

Corrosion Behaviour of Mild Steel: Insights from Tafel Extrapolation Analysis in Flowing 3.5% NaCl Solutions and Soil with Diverse Resistivity Levels

Mahalaksmi Gunasilan^a, Shaiful Rizam Shamsudin^{a,*}, Nursalasawati Rusli^b, Mohd Rafi Adzman^c and Wan Mohd Haqqi Wan Ahmad^d

^aFaculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia

^bInstitute of Engineering Mathematics, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia

^cFaculty of Electrical Engineering & Technology, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia

^dFaculty of Chemical Engineering & Technology, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia

*Corresponding author. Tel.: +604 9885035; fax: +604-9885034; e-mail: rizam@unimap.edu.my

ABSTRACT

The corrosion behaviour of AISI 1006 steel in diverse environmental conditions were comprehensively investigated to offer valuable insights into corrosion mitigation strategies for critical infrastructure protection. This study employed an optical emission spectrometer, pH measurements, soil resistivity assessment, and Tafel extrapolation conducted with a potentiostat. The study encompassed stagnant and flowing 3.5% NaCl solutions, with flow velocities ranging from 0 to 12 km/h, and considered soil corrosiveness based on soil resistivity. In stagnant 3.5% NaCl solutions, minimal corrosion was observed due to limited oxygen availability, resulting in a 6.634×10^{-3} mm/year corrosion rate. A noteworthy trend was evident in flowing 3.5% NaCl solutions, with corrosion rates peaking at 9 km/h (11.918×10^{-3} mm/year) and subsequently decreasing at 12 km/h (10.423×10^{-3} mm/year). This intriguing pattern may be attributed to the potential formation of a protective oxide layer at higher flow velocities, likely due to increased dissolved oxygen and mass transport. The soil's corrosiveness significantly influenced corrosion rates, with lower-resistivity soils exhibiting heightened corrosion rates. In very mildly corrosive soil, AISI 1006 steel displayed a corrosion rate of 2.818×10^{-4} mm/year. The corrosion rate increased as soil corrosiveness intensified, reaching its peak of 6.319×10^{-4} mm/year in severely corrosive soil. Extremely corrosive soil led to a corrosion rate of 8.033×10^{-4} mm/year, as improved soil conductivity accelerated ion transfer and electron flow, ultimately expediting corrosion-related electrochemical reactions. This study enhances the understanding of AISI 1006 steel corrosion in varying conditions, providing critical data for corrosion control in structures and assets, emphasising the need for tailored prevention measures.

Keywords: Tafel extrapolation, Mild steel, NaCl solution, Soil & corrosion rate

1. INTRODUCTION

Corrosion, a natural process affecting materials, especially metals, occurs through chemical reactions with their environment [1]. It is particularly severe in locations near the sea due to high corrosion levels, exacerbated by flow-accelerated corrosion (FAC) and erosion-corrosion in corrosive marine environments [2]. FAC takes place when fast-moving water dissolves a metal's protective oxide layer, exposing it to corrosion, and impacting structures in constant water flow like submerged hulls.

Flow velocity is a primary factor in FAC studies on carbon steels, with elevated velocities increasing corrosion rates due to accelerated oxygen transfer [3]. Naturally formed rust layers on steel surfaces have been found to mitigate FAC in seawater, reducing corrosion rates compared to exposure in a 3.5% NaCl solution under equivalent conditions. The corrosion rate fluctuates with varying flow velocities.

Crucial electrochemical parameters have been identified in corrosion studies by the Tafel extrapolation method. For instance, Pradityana et al. reported a corrosion current density (i_{corr}) of 0.3233 mA/cm^2 for carbon steel in a 3.5% NaCl solution [4]. Understanding corrosion current density

variations influenced by experimental setups, steel composition, microstructure, surface condition, and environmental factors [5]. The corrosion rate depends on factors such as oxygen dissipation, ongoing corrosion processes, continuous hydroxide ion (OH^-) production, and the presence of hydrogen ions (H^+) in the electrolyte [6-7]. Flow velocity is positively related to corrosion rates, increasing material susceptibility to corrosion [8][9]. Factors like dissolved oxygen and its role in anodic reactions also influence corrosion behaviour [10].

On the other hand, soil resistivity plays a vital role in assessing the corrosion potential of buried metal structures. Soil corrosivity varies significantly, attributed to soil resistivity, moisture content, and pH [11][12]. High soil resistivity corresponds to lower corrosion rates, while low resistivity heightens corrosion risk. Soil characteristics, moisture content, and the presence of microorganisms play pivotal roles in determining the corrosion degree [13].

Low soil resistivity conditions, featuring acidic pH, elevated temperatures, and increased moisture, elevate corrosion risk. The presence of specific soil electrolytes, like salts, compounds low resistivity, increasing corrosion risk [14-16]. Soil composition, encompassing chemical makeup and

specific resistance, significantly influences electrochemical behaviour and soil corrosiveness [17]. High-resistivity soils expedite the corrosion process in low-resistivity environments, with lower impulse impedance and a higher percentage reduction of impulse impedance compared to low-resistivity soils.

Soil resistivity, characterised as soil corrosiveness, influences polarisation, which is crucial in predicting metal corrosion in soils [18]. Soil resistivity measurements are essential for optimal grounding system placement [19]. The concentration of corrosive media in the soil significantly affects soil corrosiveness and steel corrosion rates, determined by Tafel extrapolation [20-23]. Varying soil corrosiveness levels, from mildly to extremely corrosive, impact corrosion rates, with higher concentrations of corrosive media increasing corrosion rates. Bai *et al.* [24] found that improved soil conductivity accelerates ion transfer and electron flow, ultimately expediting corrosion-related electrochemical reactions.

The Tafel extrapolation method is vital for understanding early-stage corrosion mitigation. Its absence in studies on steel corrosion in NaCl solutions and varying soil corrosiveness levels hinders precise corrosion rate determination, obscures control factors, and limits insight into corrosion mechanisms. This poses risks in practical applications. This study aims to fill this knowledge gap by investigating corrosion under different conditions, including various flow rates and soil resistivity, providing insights for more effective corrosion mitigation strategies in high-velocity seawater and diverse soil environments.

2. METHODOLOGY

The study employed low-carbon steel, commonly used in various applications despite its susceptibility to corrosion, for investigation. Chemical composition was analysed using Optical Emission Spectrometry (OES) with a Bruker Q8 Magellan instrument. Steel sample sections were prepared by cutting and grinding with 80-grit SiC paper. Then, it was sparked at five locations on each sample surface to verify material composition.

Flat bars of low-carbon steel, cut into 10 cm lengths and finely ground to 600 grit with SiC paper, were prepared for electrochemical analysis. The steel samples were thoroughly cleaned with distilled water and washing alcohol to eliminate contaminants. Preheating to around 70°C in an oven preceded the application of a polymer-based paint, enhancing adhesion and drying time while preserving a designated 1.0 cm² bare metal area for corrosion experiments.

The study employed a 3.5% NaCl solution and various soils with different pH and resistivity levels as the electrolyte. The 3.5% NaCl solution was prepared by dissolving 35g of NaCl in distilled water to achieve a 1000 ml total volume. The solution's pH was measured using a Portable pH/mV Meter (HI8424, Hanna Instruments), and resistivity was

determined according to ASTM D1125-23. Soil samples were dried in a microwave oven at 90±10°C for approximately 3 hours, ground into fine particles, and prepared with varying amounts of deionised water by weight percentage, categorised based on their resistivities. Before the Tafel extrapolation polarisation study, soil pH was measured with a pH meter (DM-15, Takemura), and resistivity followed the Wenner four-point probe method (ASTM G187-12a) using a digital earth tester (CA 6460, Chauvin Arnoux). The soils were categorised into different resistivity levels according to ASTM G187-12.

Corrosion behaviour in a 3.5% NaCl solution was studied through Tafel extrapolation tests at a constant 25°C. The experimental setup included a saturated calomel electrode (SCE) as the reference electrode, platinum as the counter electrode, and low-carbon steel samples as the working electrode. A magnetic stirrer (MS5C, Joanlab) facilitated varying flow velocities of the electrolyte solution.

Tafel extrapolation tests were conducted using a potentiostat/galvanostat (Gill AC, ACM Instruments). Steel samples were immersed in a 3.5% NaCl solution before testing, with potential measurements continuously recorded until a steady-state condition was achieved. The Tafel extrapolation test featured a potential scan rate of 3 mV/minute, covering a scan range of ±250 mV offset from the preset rest potential. Tafel plots were constructed using ACM analysis software, and Origin Pro8 software was used to analyse the raw data. The Tafel extrapolation procedure was repeated for stagnant solutions and solutions with different rotational speeds (3, 6, 9, and 12 km/h). For clarity in reporting, these rotational speeds (rpm) were converted into flow velocities (km/h) using Equation (1);

$$\text{Flow velocity (km/h)} = (2\pi \times \text{radius} \times \text{rpm} \times 60) / 1000 \quad (1)$$

The process was repeated with five soil types, each having distinct pH and resistivity characteristics, using a saturated Cu/CuSO₄ electrode. The low-carbon steel sample was buried in 1000g of these soils.

The corrosion rate was determined using the i_{corr} obtained from the Tafel plot and applied to the Equation (2):

$$\text{Corrosion rate} = K \cdot i_{\text{corr}} \cdot \text{EW} / \rho \quad (2)$$

In this equation (2), K represents a constant (8.76), i_{corr} is the corrosion current density, EW is the equivalent weight of the steel sample (27.81 g), and ρ is the density of the steel (7.85 g/cm³).

3. RESULTS AND DISCUSSION

3.1 Chemical Composition of the Steel Sample

The chemical composition of the Fe samples used in the study is shown in Table 1. The steel samples were examined for their chemical composition using OES, and the results were compared to the American Iron and Steel

Institute (AISI) classification standards. The results revealed that the samples comply with AISI 1006, medium-low carbon steel.

Table 1 Chemical composition of the sample

Element	Sample (%)	Carbon Steel	AISI 1006
C	0.097	< 1.00	0.08 max
Si	0.069	0.6 max	-
Mn	0.286	1.65 max	0.25-0.40
P	0.019	0.04 max	0.04 max
S	0.014	0.05 max	0.05 max
Cu	0.0081	0.6 max	-
Fe	Balance	Balance	Balance

AISI 1006 is a type of mild steel primarily composed of iron with a low carbon content (<0.25 wt.% C), making it suitable for welding and machining. While lacking corrosion-resistant elements like chromium and molybdenum, it still offers good corrosion resistance. With a density of 7.87 g/cm³, it's well-suited for applications in saltwater environments. This versatile material is commonly used in fabricating pipes, tubes, wires, fasteners, and various components through cold working and shaping processes.

AISI 1006, medium-low carbon steel, exhibits favourable electrochemical behaviour in a 3.5% NaCl solution but is vulnerable to chloride-induced corrosion due to its low carbon content. Its corrosion susceptibility is closely related to soil resistivity in soil environments. It displays lower corrosion rates in very mildly corrosive soil due to limited electron and ion mobility. However, in soils with higher conductivity and increased corrosiveness, AISI 1006 experiences elevated corrosion rates. While it does not match the corrosion resistance of highly alloyed stainless steel, it performs satisfactorily in moderately saline environments. Its corrosion behaviour varies with environmental conditions and the presence of chloride ions.

3.2 Electrolyte Characteristics

Studying the pH and resistivity of the electrolyte, whether it's a 3.5% NaCl solution or soil, is crucial before embarking on a Tafel polarisation study. This preliminary analysis offers valuable insights into corrosion susceptibility, protective film formation, electrical conductivity, and the validation of research conditions. In the case of the 3.5% NaCl solution, the recorded nearly neutral pH of 7.1±0.1 does not significantly mitigate corrosion through protective film formation. However, the resistivity, which measured 52.9 Ω·cm, is consistent with expectations and indicates enhanced electrical conductivity. This conductivity accelerates electrochemical corrosion processes, potentially leading to a relatively high corrosion rate in this solution.

Turning to soil samples, their classification into distinct resistivity categories, as illustrated in Table 2, holds significant implications for understanding corrosion in soil environments. Soil with a resistivity over 10,000 Ω·cm is considered "Very Mildly Corrosive." In such environments, high resistivity limits the movement of charge carriers, resulting in a relatively low corrosion rate.

Table 2 pH and soil resistivity

pH	Soil Resistivity (Ω.cm)	Soil Corrosiveness Classification (ASTM G187-12)	
		Resistivity	Corrosiveness
5.3	11000	>10000	Very mildly corrosive
5.5	8500	5001-10000	Mildly corrosive
5.8	3560	2001-5000	Moderately corrosive
6.2	1150	1001-2000	Severely corrosive
6.3	670	501-1000	Extremely corrosive

Soil samples in the "Mildly Corrosive" category have resistivity values between 5,001 and 10,000 $\Omega\cdot\text{cm}$. While conductivity somewhat improves compared to the "Very Mildly Corrosive" category, it's still relatively low, leading to a moderately higher corrosion rate. Electrical conductivity notably increases in "Moderately Corrosive" soil with a resistivity between 2,001 and 5,000 $\Omega\cdot\text{cm}$. This facilitates the mobility of charge carriers, intensifying corrosion activity and subsequently leading to a higher corrosion rate. Soil classified as "Severely Corrosive," within the 1,001 to 2,000 $\Omega\cdot\text{cm}$ resistivity range, exhibits further improved conductivity. This enhanced mobility of charge carriers causes mild steel to experience significantly higher corrosion rates. Finally, "Extremely Corrosive" soil with resistivity values between 501 and 1,000 $\Omega\cdot\text{cm}$ has high electrical conductivity. This leads to the highest observed corrosion rates, making this category the most corrosive soil electrolyte.

In addition to the insights offered by pH and resistivity, studying the electrolyte's electrical characteristics plays a fundamental role. When resistivity is low, facilitating the movement of electrons and ions, electrochemical reactions, including anodic dissolution (corrosion) and cathodic processes, occur more rapidly. This accelerates corrosion activity and may result in higher corrosion rates. Conversely, electron and ion mobility are restricted in

environments with higher resistivity, impeding these electrochemical reactions and leading to lower corrosion rates. These electrical properties directly influence the corrosion behaviour of mild steel in both the 3.5% NaCl solution and soil, highlighting the importance of understanding them in corrosion studies.

3.3 Polarisation of Studied Steel in Stagnant Water

The study utilised the Tafel extrapolation method to evaluate the polarisation behaviour of the steel in both stagnant and varying flow velocities of the 3.5% NaCl solution. This widely employed technique assesses the corrosion rate by measuring the current and voltage between the metal and reference electrodes immersed in the solution. The collected data, derived from analysing the current-voltage relationship, enables the calculation of corrosion rates.

Figure 1 displays a Tafel plot illustrating the behaviour of AISI 1006 in a 3.5% NaCl solution, and the corresponding data is presented in Table 3. The corrosion potential (E_{corr}) is recorded at -623.74 mV vs SCE, indicating that the mild steel is in an active corrosion region. In simpler terms, this means the steel is readily corroding in this salty solution because the corrosion process is stronger than the protective process.

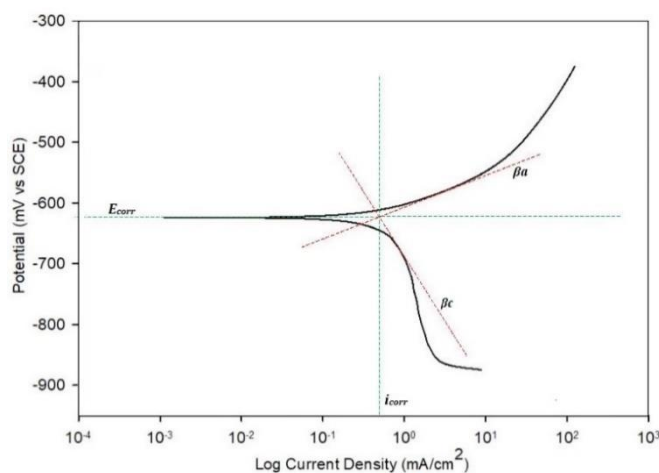


Figure 1. Tafel plot of immersed mild steel in stagnant 3.5% NaCl solution.

In Table 3, the anodic slope (β_a) was observed to be 60.108 mV/decade, while the cathodic slope (β_c) was steeper at -324.423 mV/decade. This suggests that the cathodic reaction dominates the electrochemical process on the steel surface, involving the reduction of oxygen (O_2) and the production of hydroxide ions (OH^-). The steepness of the cathodic slope indicates a more significant change in

the cathodic current density for a given change in potential, emphasising the prevalence of the cathodic reaction over the anodic dissolution of iron (Fe) to form iron ions (Fe^{2+}). Therefore, it can be concluded that the electrochemical reaction of the Fe samples in a 3.5% NaCl solution is primarily under cathodic control.

Table 3 Tafel plot data for AISI 1006 steel in 3.5% NaCl solution

Tafel Data	Stagnant water
E_{corr} (mV vs SCE)	-623.34
Anodic slope, β_a (mV/decade)	60.108
Cathodic slope, β_c (mV/decade)	-324.423
i_{corr} (mA/cm ²)	0.6426
Corrosion rate (x10 ⁻³ mm/year)	6.634

The corrosion i_{corr} value obtained in this study was 0.6426 mA/cm², which is slightly higher than the i_{corr} reported by Pradityana et al. [4], which was recorded at 0.3233 mA/cm² for carbon steel in a 3.5% NaCl solution. The report presented by Clover et al. [5] highlights those differences in corrosion current density can arise from variations in experimental setups, potential differences in the composition and microstructure of carbon steel samples, even within the same general classification, as well as other factors such as surface condition and environmental parameters. It is widely acknowledged for its importance in comprehending and interpreting corrosion behaviour. The corrosion rate is about 6.634 x 10⁻³ mm/year. The low corrosion rate is due to the fact that the Fe samples were in a stagnant water solution. This indicates that the Fe samples experienced minimal corrosion under the given conditions. The corrosion rate can be attributed to the dissipation of O₂ from the solution to the steel surface, as highlighted by previous studies [6]. Simultaneously, corrosion processes and the continuous production of OH⁻ occur under these conditions, as reported by Matloub et al. [7]. The stagnant water solution where the steel samples were immersed is a crucial factor contributing to the observed low corrosion rate.

Stagnant water environments are characterised by limited fluid movement, resulting in a reduced availability of O₂. O₂ plays a significant role in corrosion, particularly in the cathodic reaction, where it combines with water and electrons to form hydroxide ions (OH⁻). The reduced O₂ availability in the stagnant water solution likely contributes to the lower corrosion rate observed in the current study.

The absence of vigorous flow in stagnant water restricts the replenishment of dissolved O₂ near the Fe surface. As a result, the diffusion of O₂ to the metal interface is significantly hindered, leading to a reduced supply of O₂ for cathodic reactions. The limited availability of O₂ slows down the corrosion rate by impeding the rate at which the cathodic reaction occurs. Consequently, the low corrosion rate observed in the steel samples immersed in the stagnant water solution can be attributed to the decreased O₂ concentration. The stagnant nature of the water limits the exposure of the steel surface to O₂, thus minimising the extent of corrosion. It is worth noting that the corrosion rate could increase if the Fe samples were subjected to a more oxygen-rich environment, such as flowing water or aerated solutions.

3.2 Polarisation of Studied Steel In Different Flow Velocities

Figure 2 displays the Tafel plot, depicting the electrochemical behaviour of mild steel samples submerged in a 3.5% NaCl solution under varying hydrodynamic conditions, spanning from 0 to 12 km/h in flow velocities. The electrochemical data derived from the Tafel plot for each flow velocity are summarised in Table 4. A consistent and similar trend emerges when scrutinising the Tafel plot curves in Figure 2. However, upon closer inspection, notable discrepancies surface in the corrosion rate and polarisation data associated with each flow velocity.

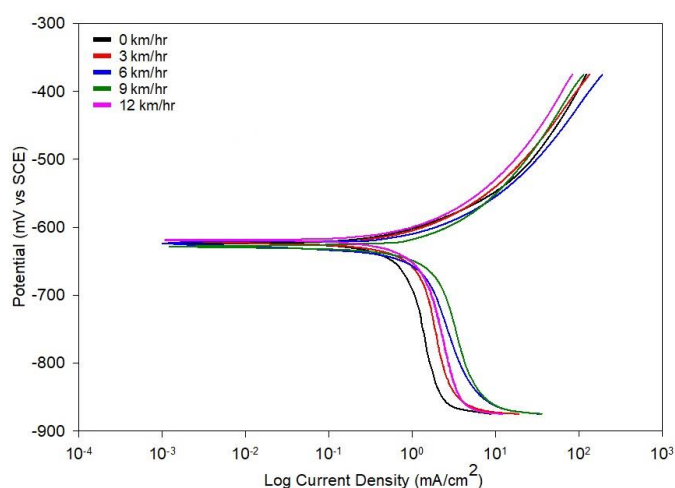


Figure 2. Tafel plot of immersed mild steel in 35% of NaCl solution at different velocities: 0, 3, 6, 9, and 12 km/h.

Table 4 Tafel plot data for AISI 1006 steel in 3.5% NaCl solution at different velocities

Tafel Parameter	Flow velocity (km/h)				
	0	3	6	9	12
E_{corr} (mV vs SCE)	-623.34	-622.98	-625.36	-627.21	-618.93
β_a (mV/decade)	60.11	64.06	58.67	81.48	84.04
β_c (mV/decade)	-324.42	-224.53	-219.14	-347.53	-365.14
i_{corr} (mA/cm ²)	0.6426	0.7071	0.8289	1.1543	1.0095
Corrosion rate (x10 ⁻³ mm/year)	6.634	7.301	8.559	11.918	10.423

Corrosion behaviour at a stagnant flow condition (0 km/h velocity) indicates a certain susceptibility to corrosion. The E_{corr} is measured at -623.34 mV vs SCE, suggesting a tendency for corrosion to occur. However, the corrosion rate, represented by the i_{corr} , is relatively low at 0.6426 mA/cm². Both β_a and β_c indicate a moderate rate of anodic dissolution (60.11 mV/decade) and cathodic reactions (-324.42 mV/decade). Overall, the corrosion rate is 6.634 x 10⁻³ mm/year, indicating a relatively low level of corrosion under stagnant flow conditions.

As the flow velocity increases, significant changes occur in the electrochemical parameters extracted from the Tafel plot. At a 3 km/h velocity, E_{corr} exhibits a slight positive shift (-622.98 mV vs. SCE), suggesting a marginally reduced susceptibility to corrosion compared to stagnant flow conditions. However, it's worth noting that this E_{corr} variation, while observed, may be considered insignificant due to its minimal magnitude. Conversely, the i_{corr} value experiences a notable increase, reaching 0.7071 mA/cm², indicating a higher corrosion rate than in stagnant conditions. This rise in i_{corr} indicates an accelerated anodic dissolution and cathodic reaction, further substantiating the intensified corrosion process. Consequently, the corrosion rate escalates to 7.301 x 10⁻³ mm/year, signifying a substantially higher level of corrosion when compared to stagnant conditions.

The E_{corr} further decreases at a 6 km/h velocity, and the i_{corr} increases to 0.8289 mA/cm², indicating a higher corrosion rate compared to the previous velocities. The β_a and β_c continue to increase, reflecting an intensified acceleration of anodic dissolution and cathodic reactions. Consequently, the corrosion rate rises further to 8.559 x 10⁻³ mm/year, indicating an elevated level of corrosion. Notably, E_{corr} at 9 km/h becomes most negative at -627.21 mV vs SCE, indicating an increased susceptibility to corrosion. The i_{corr} significantly increases to 1.1543 mA/cm², surpassing the corrosion rates observed at all previous velocities. The β_a and β_c exhibit substantial increases, indicating a significant acceleration of both anodic dissolution and cathodic reactions. Remarkably, the corrosion rate reaches its maximum value of 11.918 x 10⁻³ mm/year at this velocity, representing the highest level of corrosion observed.

The E_{corr} returns to a similar range as the stagnant and lower velocities at a 12 km/h velocity, measuring -618.93 mV vs SCE. The i_{corr} decreases significantly to 1.0095 mA/cm², suggesting a lower corrosion rate compared to

the previous velocity. The β_a and β_c decrease, indicating a deceleration of anodic dissolution and cathodic reactions. Consequently, the corrosion rate decreases to 10.423 x 10⁻³ mm/year, signifying a lower corrosion level than the previous velocity. The results recorded in this study align with claims that increasing velocity increases the corrosion rate, as reported by Hasan & Abdul-Jabbar [8] and Ferry et al. [9].

The Tafel data analysis (Table 3) reveals a clear trend: as the flow velocity increases from 0 to 6 km/h, the corrosion rate rises, indicating a more aggressive environment due to the increased transport of corrosive substances. Higher flow velocities enable the removal of reaction products from the metal surface, promoting fresh exposure to the corrosive environment. An interesting observation is that the corrosion rate initially increases with flow velocity, peaking at 9 km/h before decreasing at 12 km/h. This suggests pseudo-passivation, where a temporary protective oxide layer forms on the metal surface, reducing corrosion. Factors like increased dissolved oxygen and mass transport at higher flow velocities contribute to this pseudo-passivation.

Changes in flow velocity can alter the corrosion mechanism. At lower velocities, corrosion is predominantly controlled by chemical reactions at the metal-electrolyte interface, while at higher velocities, mass transport becomes dominant, affecting oxide layer formation. This aligns with discussions in electrochemical polarization studies, such as the Tafel plot analysis by Zeng et al. [10], highlighting the influence of factors like dissolved oxygen.

The temporary protective oxide layer at higher flow velocities mitigates corrosion by acting as a barrier between the metal and the corrosive environment. It can even self-heal, repairing localized defects caused by corrosion processes. Note that factors like electrolyte composition, temperature, and impurities can influence the corrosion rate with increasing flow velocities. Furthermore, the pseudo-passivation phenomenon observed at a specific flow velocity may not be universally applicable and can vary based on material, electrolyte, and environmental conditions. Further research is needed to fully understand these mechanisms and optimize corrosion prevention strategies for mild steel in NaCl solutions under varying hydrodynamic conditions.

3.3 Polarisation of Studied Steel in Different Soil Resistivities

Figure 3 displays the Tafel plot, depicting the electrochemical behaviour of mild steel samples submerged in different soil resistivities, spanning from very mildly corrosive to extremely corrosive

environments. A consistent and similar trend emerges when scrutinising the Tafel plot curves in Figure 3. The electrochemical data derived from the Tafel plot for each flow velocity are summarised in Table 5. However, upon closer inspection, notable discrepancies surface in the corrosion rate and polarisation data associated with each resistivity.

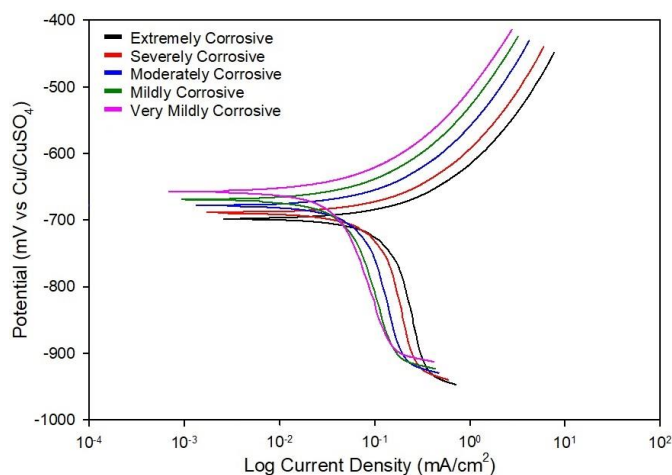


Figure 3. Tafel plot of mild steel in soil medium at different soil resistivity categories.

Table 5 Tafel plot data for AISI 1006 steel in soil medium at different soil resistivity

Tafel Parameter	Soil Corrosiveness				
	Very Mildly Corrosive	Mildly Corrosive	Moderately Corrosive	Severely Corrosive	Extremely Corrosive
E_{corr} (mV vs Cu/CuSO ₄)	-657.17	-669.10	-677.41	-688.51	-698.07
Anodic Slope (mV/decade)	57.467	59.532	62.325	65.716	66.636
Cathodic Slope (mV/decade)	-183.81	-189.235	-196.772	-209.532	-220.338
i_{corr} (mA/cm ²)	0.0273	0.0432	0.0544	0.0612	0.0778
Corrosion Rate (x10 ⁻³ mm/year)	2.818	4.461	5.617	6.319	8.033

The corrosion behaviour in a very mildly corrosive soil medium suggests a particular susceptibility to corrosion. However, compared to a NaCl solution, the steel in the very mildly corrosive soil exhibits a relatively positive E_{corr} of -657.17 mV vs Cu/CuSO₄. The β_a is less steep at 57.467 mV/decade than the β_c at -183.814 mV/decade. The i_{corr} is measured at 0.0273 mA/cm², resulting in an overall corrosion rate of 2.818 x 10⁻⁴ mm/year, indicating a relatively low level of corrosion in a very mildly corrosive environment.

As the level of corrosiveness increases, notable and substantial changes manifest in the electrochemical parameters obtained from the Tafel plot data. In a mildly corrosive soil medium, the E_{corr} exhibits a slight shift towards a less positive value, measuring -669.10 mV vs Cu/CuSO₄. This shift implies an elevated susceptibility to corrosion compared to the very mildly corrosive medium. Correspondingly, the i_{corr} experiences an increase, measuring 0.0432 mA/cm², signifying a higher corrosion

rate in this environment. Furthermore, both the β_a and β_c slopes show an increase, indicating an intensified acceleration of anodic dissolution and cathodic reactions within the medium. Consequently, the overall corrosion rate rises to 4.461 x 10⁻⁴ mm/year, indicating higher corrosion activity. The notable shifts in electrochemical parameters when moving from a very mildly corrosive to a mildly corrosive environment emphasise how different levels of corrosiveness affect the corrosion characteristics of mild steel.

In a moderately corrosive soil medium, there is a further decrease in the E_{corr} , which measures -677.41 mV vs Cu/CuSO₄. This decrease highlights an even higher susceptibility to corrosion compared to the previous corrosiveness levels. Simultaneously, the i_{corr} increases to 0.0544 mA/cm², indicating a higher corrosion rate in this environment. Moreover, both the β_a and β_c slopes continue to exhibit increases, signifying an intensified acceleration of anodic dissolution and cathodic reactions within the

medium. As a result, the corrosion rate rises even further, reaching a value of 5.617×10^{-4} mm/year. This value signifies an elevated level of corrosion activity compared to the previous levels of corrosiveness. The trend continues in a severely corrosive soil medium as the E_{corr} becomes less negative, measuring -688.51 mV vs Cu/CuSO₄. This observation suggests that mild steel is even more prone to corrosion as the level of corrosiveness increases. Notably, the i_{corr} experiences a significant increase, measuring 0.0612 mA/cm², indicating a higher corrosion rate than the previous corrosiveness levels.

Additionally, both the β_a and β_c slopes exhibit substantial increases, underlining a significant acceleration of both anodic dissolution and cathodic reactions within the severely corrosive medium. Remarkably, the corrosion rate reaches its maximum value of 6.319×10^{-4} mm/year in this environment, representing the highest level of corrosion observed among the tested conditions. These observations emphasise the profound impact of varying corrosiveness levels on the corrosion behaviour of mild steel, with severe corrosion environments leading to the most substantial corrosion rates and accelerated electrochemical reactions.

The decrease in resistivity significantly impacts the electrochemical parameters derived from the Tafel curve, ultimately influencing the corrosion behaviour of mild steel. In an extremely corrosive medium, the E_{corr} shifts to the most negative potential of -698.07 mV vs Cu/CuSO₄, signifying an increased susceptibility to corrosion compared to a very mildly corrosive soil medium. Simultaneously, the i_{corr} increases to 0.0778 mA/cm², indicating a higher corrosion rate within the extremely corrosive soil environment. Furthermore, both the β_a and β_c slopes experience increases, suggesting an acceleration of anodic dissolution and cathodic reactions in this highly corrosive setting. Consequently, the corrosion rate reaches 8.033×10^{-4} mm/year, signifying a higher corrosion level than the very mildly corrosive soil. These observed changes in the electrochemical parameters underscore the substantial impact of decreasing resistivity on corrosion behaviour. Soils with lower resistivity are classified as highly corrosive due to their conducive environment, which facilitates the flow of electrical current. This heightened conductivity creates favourable conditions for the electrochemical reactions integral to corrosion processes.

Moreover, lower resistivity soils typically exhibit higher moisture levels, which, in turn, increase the availability of essential water and electrolytes necessary for corrosion reactions. In concurrence with Bai *et al.*, the findings support the notion that enhanced soil conductivity accelerates electrochemical reactions, emphasising the intricate relationship between soil resistivity, moisture content, and corrosion behaviour [24]. This reinforces the importance of targeted corrosion prevention measures, particularly in low-resistivity environments, for safeguarding infrastructure and assets effectively.

Conversely, as noted by Melchers & Wells [18], when soil resistivity increases, it obstructs electrical current flow, restricting the movement of electrons and ions. This impediment hinders the electrochemical reactions critical to corrosion, ultimately reducing the corrosion rate due to heightened soil resistance. The results of this study align with Melchers & Wells [18], where the corrosion rate is found to be directly influenced by the resistivity of the soil. Lower resistivity soils, characterised as extremely corrosive, promote faster corrosion reactions due to their higher conductivity, increased moisture content, and facilitated ion and electron flow. On the other hand, higher resistivity soils inhibit corrosion by impeding the movement of electrons and ions, resulting in a reduced corrosion rate.

Soil resistivity stands as a pivotal factor in governing the intricate dance of electrons and ions in the corrosion process. It plays a central role in orchestrating the movement of these charged particles within the soil environment. The level of soil resistivity acts as a conductor, dictating the ease with which electrons and ions traverse through the earth. When the soil exhibits low resistivity, it becomes an accommodating pathway for the flow of electrical current. This characteristic translates into a phenomenon where electrons and ions experience heightened mobility.

In such electrically conducive environments, both the anodic dissolution (corrosion) and the cathodic reactions occur with great alacrity. The propensity for electrons to embark on their journey from the anode (where corrosion transpires) to the cathode (the site of reduction reactions) becomes pronounced. Similarly, ions, which are pivotal players in the corrosion dance, move swiftly, facilitating the critical electrochemical reactions integral to the corrosion process. As a consequence of these conditions, corrosion rates surge to higher levels.

Conversely, when soil resistivity ascends to higher levels, it acts as a constriction in the path of electrons and ions. This increased resistance impedes the free movement of these charged particles. Electrons, the electrical charge carriers, find their passage hindered, leading to a deceleration in their journey from the anodic sites where metal dissolution commences to the cathodic regions where reduction reactions occur. This impedance to the flow of electrons profoundly affects the corrosion process.

Simultaneously, ions, responsible for mediating the corrosion reactions, confront restrictions in their movement. Their reduced mobility slows down the electrochemical reactions taking place on the metal surface. As a result, both the anodic dissolution and cathodic reactions proceed at a more lethargic pace. This slowing of essential electrochemical reactions directly corresponds to a decreased corrosion rate.

The movement of electrons and ions in the soil matrix thus stands as a fundamental and non-negotiable aspect of corrosion processes. Soil resistivity, serving as the maestro in this symphony, orchestrates the rate and intensity of corrosion. It acts as a switch, controlling the tempo at which the corrosion reactions play out. This pivotal role of soil resistivity in influencing corrosion rates emphasises the importance of understanding and managing this factor in the context of corrosion prevention and mitigation. Corrosion experts and engineers tasked with safeguarding critical infrastructure must consider soil resistivity as a chief determinant in the corrosion equation. By doing so, they can effectively tailor corrosion control strategies to specific environmental conditions, ensuring the longevity and reliability of vital structures and assets.

The intricate interplay of pH levels within diverse soil environments adds a layer of complexity to the corrosion behaviour of mild steel. One of the pivotal factors contributing to this complexity is the pH of the soil, a parameter characterising its acidity or alkalinity. In soil corrosion studies, pH values serve as a critical indicator, and they typically fall within a range of acidic to slightly alkaline conditions, maintaining a pH below 7.

In environments characterised by acidic soils, where pH values typically register below the neutral point of 7, a particular set of electrochemical processes comes into play. The hallmark of acidic conditions is the presence of free hydrogen ions (H^+), which significantly impact the corrosion dynamics. These hydrogen ions are integral to the corrosion process as they facilitate the formation of metal ions, such as Fe^{2+} , during the anodic dissolution of metals.

This phenomenon within acidic media is of paramount importance in understanding corrosion behaviour. The acidic milieu accelerates the corrosion process by promoting the formation of metal ions, which are critical intermediaries in the corrosion mechanism. Consequently, metals, particularly mild steel, are more prone to anodic dissolution in these conditions. The increased presence of free hydrogen ions expedites the corrosion reactions, ultimately leading to a heightened corrosion rate. This observation underscores the pivotal role of soil pH in influencing the corrosion behaviour of mild steel, particularly in environments with a tendency towards acidity.

Notably, the prevalent pH values within these soil environments tend to be below the neutral point of 7, emphasising the prevalence of mildly acidic to near-neutral conditions. This range encompasses the most common scenarios encountered in soil corrosion studies and practical applications, making it crucial for corrosion experts and engineers to consider the implications of these conditions. The ability to decipher the corrosion mechanisms that unfold in mildly acidic to neutral soils is of utmost significance in material selection and the development of effective corrosion mitigation strategies.

3.4 Steel Corrosion & Environmental Factors

The corrosion behaviour of AISI 1006 steel was comprehensively investigated across various environmental conditions. The corrosion behaviour in stagnant water typically tends to be slower than in flowing environments. Stagnation limits the availability of oxygen, which is essential for many corrosion processes. As a result, AISI 1006 steel experiences minimal corrosion under these conditions. When subjected to different flow velocities, corrosion rates increased with higher velocities, indicating that increased flow promoted faster corrosion reactions by facilitating the transport of corrosive substances. This increased corrosion rate in flowing environments like a 3.5% NaCl (sodium chloride) solution is often associated with a higher corrosion rate due to increase dissolved O_2 and improved mass transfer, as observed. The corrosiveness of soil can vary based on factors like soil resistivity, pH, and the presence of corrosive substances.

Soil resistivity played a significant role, with lower resistivity environments encouraging higher corrosion rates by enhancing electron and ion mobility, while higher resistivity soils led to reduced corrosion. The influence of soil pH was evident, particularly in mildly acidic settings, where the presence of free hydrogen ions accelerated the corrosion process. These findings provide valuable insights for material selection and corrosion mitigation strategies in practical applications across diverse environmental conditions. The Tafel extrapolation method was employed to confirm the minimal corrosion experienced by AISI 1006 steel in stagnant water, underlining the importance of considering specific environmental conditions when selecting materials and implementing corrosion prevention measures.

A comprehensive understanding of these intricate interrelationships is invaluable for professionals engaged in protecting critical infrastructure against the multifaceted challenges posed by corrosion. It empowers them to make informed decisions regarding material selection, corrosion control strategies, and preserving vital structures and assets in varying soil environments. The complexity of these processes underscores the need for a nuanced approach to corrosion management, with due consideration of the specific environmental conditions and their influence on corrosion behaviour.

4. CONCLUSIONS

This study explores the corrosion behaviour of AISI 1006 steel under diverse environmental conditions. It encompasses stagnant and flowing 3.5% NaCl solutions, with flow velocities ranging from 0 to 12 km/h, and considers soil corrosiveness determined by soil resistivity per ASTM G187-12 standards. In stagnant 3.5% NaCl solutions, corrosion remains minimal due to limited oxygen availability in this environment. In flowing 3.5% NaCl solutions, a noteworthy pattern of corrosion rates is

observed, peaking at 9 km/h and subsequently decreasing at 12 km/h. This trend may be attributed to the potential formation of a protective oxide layer, likely due to increased dissolved oxygen and mass transport at higher flow velocities. The soil's corrosiveness significantly influences corrosion rates, with lower-resistivity soils accelerating the process. Therefore, this study enhances the understanding of AISI 1006 steel's corrosion behaviour in various settings and soil conditions.

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