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Effect of Concentration and Exposure Time on Mild Steel Corrosion in Sodium Chloride

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Abstract

One of the major aspects in terms of cost and security of both industrial and marine environments is corrosion. This paper is an experimental study of the corrosion behavior of mild steel in sodium chloride at various concentrations (0.5 -10 wt. %) after 168 hours. The methods used were in visual analysis and microscopy. It was established that corrosion rate increased with concentration of NaCl but deviated at higher concentrations. The mass loss versus time was almost linear in a graphical representation and the rate of corrosion versus concentration exhibited a maximum level. These findings are related to the electrochemical concepts of oxygen diffusion and formation of corrosion products, which are explained. Highest corrosion risk is determined and recommendations made concerning the best concentration which presents maximum corrosion risks and protective measures are recommended to the marine structures.

Keywords: Mild steel corrosion, sodium chloride concentration, oxygen diffusion limitation.

1. Introduction

Corrosion is a major degradation phenomenon affecting that modern infrastructure, causing significant economic losses estimated at about 2.5 trillion USD annually, which corresponds to roughly 3.4% of the global GDP [1, 2]. These economic losses are accompanied by safety failures, unplanned outages, and environmental contamination, unplanned outages and environmental contamination [3, 4]. Mild steel (low-carbon steel) is one of the most widely used metallic materials in terms of industrial significance, as it has good mechanical characteristics, can be welded, and is cheap, making it invaluable in the construction industry, transport of hydrocarbons, shipbuilding, and marine engineering [4, 5]. Despite the widespread industrial use, mild steel remains highly vulnerable to corrosion in chloride containing environments, particularly in marine conditions and regions where de-icing salts are applied. Passive oxide films are attacked and broken by the aggressive species, namely chloride ions which promote localized corrosion such as pitting. Seawater is a common, widespread, and highly corrosive electrolyte with the salinity being about 3.5 % weight of NaCl [6, 7]. Although many studies have investigated corrosion in NaCl media, there is still a knowledge gap in the specific non-linear relationship that exists between NaCl concentration and corrosion kinetics under long-term, static exposure (168 hours). Many studies assume a monotonic relationship that increased salinity will always increase the rate of corrosion [8, 9]. Nevertheless, preliminary findings suggest that corrosion rates may plateau or even decrease once salinity surpasses an optimal threshold, likely due to the reduction in oxygen solubility. Although thermodynamically feasible this phenomenon has not been sufficiently measured using gravimetric methods under laboratory-controlled conditions. In addition, the shift of uniform to pitting morphology with observation of chloride loading must be documented systematically as indicated by visual and microscopic records [10, 11]. The current study addresses these gaps by a controlled experimental matrix based on measuring weight loss (ASTM G1), optical microscopy and temporal mass loss profiling. The study will assess mild steel coupons in contact with 0.5 wt. %, 3.5 wt. %, and 10 wt. % NaCl solutions within 168 hours to measure the non-linear relationship between the concentration of NaCl and the corrosion rate. Suggesting diffusion limitation by oxygen and offer practical data to determine the risk of corrosion and optimization of mitigation measures in marine structures.

2. Experimental Methodology

2.1 Materials and Equipment

Specimens, the mild steel coupons (30 mm x 20 mm x 2 mm), polished using abrasive papers up to 800 grits degreased with acetone and air-dried [9, 10]. Solutions of NaCl of 0.5 wt. %, 3.5 wt. % simulated seawater, and 10 wt.% NaCl were prepared using analytical-grade NaCl dissolved in distilled water. Materials and instruments as digital balance (±0.0001 g), glass beakers, thermostatic bath (25 ºC), calipers, optical microscope, and digital camera were also used [10, 11].

2.2 Procedure

Initial weight and dimensions of all coupons were measured. Coupons were immersed in 500 mL of each NaCl solution with concentrations of 0.5 wt. %, 3.5 wt. % and 10 wt. % exposed for seven days. Coupons were removed at 24, 72, 120, and 168 hours and cleaned of corrosion products (Clarke solution ASTM G1), dried, and weighed [10, 11]. The rate of corrosion (CR) was determined by the following formula [11, 12].

$$\mathbf{CR = (K \times W / A \times T \times D)}$$

Where represent K is a constant = 87600, W is mass loss (g), A is area (cm^2) and T is time (hours) and D is density (g/cm^3) [9, 10]. Also, surface morphology was examined using an optical microscope.

3. Results and Discussion

3.1 Non-Linear Concentration Dependence

Results indicate a non-linear dependence of corrosion rate on NaCl concentration [12, 13]. The experimental results without any doubt prove that the rate of corrosion of mild steel in NaCl media does not follow a monotonic relationship with salt concentration. The average mass loss at 0.5 wt.% NaCl was 0.102 g (CR = 1.21 mm/year), when the concentration was 3.5 wt.%, the corrosion rate increased to almost triple (0.278 g; 3.30 mm/year). However, at 10 wt.% NaCl, the corrosion rate decreased to 2.86 mm/year, as shown in table 1 and figure 1. This behavior may be attributed to reduced dissolved oxygen and the formation of corrosion products at high salinity. The iron metal ($Fe \rightarrow Fe^{+2} + 2e^-$) and the inhibitory effect of reduced dissolved oxygen on the cathodic oxygen reduction ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$) of the metal at higher ionic strengths [14, 15].

Table 1: Effect of NaCl concentration on mass loss and corrosion rate.

NaCl Conc. (%)	Exposure Time	Avg. Mass Loss (g)	Corrosion Rate (mm/year)
0.5	168	0.102	1.21
3.5	168	0.278	3.30
10	168	0.241	2.86

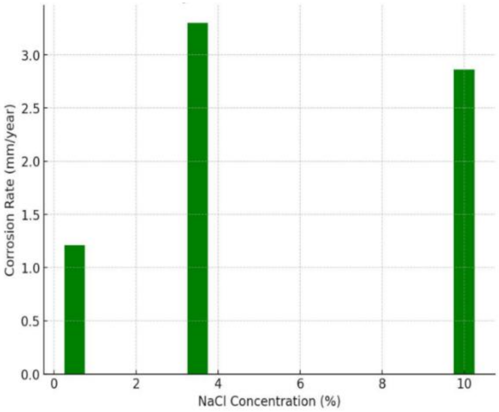

Figure 1: Corrosion rate of mild steel as a function of NaCl concentration after 168 hours exposure.

3.2 Temporal Mass Loss Linearity

Linear increase in mass loss was observed during the 168 hours exposure indicates that the corrosion rate may remain immersion conditions in the absence of significant formation of protective films (figure 2) [14]. No significant passivation behavior was observed, even at 10 wt. % of NaCl. This contrasts with flowing conditions, where turbulence can enhance oxygen transport and formation of oxide layers. The stagnant regime used herein is thus a worst-case scenario of sustained corrosion activity [15].

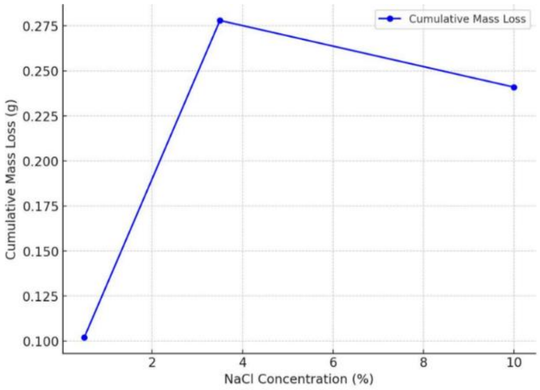

Figure 2: Temporal evolution of mass loss for mild steel immersed in NaCl solutions over 168 hours.

3.3 Pitting Morphology and Chloride Synergy

Microscopic analysis (figures 3-5) showed that general corrosion predominated at 0.5 wt.%, and 3.5 wt.% NaCl. Whereas localized pitting corrosion was observed at 10 wt.% NaCl. This is explained by the fact that. This behavior can be attributed to the presence of critical chloride concentration required to destabilize the passive film [16]. Highly damaging and it serves as a stress concentrator and a precursor to fatigue cracking. This result indicates that a lower uniform corrosion rate at 10 wt.% NaCl does not necessarily mean improved structural integrity, because localized pitting corrosion can significantly weaken the material has already occurred in the metal [16].

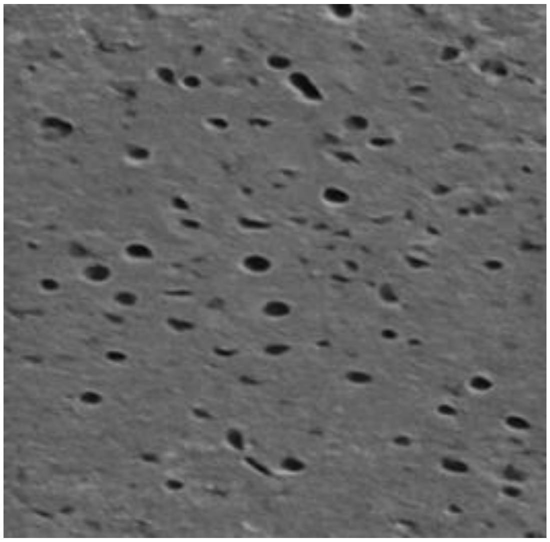

Figure 3: Surface morphology of mild steel after exposure to 0.5 wt.% NaCl (168 hours).

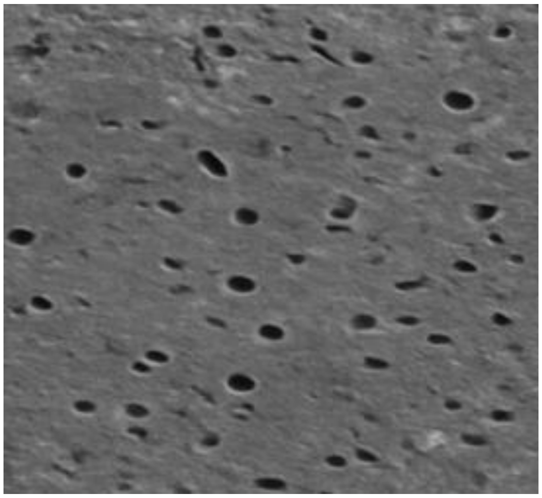

Figure 4: Surface morphology of mild steel after exposure to 3.5 wt.% NaCl (168 h).

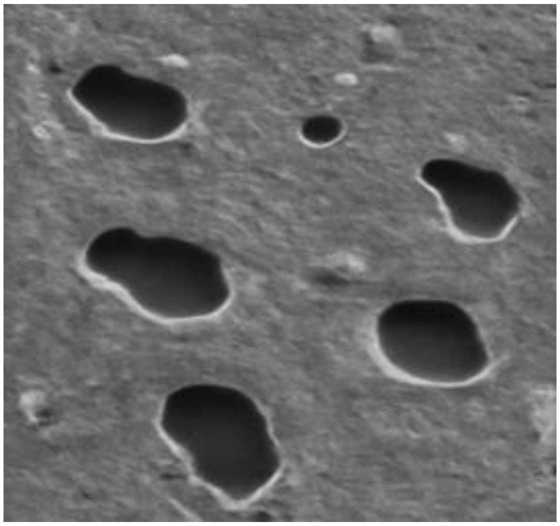

Figure 5: Surface morphology of mild steel after exposure to 10 wt.% NaCl showing pitting corrosion.

3.4 Electrochemical Interpretation and Comparison

The highest rate of corrosion was observed at 3.5 wt. % NaCl, which is close to the typical salinity of seawater. The result supports the environmental relevance of experimental design. In comparison, the corrosion rate of mild steel at stagnant 3.5 wt. % NaCl in this study had a corrosion rate that was 6.63 × 10^{-3} mm/year, which was three orders of magnitude less than in Gunasilan et al. [17]. Difference can be explained by the fact that they used short-term Tafel extrapolation (instantaneous rate) as compared to our cumulative 168 hours weight loss (integrated rate). Electrochemical techniques such as Tafel extrapolation measure instantaneous corrosion rates and Gravimetric methods integrate both the initiation and propagation of corrosion over time, which evaluates within the cumulative damages [18].

3.5 Implications for Marine Structures and Protective Strategies

Results of this study confirm that unalloyed mild steel is highly susceptible to corrosion in chloride-containing environments. It shows that the non-linear response means that a reduction of salinity (e.g. mixing brackish zones) does not necessarily decrease risk in proportion. In offshore platforms, ship hulls and coastal infrastructure, the use of barrier coatings is strongly recommended [18]. New inorganic zinc composite coating by alkali-activated technology has shown a cathodic protection lifetime exceeding 2800 hours, representing a 200% increase over the previously used organic systems [19]. Likewise, $Zn_3In_2S_6/ZnMoO_4$ heterojunction-based photocathodic protection coating is a novel frontier in the field of smart corrosion control, with the ability to impose cathodic current on steel substrate by taking advantage of solar energy. Although these technologies are not yet widely adopted, they are promising avenues of ensuring that the service life of marine steel assets is extended [19].

4. Conclusion

The rate of corrosion of mild steel in NaCl solutions depends on NaCl concentration, with a maximum at 3.5 wt. % NaCl. Long-term exposure results in progressive mass loss, therefore, preventive measures should be implemented early. Pitting corrosion becomes more pronounced at higher chloride concentrations, which is a major threat to structural integrity. Steel structures exposed to marine environments should be protected using coatings, cathodic protection, or the use of corrosion-resistant alloys.

5. References

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