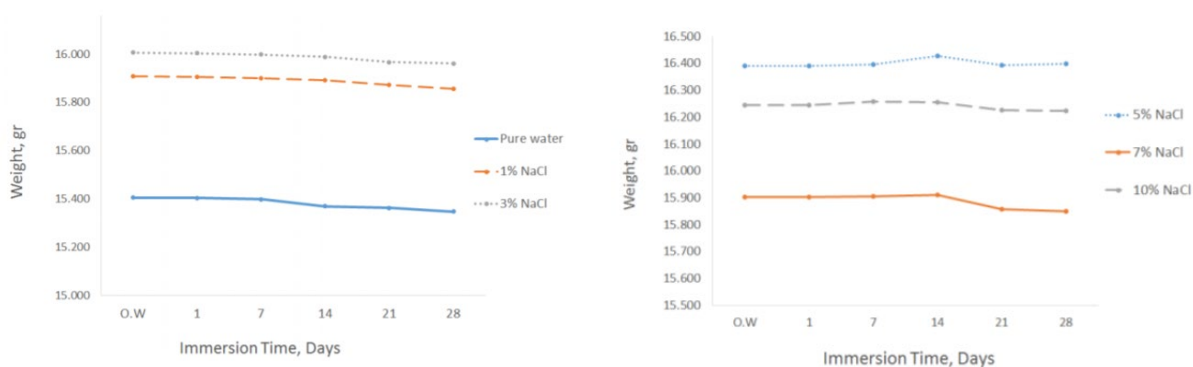


Figure 34: The obtained results after 28 days from a study in the literature showing consistent results (May, 2016).

On the other hand, the results of the Sodium Carbonate showed no corrosion or mass loss whatsoever which means that the addition of this salt might have worked as an ‘inhibitor’ to corrosion. This outcome has been confirmed in other studies (Oloruntoba, 2016) wherein the Sodium Carbonate acted as an ‘anodic’ inhibitor for mild steel components. The higher the concentration of the Sodium Carbonate, the higher the corrosion inhibition efficiency. The experiment by Oloruntoba et al. (Oloruntoba, 2016) revealed that a protective film has been formed on the surface of the meta and this has provided a shield against any corrosion of the surface. In other words, this outcome shows that the Sodium Carbonate is not corrosive, on the contrary, it is a corrosion inhibitor. This salt can be applied to water for applications wherein corrosion is not preferred such as car washing applications alongside several other applications (Oloruntoba, 2016).

On the other hand, the Sodium Sulphate samples have shown a significant amount of corrosion and mass loss. This type of corrosion exists in gas turbines, boilers and crude oil pipelines. In gas turbines, for instance, the Sulphur from the fuel reacts with sodium chloride from air at elevated temperatures to form Sodium Sulphate. This product then deposits on the hot section components in gas turbines leading to accelerated corrosion attack. In boilers, Sodium Sulphate from combustion reacts with oxygen and causes corrosion attack on the tubes of the boiler. In crude oil applications, Sodium Sulphate is present in high concentrations which causes corrosion for the handling pipelines. This behaviour can be attributed to the increased electro-conductivity because of the risen salt content (Hasan, 2013). The variation of solution conductivity with increasing the amount of Sodium Sulphate is studied elsewhere (Emori, 2017). The change in concentration of the salt with conductivity is shown in Figure 35.

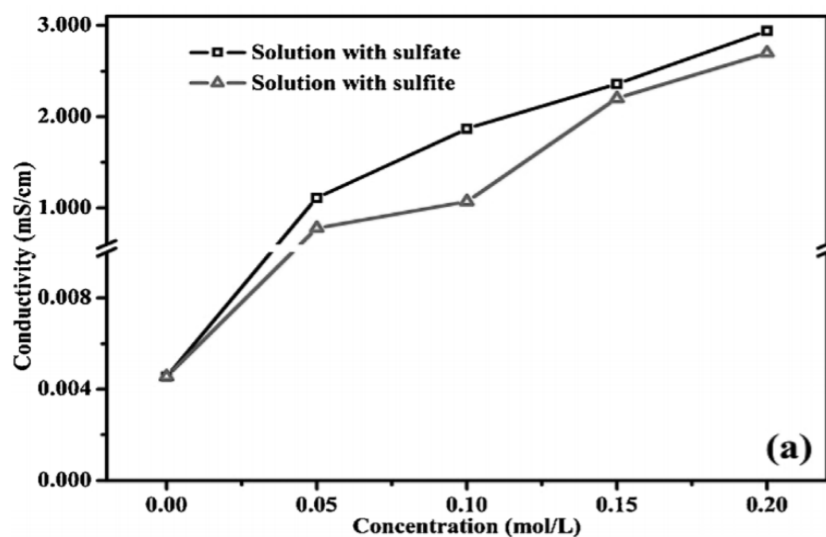


Figure 35: The conductivity

the amount of Sodium Sulphate (Emori, 2017).

variation in
with increasing

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

From the current project, several conclusions can be drawn as follows:

- Corrosion of mild steel is considered dangerous as it might cause fracture to structure and engineering applications while in service.
- The corrosion of the samples in water was very minimal over the duration of the current project.
- The corrosion of the sample in water and Sodium Chloride was significant due to the penetration of chlorides into the metal and the high conductivity of the solution.
- There was no corrosion of the sample in water and Sodium Carbonate due to the fact that the Sodium Carbonate is actually a corrosion inhibitor. This is due to the formation of the protective layer on the surface of the metal which protects it from corrosion.
- The corrosion of the sample in water and Sodium Sulphate was significant due to the high conductivity of the solution and the severity of the salt on the metal.
- The surface roughness measurements have confirmed the obtained outcomes. In other words, the higher the corrosion rate, the larger the amount of material lost from the surface and hence the rougher the surface.
- The mass loss was highest for the Sodium Sulphate samples when compared to the Sodium Chloride samples. This can be observed in the slope of the measured mass vs. time plots wherein the higher the slope the quicker the corrosion rate.

5.2 Recommendations

From the current project, several recommendations for future can be drawn:

- In future, the effect of temperature on corrosion can be studied. This can involve the same types of salts but with the application of certain temperature.
- In future, the effect of water movement on corrosion can be studied. This involves using the same types of salts and simulate the motion of water in sea.
- In future, more concentrations of salts can be applied. Moreover, more salt types can be involved with longer duration times.
- In future, other types of materials can be use in the experiment. This can include ferrous and non-ferrous materials as well as non-metallics, e.g. polymers or ceramics.
- In future, microscopy and other means of investigations can be used to closely study the surface morphology and investigate the obtained behaviour of the material.
- In future, mechanical testing such as tensile or fatigue might be involved. This will help to study the effect of corrosion on the mechanical properties of the material.

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