

Investigation of the Impact of Marine Algae on the Corrosion of Mild Steel

Hayden Allwright¹, Hossein Enshaei²

¹Australian Maritime College, University of Tasmania

²Australian Maritime College, University of Tasmania

Received: December 14, 2015

Accepted: February 22, 2016

ABSTRACT

Corrosion is a significant and continuous issue for all structures and vessels in the marine environment. Biocorrosion is a complex and poorly understood component of this and algal factors in isolation are the focus of this enquiry.

An experiment was conducted to investigate the effects of the presence of marine algae *Dunaliella tertiolecta* on the corrosion of mild steel. These particular algae were selected because of their robustness and tolerance of adverse environmental conditions and their widespread existence. The aim of the experiment was to ascertain the effects of blooming algae on the corrosion of steel in a marine structure. Seven tubs of water were setup: a control containing filtered seawater; three to which a certain amount of algae was added; and three with double the concentration of algae added. In each of these tubs a piece of mild steel was suspended.

The results uncovered three main findings. After 70 days, the amount of steel lost through corrosion was greater in the pieces exposed to algae than in the control, but the difference is small. Over a more extended period of time, the difference in corrosive damage was shown to be more for pieces immersed in algae. The nature of corrosion in seawater is more detrimental than in pieces subjected to algae.

KEYWORDS: Corrosion, Biocorrosion, Algae, Mild steel, Marine environment

1 INTRODUCTION

Corrosion is a perpetual and very costly problem faced by almost all industries. Its effective prevention, especially regarding steel, is a necessity and in the marine environment it is one of the most challenging and severe problems facing engineers. There are many contributing factors to corrosion and its prevention and not all of these are well understood. Biocorrosion, namely corrosion influenced or caused by organic organisms, is one such misunderstood aspect.

In this investigation, the effects of algae on the corrosion of mild steel in seawater were investigated to determine any positive and/or negative impacts. As algae photosynthesise and produce oxygen, it is expected that their presence should increase the corrosion of steel, as oxygen is required for corrosion to occur. However, biological factors are many and can often work against each other when involved with inorganic processes.

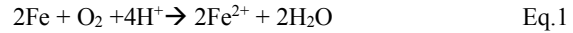
Mild steel is a commonly used material in offshore structures because it is relatively cheap, strong and easy to work with, but it is also a material that is very easily corroded.^[1] The most common method for preventing corrosion in mild steel is to use a coating (paint, polymeric or bituminous coal tar and asphalt dip), with cathodic protection (impressed current or sacrificial anode) also sometimes being used in limited applications.^[1] In mild steel, pitting corrosion is most commonly found in piping systems, heat affected areas/weld seams and regions where a protective coating has been damaged such that a small locality loses protection^[2].

A summary of investigations already conducted into the effects of algae on corrosion was discussed by Edyvean and Terry^[3] some years ago. There is little evidence of further investigation into the explicit effects of algae on the corrosion of steel since that time. Investigation has instead widened to consider concrete structures, where corrosion still occurs in the reinforcing bars through algal effects.^[4] Those studies show that algae contribute to the deterioration of concrete as well as corroding steel in mechanisms discussed below. Lane^[1] claims that whilst the effects of algae and other organisms contribute to corrosion, it is only recently that much interest has been directed toward microbiologically influenced corrosion. Videla and Herrera^[7] state that interest began in the late 1990s with the development of new analysis techniques. Regarding algae, most of the interest in its effects on corrosion has been in how it facilitates life for various bacteria that can feed on decaying algae. Hill^[8] and Edyvean and Terry^[3] are amongst those investigating these issues.

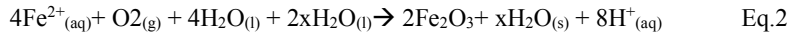
1.1 Corrosion

Corrosion is defined by Lisson^[8] as the oxidation of a metal in its environment. In steel, corrosion is the oxidation of iron atoms. The equation for the oxidation of iron is presented in Equation 1 below.

*Corresponding Author: Hossein Enshaei, Australian Maritime College, University of Tasmania,
Tel: +61363249618, Fax: +61363249720, hossein.enshaei@utas.edu.au



For steel to corrode (rust), both moisture and air are required to be in the environment of the steel. Air contains oxygen and moisture contains the water molecules necessary for rust to form in the corrosion chemical reaction. This reaction is presented in Equation 2 below.



Pitting corrosion is a localised form of corrosion where small, deep pits and holes are formed in a metal. Pitting corrosion is caused by differential aeration cells.^[10] Differential aeration cells are described as the most widespread form of corrosion offshore, occurring under all types of marine fouling^[3]. Edyvean and Terry^[3] explain that a differential aeration cell is a site where an oxygen gradient exists, such as under marine fouling compared to an uncovered surface, and that the location with the lower oxygen concentration will experience accelerated corrosion due to the development of an aerobic cathodic reaction. They also report that algae can cause similar activity through a differential pH cell that will also influence corrosion. It is reported that the effects of differential aeration on crevice corrosion and pitting have been investigated in stainless steels with respect to the action of bacteria by Krougman and Ijsseung in 1984, but they fail to mention algae.^[3]

1.2 Algae

An algal bloom is defined by a very rapid increase in the population of algae. Like all living organisms, algae require certain nutrients to grow and survive. An algal bloom occurs when there is a sudden increase in the amount of some nutrients (eutrophication) available to algae necessary for growth that were a limiting factor in an environment otherwise abundant in remaining required nutrients.^[11] Potentially, the installation of a steel marine structure could lead to a small algal bloom in the right conditions where its corrosion produced the necessary iron ions that were previously in deficit.

It has been suggested that iron fertilisation of the phosphate-rich Southern Ocean could be a method of increasing carbon dioxide sequestration to solve climate change issues.^[12,13] Thus, it must be considered that marine structures in this ocean could catalyse a small local algal bloom.

The marine species *Dunaliella tertiolecta* was selected to be used in this experiment for its robustness, tolerance of adverse environmental conditions^[14] and its widespread existence. Cells of *Dunaliella tertiolecta* are coated in a mucilaginous substance^[15] that is mainly made up of polysaccharides^[21]. Some of this is deposited as algae moves across a surface. According to Stewart,^[16] these polysaccharides are mainly produced during the stationary growth phase which, in this experiment, took place whilst the algae were in the tubs because the results show that it went through both growth and decay. This mucilage is known to affect corrosion in a multitude of ways^[7]. Relevant ways include alteration of chemical transport between the metal and solution, forming differential aeration cells, changing oxidation-reduction characteristics at the metal-solution interface and altering the structure and presence of inorganic passivating films.

1.3 Effects of algae on corrosion

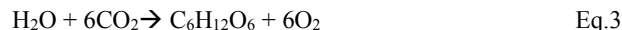
The work of Edyvean and Terry^[3] presents various ways in which algae can contribute to corrosion. Algae can affect corrosion directly, indirectly and by disrupting corrosion protection systems. Algae modify their environment by changing the pH and influencing the oxygen concentration in the local environment, as well as changing the electrolyte by producing metabolites, generally making the electrolyte more aggressive for corrosion. The work of Edyvean and Terry^[3] has shown that photosynthesising algae can raise the pH to above 10 and, whilst decaying, can lower the pH to below that of ambient seawater. In one case they recorded pH 1.8 in a decaying culture.

Of valuable note by Edyvean and Terry^[3] is that metal surfaces produce different surface films when immersed in natural seawater as opposed to artificial seawater (sodium chloride solution). Mucilage is a viscous secretion produced by algae that spreads across surfaces as algae move. It has been found that this spread is most often uneven and contributes towards corrosion as cathodic depolarisation has been observed on test subjects. Depolarisation enhances corrosion as it slows the production of hydrogen gas that would have formed water with dissolved oxygen.

Algae covering on surfaces can provide conditions for the growth of bacteria.^[3] This is an indirect mechanism in which algae affect corrosion, but is reported to be amongst the most severe. Sulphate reducing bacteria (SRB) are reported by Edyvean and Terry^[3] to be amongst the bacteria that can flourish in decaying algae and the effect of this is discussed by Hill.^[8] SRB are known to thrive in oxygen gradients, such as those produced by the presence of algae. SRB enhances corrosion in various ways. It can produce toxic hydrogen sulphide gas, cause ferric sulphide to form that yields pitting corrosion and reduce sulphates to corrosive sulphide amongst other methods.

Despite the many ways in which algae can contribute to corrosion, some work has been done on the prevention of corrosion by algae. It is reported^[3] that in 1977 some work was conducted that found an initial thin covering of sea lettuce provided an effective barrier to corrosion, but later had a negative impact as it provided conditions for SRB and is known to produce hydrogen sulphide^[17]. Kamal and Sethuraman^[18] investigated a species of algae, *Hydroclathrusclathratus*, as an inhibitor of acid corrosion of mild steel and concluded that their analyses supported an inhibitive action by the algae.

Dissolved oxygen in seawater has several important considerations for this project. As shown in the equations above, oxygen is required for corrosion to occur and the main source of oxygen in seawater is dissolved oxygen. It is reported by Baboian^[19] that corrosion of mild steel increases linearly with dissolved oxygen concentration at constant temperature. Also of note, he states that marine plants can cause supersaturating of oxygen in surface seawater by up to 200% of the equilibrium concentration. If the dissolved oxygen increased to 200%, then the corrosion rate of the steel could also double. Oxygen is a product of photosynthesis as shown below in Equation 3.^[20] Below the surface of water this oxygen will be dissolved.



2 METHODOLOGY

The experiment was designed to test corrosion impacts by exposing pieces of steel to differing concentrations of algae and recording selected parameters and analysing them. These parameters were the mass of steel pieces, water alkalinity, and concentration of algae in the tubs and corrosion potential of the steel in the water. Photographs were also taken to document surface changes.

In this setup, two different concentrations of algae were tested as well as a control that was a piece of steel exposed to filtered seawater only and not any algae. The temperature was regulated so that it was even across all tubs. The two different algae conditions were a certain concentration and double that concentration. The concentrations selected were intended to simulate coastal marine regions where algae concentrations are higher than oceanic regions. This also helped to ensure that useful results could be collected in a shorter time period. Each of these concentrations was triplicated to best ensure that the observed changes were replicable and accurate.

The conditions were tested by suspending pieces of steel in tubs of water under different algal concentrations and recording the defined parameters at regular intervals. Preparations of the steel and the types of parameters to record were undertaken according to advice from a materials technology specialist with experience in corrosion testing and analysis. The set-up of the algae tubs was based on advice from a senior phytoplankton biologist and the growing of the algae was supervised by a senior laboratory co-ordinator.

2.1 Steel specimen preparation

Each steel specimen was cut from a length of 65x3 mm mild steel flat bar. The grade of steel was JIS G3101 SS400. The steel was soda bead blasted to remove mill scale before sanding down with 400 grit paper. A hole was drilled in each piece from which it could be suspended in water and each was stamped with a number punch (1–7). A line was scribed across the pieces marking 50 mm from the bottom to denote the submergence distance. Each piece was cut to be 14 mm wide and accurately weighed before the experiment began.

2.2 Experiment layout

The experiment was conducted in a temperature-controlled insulated room. The temperature was set to 18°C. In this room the light exposure could also be controlled and was maintained at a specific level throughout the experiment.

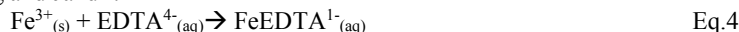
The seawater for each tested condition was contained within a transparent 20 L container. These containers were placed on a wooden bench. Over this, a length of timber ran from which the steel specimens were suspended using steel tie wire. Each tub was marked to hold 14.5 L of seawater filtered to 0.2 µm.

The algae were grown from a stock solution in a 10L carboy for 10 days before they were ready to be divided into the tubs. Growth was facilitated by an air supply bubbling into the water and the addition of f2 growth medium. The water was natural seawater filtered to 0.2 µm. Some algae were saved from each carboy to be used to grow the subsequent batch. The concentration of algae in the carboy at the end of each cultivation was in the order of 1×10^6 cells/mL. After distribution the two concentrations would be 7×10^4 and 14×10^4 cells/mL. No further nutrients were provided to the algae. These concentrations are similar to coastal marine zones.^[21]

2.3 Removing corrosion

Initially a steel-wire brush was used to carefully remove the bulk of corrosion products, however care was taken not to brush too hard to avoid inadvertently removing steel as well. After this the remainder was removed by immersing the steel pieces in a solution of ethylene diamine tetra acetic acid (EDTA) and brushing with a nylon-bristled brush. The EDTA was dissolved from a disodium salt. Nylon is softer than steel so it could be confidently used without fear of removing steel.

In this application EDTA acts as a chelating agent to remove the iron ions from the iron oxide and into solution according to Equation 4 adapted from Zeng and Jandir.^{[6][23]}



3 Data recorded

Four data measurements were taken nearly every day for each steel specimen as well as photographs. The algal density was measured by taking a relative fluorescence measurement of a small water sample. This sample was placed into a fluorometer which measured the chlorophyll density, corresponding linearly with algal density. A pH measurement of the alkalinity of each tub was made using a handheld electronic pH meter.

The corrosion potential of each setup was measured using a digital multimeter and silver-silver chloride reference electrode (correct type for seawater measurements). The negative lead from the multimeter was connected to the reference electrode probe and the testing end immersed in the water. The positive lead was clipped onto the steel piece and the digital multimeter set to measure direct current voltage. This circuit allowed the corrosion potential of each tub (acting as a galvanic cell) to be measured in millivolts.

The mass of each steel specimen was recorded. The pieces were removed from the solution and rinsed with fresh cold tap water. The pieces were then dried using a hairdryer and allowed to cool to room temperature before weighing on a scientific scale measuring to 10^{-4} grams.

3.1 Surface profile

A metallurgical microscope was used in the early stages of the corrosion process to take records, but over time the rough nature of corrosion made obtaining a clear and useful picture impossible. An iPhone 5S camera phone was used to take photos of the image through the eyepiece. Photos of the steel pieces were taken throughout the experiment to evaluate each side of the steel specimens as a whole, using the same camera phone. Later in the experiment access to a stereomicroscope connected to a digital SLR camera was achieved for taking photographs and this was used to take photos from 12.5-80x magnification.

4 RESULTS AND DISCUSSION

The experiment followed a cyclic pattern of algal growth and decay and this is reflected in the results obtained for the corrosion potential and alkalinity, as well as the density of algae in the seawater. The reason for this was the algae died over time due to a number of factors. These factors were a lack of dissolved oxygen in the water, no additional growth media supplied and the concentration of iron ions in the water increasing to toxic levels.

4.1 Algal concentration

The density of the algae is presented below in Figure 1. Clearly the density followed a cyclic pattern as described above. After the algae had died in each cycle, the water was replaced completely to avoid further increasing iron concentration in the seawater. The range of fluorescence readings corresponds to algae cell densities found in coastal regions.^[21]

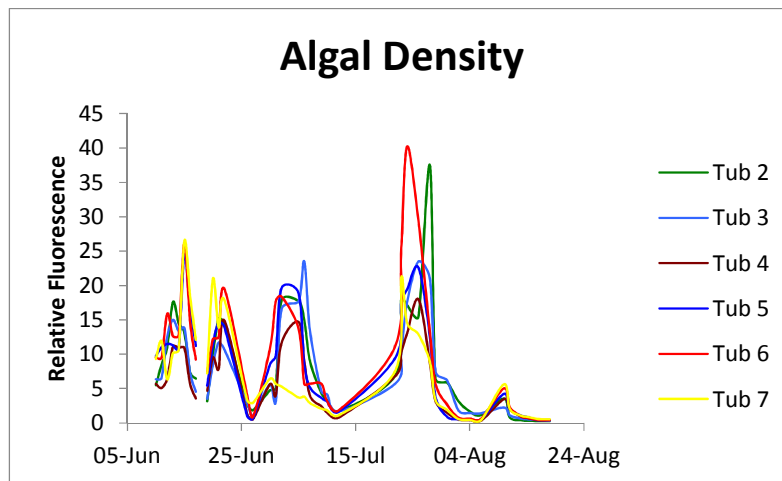


Figure 1: Cell density of algae presented as relative fluorescence.

From the graph it is very hard to distinguish a clear difference between the two concentrations of algae tested. It was found during each cycle that controlling the growth rate and concentration of algae was very challenging. Initially the two concentrations were set as desired; one doubles the other. From there it was observed that the tubs containing the lesser amount of algae grew faster than the tubs containing the higher concentration and during more than one cycle a tub starting with a lower concentration grew to have a higher concentration than the tubs intended to hold the higher concentration. The tubs starting with the lower concentration also held a higher concentration longer before decaying.

4.2 Surface profile

The differences in corrosion activity on the steel surfaces suggest that the algae have a physical effect on the steel and not just a chemical effect. This is shown in Figure 2 where interesting distributions of corrosion products can be observed after only 30 days. The control piece (number 1 on left) presents more extensive corrosion in three

areas with corrosion products streaking downwards. On the remaining pieces that have been exposed to algae, a very large and obvious zone of minimal corrosion can be seen on three of the pieces. These zones are the top areas of pieces 3, 4 and 7 where a green tinge can be seen in place of the reddish brown corrosion. On the other side, similar zones can be seen on pieces 5 and 6.



Figure 2: Photograph taken 9 July (30 days) showing distribution of corrosion products on steel.

It was noted by Videla and Herrera^[7] that the mucilage developed by algae and deposited on steel surfaces alters the structure and formation of a passivating film. This is definitely reflected in the figure. Mucilage has been deposited in these zones and has effectively prevented corrosion at this point in time.

It was also noted that mucilage can facilitate the forming of differential aeration cells when a patchy coverage occurs as observed in Figure 2. This occurred where there was a difference in the concentration of dissolved oxygen between two points of the same metal surface. Since the direction of the reaction was towards equilibrium, the only way that equilibrium could be approached by corrosion was reduction in concentration of oxygen where it was highest. Evidence of this is also present by the corrosion products in other areas. These are visibly more extensive than the control piece and this is to be expected. Under the mucilage biofilm the steel is shielded from the oxygen needed for corrosion to occur. In other regions the oxygen is more concentrated and a concentration cell is developed, exacerbating corrosion. The production of metal ions in these zones decreases the local pH, further increasing corrosion.

It is shown in Figure 5 that, by mass, there is a much more extensive passive film on the surface of the control steel piece. Mucilage increases dissolution of iron and its removal from the steel surface. This will reduce the capability of the steel to develop a passive film, as observed and shown to be clear in Figure 2.

Figure 3 presents photographs taken using a stereomicroscope of the control steel piece and a piece exposed to algae. The images target the most extensive pitting on each specimen. It can be seen on the control piece (left) that the pitting has very defined sharp edges and is deep. By contrast, the pits caused by corrosion on the second piece (right) are shallower and spread more broadly over the piece. The pits also have rounded smoother edges.



Figure 3: Pitting comparison between control and steel exposed to algae.

These effects can be attributed to the spread of mucilage over the steel that smooths the corrosion process in certain zones, leading to a larger area corroding to a shallower depth for the same amount of steel removed.

The deep pitting in the control piece is typical of pitting corrosion where a greater distance to the centre of the pit makes it anodic.^[9]

The consequence of the pitting differences is considerable. The results in Figure 5 show that a similar amount of mass loss occurred on all steel pieces. In the case of the control piece, much of this was due to pitting corrosion whereas in the pieces immersed in algae this mass loss was more reminiscent of general corrosion. The larger area of general corrosion means that the thickness losses will be less than for pitting corrosion for the same amount of steel removed. According to the survey standards of such societies as Det Norske Veritas^[10] and Lloyd's Register^[22], thickness diminution is the standard used to determine material wear out due to corrosion. Hence the pitting corrosion present in the control piece can be considered as more harmful.

It was observed on each of the steel pieces exposed to the algae after removal of corrosion products that there was extensive attack at the bottom of the pieces. As discussed, it was also observed that mucilage films tended to develop on the upper areas of the steel.

With light supplied from above the water, the light intensity will decrease as the depth increases. This will cause more algae growth to occur at the surface, accounting for a greater production of mucilage in these areas. This would explain why the steel appeared to be protected from corrosion in these areas in preference to the bottom.

It is widely known that more extensive corrosion will occur on a steel column in seawater at the junction between water and air. This is because there is a greater amount of dissolved oxygen in the water at this level. If a film of living organic material forms over this area and protects it from corrosion, as observed in this experiment, then the region of greatest attack will not be at the air-seawater junction, it will be below the surface below the mucilaginous film.

4.3 Alkalinity of seawater solutions and corrosion potential

The results for both alkalinity of the tub water and corrosion potential of the steel pieces in the seawater were found to have very small changes so would have a minimal impact on the corrosion of steel.

The range of alkalinity data collected from all tubs varied between 8.03 and 8.44 pH. The range of corrosion potential recorded was -698 and -600 mV. According to the Pourbaix diagram for iron this places the system in the corroding region.^[8] The variations in both alkalinity and corrosion potential do not change this position so will have no effective impact on the corrosion.

4.4 Mass

4.4.1 Percentage mass loss

Figure 4 presents the decrease in mass of the steel specimens over time as a percentage of their original mass. The mean at each instance of time has been taken for the replicated conditions. This does not present data for after the corrosion products were removed from the steel.

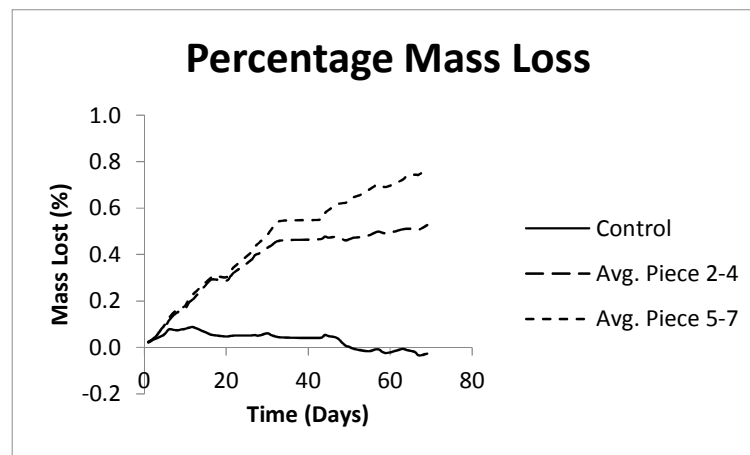


Figure 4: Mass loss in steel specimens as percentage of original mass.

The figure shows that over time the control piece lost mass initially before settling and a mass increase was observed. This is opposite to the expected mass decrease. As the steel is corroded and iron atoms are removed into the solution the mass should decrease. However the formation of corrosion products on the surface will cause a mass increase. As the iron atoms bond with oxygen atoms the mass increases. If the total mass of oxygen atoms bonding to iron is greater than the mass of iron atoms entering the solution then the mass of the steel piece will increase.

Conversely, the tubs containing algae showed a continual decrease in mass that followed a logarithmic pattern. The tubs containing the higher algae concentration began to clearly cause more mass loss than the lower concentration after 30 days. The mass loss in the tubs containing the greater concentration of algae is only just beginning to trend away from a linear curve towards a logarithmic function after 70 days. This demonstrates that a higher concentration of algae is positively correlated with a greater rate of mass loss in steel suffering from

corrosion. It is very apparent that the tubs containing algae caused a much greater mass loss than the control specimen in filtered seawater.

4.4.2 Final mass loss

The removal of the corrosion products at the end of the testing period revealed some interesting results that can be seen in Figure 5. The figure presents the overall percentage decrease in mass for the steel specimens both before and after the corrosion had been removed from the initial condition.

After the removal of corrosion products from the steel specimens, it was found that the mass decreased in all as expected. A greater decrease in mass was recorded in the steel specimens exposed to the algae and an increasing amount of algae yielded a greater decrease in mass, indicating increased corrosion. However, the observed difference is actually small: one quarter of a percent is the difference between the control and higher algae concentration condition after 70 days of exposure. This is in stark contrast to the mass removed before corrosion product removal.

The difference between the two columns of data is interesting; it represents the mass of corrosion products on the specimens as a percentage of their original mass. It can be seen that there is a very large difference for the control specimen; this means that there was much more corrosion attached to this piece of steel. For the two conditions of algae concentration tested, it can be seen that the difference is less than the control and lessens as the concentration of algae is increased. This means that the presence of algae is negatively correlated to the amount of corrosion products attached to the steel specimen. This can be expected to restrict the potential for a passivating film to develop over the surface of the steel, leading to increased corrosion.

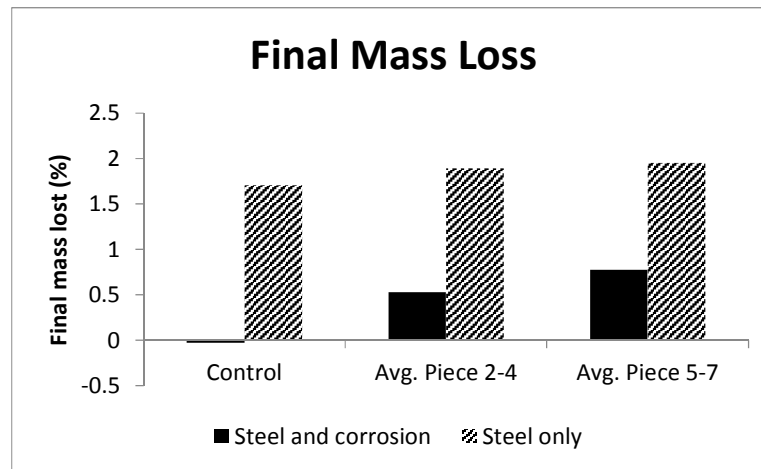


Figure 5: Final mass loss as a percentage of original mass.

4.5 Analysis by artificial neural network

Artificial neural network (ANN) is a type of Artificial Intelligence technique that mimics the behaviour of the human brain.^[4] ANNs have the ability to model linear and non-linear systems without the need to make assumptions implicitly as in most traditional statistical approaches.

Various network architectures were investigated in order to determine the optimal Multilayer Preceptor (MLP) architecture (i.e. the highest coefficient of determination, the lowest root mean square error and the lowest mean bias error) for each combination of input variables. The two sets of data used for training the network were the Average Fluorescence ($\mu\text{g/L}$) and mass reduction in steel specimen. The coefficients obtained from the model were used in designing a LabVIEW program, which functions as a decision-making tool, shown in Figure 6.

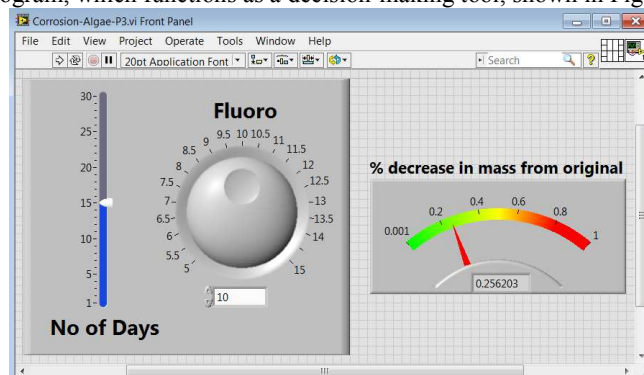


Figure 6: LabVIEW decision-making tool working with the ANN model

Table 1 below presents sample data from the LabVIEW program comparing the effects of time and algae density on the corrosion of steel. The corrosion is expressed as a percentage decrease in mass. In the table on the left, the numbers of days range between 0 and 30 days and the algae density is set at 10. In the table on the right, the algae density ranges between 5 and 15 and the number of days is set at 15.

The tables show that time has a much larger impact on the corrosion than does algae density. This simulation program can be developed to provide very accurate data to users that can be beneficial in predicting the extent of corrosion on a marine structure after an abnormal event such as an algal bloom. The program could be used as a decision-making model for maintenance and reliability purposes.

Table 1 Sample data comparing effect of time and algae density on mass loss by corrosion.

Fluoro 10		Days 15	
No. Days	% mass loss	Fluoro	% mass loss
0	0.000	5	0.261
3	0.095	6	0.242
6	0.182	7	0.239
9	0.230	8	0.244
12	0.249	9	0.252
15	0.256	10	0.256
18	0.263	11	0.258
21	0.285	12	0.258
24	0.344	13	0.258
27	0.410	14	0.258
30	0.439	15	0.258

5 Conclusions

The experiment revealed three key findings regarding the effects of algae on the corrosion of mild steel.

Weighing the steel specimens at the end of the experiment after removing the corrosion products revealed that mass of steel lost was similar for all pieces. Slightly more steel was removed from the pieces exposed to algae, but the difference was only 0.25%. This shows that after the 70-day testing period algae had only a small impact on the corrosion of the steel.

The mass lost from the steel pieces immersed in algae was shown to increase over a longer time period. This suggests that short exposure times to seawater without algae will cause more damage than in water with algae. It also suggests that over a long period of time, immersion of steel in seawater containing algae is more damaging. The crossover time cannot be found from the data collected in this experiment. If the experiment continued over a longer period it would be expected that the difference in mass between the control and test pieces of steel would increase, showing that the presence of algae increases the corrosion rate of mild steel.

The surface profiles of the steel pieces showed that the quality of corrosion experienced by steel immersed in seawater only is much more damaging when assessed according to the standards of classification societies. This is evidenced by the extensive and aggressive pitting, which is regulated and analysed by societies to determine and grade corrosion damage. By comparison, the more evenly spread corrosion on the other pieces was similar to general corrosion and would allow a steel structure to remain in its corroded state longer and continue to comply with classification society regulations.

In terms of an overall comparison comparing the effects of corrosion on mild steel between seawater with and without algae, the quantitative analysis showed seawater with algae to be more damaging. The results show that in the very short term seawater only is the most damaging, but over time the increased mass lost as a result of the presence of algae should overtake the damaging effects despite quality differences. Thus there must be a point in time for any system at which the damaging effects of algae in seawater is more than seawater without algae. Establishing a method to find this point could be very beneficial as it would provide a powerful corrosion analysis tool. Along with more data collection, the ANN program developed in this work could be modified and built upon to achieve this aim.

5.1 Improving the method

There are various ways in which the method could be improved in this experiment and these are detailed below.

Conducting the experiment for a longer period of time would be beneficial. Whilst it was shown in the control that corrosion effectively stopped after only a very short period of time, this was not the case for the steel exposed to algae. Here it was found that the corrosion continued right up until the end of the experiment and testing for a longer

period or under conditions that further increased the rate of corrosion would be beneficial to investigate longer term effects and track the mass loss until it converged and plateaued.

The results showed that despite intending to test two different concentrations of algae, the actual concentrations in the tubs were very similar. Repeats of the experiment would be better conducted by inoculating seawater with just one concentration of algae and also replicating the control condition.

Methods to keep the algae alive longer would also be beneficial as this would allow each cycle to be continued for a longer period of time. Supplying the algae with more nutrients necessary for growth would be a solution and could potentially speed up the corrosion process. A larger volume of water respective to the mass of the steel pieces tested should also increase the longevity as it would take longer for toxic levels of iron to accumulate.

Experience showed that the photographs taken could be improved. The metallurgical microscope produced images of little use in this experiment. The variations in depth of corrosion products made obtaining a focused image impossible. The stereomicroscope was very useful for examining the surface of the steel pieces, particularly after the experiment had ended. It should have been used throughout the experiment. Taking comparison photos of all steel pieces was also valuable to document the changes. Using an iPhone camera was a passable solution, but Figure 2 shows that the image has poor resolution. A camera capable of taking very high-resolution images of the whole steel pieces would be beneficial for documentation and comparison purposes.

5.2 Expanding the research scope

There is ample opportunity for this work to be continued in a number of different ways.

Testing longer lengths of steel in water containing algae could allow the vertical distribution of corrosion to be investigated. Different depths of water could also be incorporated to determine if they are a factor. The effects over the length of the steel could be effectively analysed using photography.

Different species of algae could be tested to determine the similarity of the results between different species. *Dunaliella tertiolecta* are a unicellular motile alga that does not adhere to a surface. Different sorts of algae could be expected to have different impacts, especially an alga that will adhere to the surface of a metal. Such species could be expected to deposit more mucilage on the surface.

The experiment duration could be varied to determine the point at which mass lost from steel to corrosion becomes greater from algae exposure than seawater exposure.

REFERENCES

1. Lane, R.A., 2005. Under the Microscope: Understanding, Detecting, and Preventing Microbiologically Influenced Corrosion. Journal of Failure Analysis and Prevention, 5:10-12, 33-38.
2. Little, B.J., P.A. Wagner and F. Mansfeld, 1997. Microbiologically Influenced Corrosion (Vol. 5). NACE International, Houston, Texas.
3. Edyvean, R.G.J. and L.A. Terry, 1986. Studies in Environmental Science. In: L.V. Evans and K.D. Hoagland, Algal Biofouling pp. 1, 211–230. Elsevier Science Publishing Company Inc., New York, USA.
4. Javaherdashti, R., H. Nikraz, M. Borowitzka, N. Moheimi and M. Olivia, 2009. On the Impact of Algae on Accelerating the Biodeterioration/Biocorrosion of Reinforced Concrete: A Mechanistic Review. European Journal of Scientific Research, 36(3): 394-406.
5. Haykin, S., 2009. Neural Networks and Learning Machines. 3rd edition, Pearson Education, Inc., New Jersey.
6. Oxtoby, D., H. Gillis and A. Campion, 2008. Principles of Modern Chemistry. 6th edition, Arden Shakespeare, California.
7. Videla, H.A. and L.K. Herrera, 2005. Microbiologically Influenced Corrosion: Looking to the Future. International Microbiology, 8: 169-180.
8. Hill, E.C., 2003. Microbes in the Marine Industry. IMarEST, London, UK.
9. Lisson, D.N., 2008. Materials Technology Lecture Notes. Erbacher J., Ed. 5. Australian Maritime College, Launceston, Australia.
10. Det Norske Veritas, 2007. Allowable Thickness Diminution for Hull Structure of Offshore Ships. DNV, Veritasveien 1, NO-1322 Høvik, Norway.
11. Sellner, K., G. Doucette and G. Kirkpatrick, 2003. Harmful Algal Blooms: Causes, Impacts and Detection. Journal of Industrial Microbiology and Biotechnology, 30(7): 383-406.

12. Joos, F., J.L. Sarmiento and U. Siegenthaler, 1991. Estimates of the Effect of Southern Ocean Iron Fertilization on Atmospheric CO₂ Concentrations. *Nature*, 349(6312): 772-775.
13. Martin, J.H., S.E. Fitzwater and R.M. Gordon, 1990. Iron Deficiency Limits Phytoplankton Growth in Antarctic Waters. *Global Biogeochemical Cycles*, 4(1): 5-12
14. McLachlan, J., 1960. The Culture of *Dunaliella Tertiolecta* Butcher—A Euryhaline Organism. *Canadian Journal of Microbiology*, 6(3): 367-379.
15. Avron, M. and A. Ben-Amotz, 1992. *Dunaliella: Physiology, Biochemistry, and Biotechnology*. Florida, USA.
16. Stewart, W.D.P., 1974. *Algal Physiology and Biochemistry*. Vol. 10. University of California Press, California.
17. BBC Producer, 2009. Seaweed Suspected in French Death. [Newspaper article] Retrieved from <http://news.bbc.co.uk/2/hi/europe/8242649.stm>, 25 March 2015.
18. Kamal, C. and M.G. Sethuraman, 2012. *Hydroclathrus Clathratus* Marine Alga as a Green Inhibitor of Acid Corrosion of Mild steel. *Research on Chemical Intermediates*, 39(8): 3813-3828.
19. Baboian, R., 1995. *Corrosion Tests and Standards, Application and Interpretation*. ASTM International.
20. Blankenship, R.E., 2013. *Molecular Mechanisms of Photosynthesis*. John Wiley & Sons.
21. Chang, F., 1988. Distribution, Abundance, and Size Composition of Phytoplankton off Westland, New Zealand, February 1982. *New Zealand Journal of Marine and Freshwater Research*, 22(3): 345-367.
22. Lloyd's Register Marine, 2014. Thickness Measurement and Close-Up Survey Guidance. Working together for a safer world. Lloyd's Register Group Limited, United Kingdom.
23. Petrucci, R., 2007. *General chemistry*. 9th edition, Prentice Hall, Upper Saddle River, New Jersey.