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# EXPLORING THE CORROSION DYNAMICS OF MILD STEEL IN AQUEOUS HYDROCHLORIC ACID MEDIUM

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## *Abstract*

*The current study investigates the corrosion behaviour and kinetics of mild steel in aqueous hydrochloric acid solutions of concentrations of 1M, 2M, 3M, and 4M as a corrosive media. The experiments were conducted at room temperature (25 ± 0.5°C) using the weight loss measurement technique. Plots of metal loss per unit area and corrosion rate in mils per year (mpy) against immersion time interval ranging from 2 hrs to 14 hrs were used to demonstrate the corrosion behaviour of mild steel. It has been observed that, the corrosion kinetics of mild steel in varying concentrations of hydrochloric acid followed the first-order kinetics. The corrosion rate, rate constant, and half-life of mild steel in hydrochloric acid were found to be 11342.19 mpy, 0.0248 hr*$^{-1}$*, and 37.8640 hrs, respectively.*

**Keywords:** *mild steel, corrosion, weight loss, hydrochloric acid, kinetics*

## 1. Introduction

Corrosion refers to the chemical process that leads to the degradation of metal, resulting in the formation of more stable metal compounds through reactions with the surrounding environment [1]. Mild steel is a type of carbon steel with a low amount of carbon. The chemical composition of mild steel is Fe-99.30%, C-0.076%, Si-0.026%, Mn-0.192%, P-0.012%, Cr-0.050%, Ni-0.050%, Al-0.023%, and Cu-0.135% and having density 7.87 g/cm$^3$ [2]. The factors contributing to mild steel corrosion include exposure to atmospheric elements, humidity, industrial gases, alkalis, acids, salty and fresh water, as well as various organic and inorganic components [3]. Due to its favourable mechanical properties and relatively low cost, mild steel is widely used in construction and in sectors such as petroleum, nuclear, marine, lignite, and agriculture. Consequently, corrosion of mild steel has attracted considerable attention from researchers. Studies indicate that the degree of corrosion of mild steel is influenced by factors such as the concentration of the corrosive medium, the duration of exposure, and the prevailing temperature conditions [4]. Hydrochloric acid, a key chemical in industries like fertilizer production, mineral processing, oil refining, and chemical synthesis, is also an essential component in acidic drain cleaners. The corrosion of mild steel in hydrochloric acid has been of significant interest, especially in the oil and gas sector. Corrosion is a complex process, leading to scientific research in the field, which integrates both fundamental sciences and engineering [5]. One of the primary methods for monitoring corrosion is weight loss, where the material being studied is exposed to the corrosive environment for a specific period. At regular intervals, the specimen is removed and weighed before and after exposure to determine the weight loss, which is then used to calculate the corrosion rate. The study of corrosion kinetics can help to estimate the lifespan of materials used in construction and industrial applications. Literature survey reveals that, the weight loss method has been employed to assess the corrosion behaviour of metals in different environments. For instance, Wallinder and Hannoyer explored the atmospheric corrosion of various metals [6-7], while Akuso and colleagues investigated the corrosion kinetics of N-80 oil well tubular steel in 15% hydrochloric acid solution, utilizing Ficus abutilifolia plant extract for inhibition [8]. Similarly, Quraishi and others examined a green approach to corrosion inhibition using Murraya koenigii leaf extract in hydrochloric acid solutions [9]. Additionally, Patil and his team studied the corrosion kinetics of iron in both acidic and basic media [10]. Gregory and Igho (2003) studied the inhibitive action of Vernonia amygdalina on the corrosion of aluminium alloys in acidic media [11]. This study aims to investigate the behaviour and corrosion mechanism of mild steel in aqueous hydrochloric acid solutions, ranging from 1M to 4M, at room temperature (25 ± 0.5°C).

## 2. Material and Method

### 2.1 Material

Analytical grade hydrochloric acid, acetone, and ethyl alcohol were sourced from SD fine chemicals company limited. Hydrochloric acid solutions of concentrations 1M, 2M, 3M, and 4M were prepared in double-distilled water. The study utilized a desiccator containing anhydrous calcium chloride, along with a digital analytical balance with a precision of 1 mg. The 3 mm thick rectangular mild steel strip was purchased from a local hardware store in Nagpur. This strip was then cut into four pieces referred as coupons of the desired size and were labelled as coupon-1, 2, 3, and 4. The coupons were polished using emery paper of various grades (400, 600, 1000, and 1500) to eliminate surface impurities. Prior to using the specimens for gravimetric analysis, each coupon was thoroughly washed with tap water, cleaned with ethyl alcohol, rinsed with double-distilled water, degreased in acetone, and dried in a desiccator. The dimensions of each coupon were measured using a graduated centimetre scale, and the weight was recorded using a digital balance with 1 mg accuracy. The total surface area and weight of each coupon were calculated and are presented in Table 1.

**Table 1:** Dimensions, surface area and weight of coupons

| Coupon No. | Length (cm) | Breath (cm) | Width (cm) | Total surface area ($cm^2$) | Weight (g) |
|---|---|---|---|---|---|
| 1 | 2.5 | 2.5 | 0.3 | 15.5 | 16.6421 |
| 2 | 2.5 | 2.5 | 0.3 | 15.5 | 16.6439 |
| 3 | 2.4 | 2.5 | 0.3 | 14.94 | 16.1325 |
| 4 | 2.4 | 2.5 | 0.3 | 14.94 | 16.1332 |

## 2.2 Method

Weight loss method was employed for the determination of metal loss and corrosion rate [12]. The mild steel coupons, labelled as 1, 2, 3, and 4, were immersed in corrosion medium of hydrochloric acid test solutions of concentrations 1M, 2M, 3M, and 4M, respectively. Each coupon was suspended by a thread at a right angle to the beaker, ensuring that the edges of the coupons did not come into contact with the inner walls of the beaker. After each 2-hour interval (up to 14 hours), the specimens were removed from the test solutions and first rinsed with tap water. This was followed by washing with distilled water, cleaning with a fine cloth, and rinsing again with distilled water. The coupons were then cleaned with acetone and dried with hot air. Finally, the specimens were weighed using an analytical balance and the weight differences at each time interval was recorded. Throughout the experiment, the hydrochloric acid solution levels in all samples were maintained by adding distilled water to ensure consistent concentrations during immersion. All experiments were conducted in unstirred solutions. The weight loss after each regular interval of 2 hrs is converted to metal loss (ML) and corrosion rate (CR) using the following equations,

$$Metal\ Loss\ (ML) = \frac{\Delta W * K}{\rho * A}\ mils \tag{1}$$

$$Corrosion\ Rate\ (CR) = \frac{\Delta W * K}{\rho * A * T}\ mils/year\ (mpy) \tag{2}$$

Where,

$\Delta W$ = Weight loss (g) at each time interval.

$\rho$ = Density ($g/cm^3$) of mild steel sample ($\rho = 7.87\ g/cm^3$)

A = Exposed surface area ($cm^2$) of mild steel coupon

T = Time interval (hrs)

K = Constant factor (The value of depends on the desired unit of ML and CR)

The value of K for ML (mils) is 393.7 and for CR (mpy) is $3.45 \times 10^6$

The specific reaction rate were calculated from the initial weight of the mild steel specimen coupons and their weight at various time intervals in the hydrochloric acid corroding medium. The calculation was done using the first-order rate expression, as shown in Equation 3, for each time interval. Additionally, the half-life period for each value of the rate constant was determined using Equation 4.

$$Rate\ Constant\ (K) = \frac{2.303}{T} Log \frac{W\ (initial)}{W(at\ time\ T)} \qquad (3)$$

$$Half\ life\ period = \frac{0.693}{K} \qquad (4)$$

## 3. Result and Discussion

### 3.1 Mild steel weight loss against immersion time

During the corrosion experiments, a continuous decrease in the weight of the mild steel coupons was observed with an increase in immersion time in the corrosive medium. The plot showing the relationship between the weights of mild steel coupons and varying immersion time intervals is presented in figure 1 for different molar concentrations of the corrosive acid medium. As the mild steel specimens reacted with the hydrochloric acid, hydrogen gas ($H_2$) was liberated. From Fig. 1, it can be concluded that as the acid concentration increased, the slope of the curve also increased, indicating a higher rate of corrosion. However, for 3M and 4M HCl concentration, the mild steel coupons does not show the noticeable weight loss between 8 and 14 hours of immersion. This can be attributed to the formation of a protective oxide layer, likely $Fe_2O_3$, at high acid concentrations, which passivates further corrosion [13]. On the other hand, at lower concentrations and shorter immersion times, the continuous reduction in weight of the coupons indicates an accelerated dissolution of the mild steel, as no insoluble protective film is formed on the metal surface to protect it from further corrosion. The weight loss calculated from the initial weights and weight after different immersion time of mild steel coupons in different concentrations of corroding medium is given in table 2.

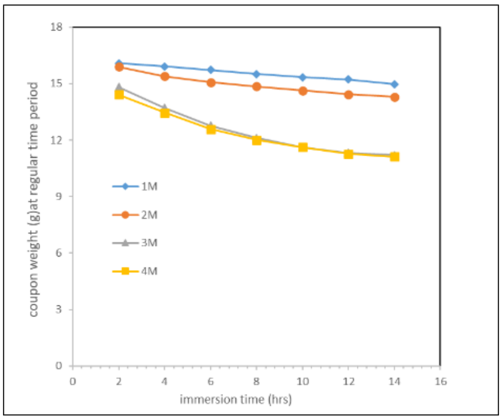

**Fig.1:** Plot of mild steel weight against immersion time

**Table 2:** weight loss at regular immersion time intervals in different HCl concentrations

| HCl concentration | weight loss (g) at regular immersion time intervals | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2 hrs | 4 hrs | 6 hrs | 8 hrs | 10 hrs | 12 hrs | 14 hrs |
| 1M | 0.5602 | 0.7342 | 0.9183 | 1.1332 | 1.3129 | 1.4211 | 1.6771 |
| 2M | 0.7512 | 1.2512 | 1.5758 | 1.7951 | 2.0143 | 2.2121 | 2.3518 |
| 3M | 1.3146 | 2.4316 | 3.3616 | 4.0241 | 4.5312 | 4.8126 | 4.9331 |
| 4M | 1.7216 | 2.6781 | 3.5616 | 4.1213 | 4.5117 | 4.8658 | 5.0234 |

### 3.2 Metal loss and corrosion rate

The metal loss (ML) in mils and the corrosion rate (CR) in mils per year (mpy) for mild steel coupons in various molar concentrations of hydrochloric acid were calculated using Equations 1 and 2, respectively, at room temperature (25 ± 0.5°C). These calculations were made for different immersion time intervals for 2 hrs, 4 hrs, 6 hrs, 8 hrs, 10 hrs, 12 hrs, and 14 hrs. The results are presented in Table 3 and 4 for metal loss and corrosion rate respectively. The corresponding plots of metal loss (ML) and corrosion rate (CR) as functions of immersion time (hrs) are shown in figure 2 and figure 3 respectively. The average corrosion rate was determined to be 11342.19 mpy.

The results obtained from the study revealed that, both metal loss (ML) and corrosion rates (CR) increased with the concentration of the corrosive medium, reaching their maximum values at the highest concentration of 4M HCl except for the immersion time of 8 hrs to 14 hrs for which maximum values were obtained at 3M HCl. As the concentration of hydrogen ions increases, the pH decreases, which leads to an increase in the corrosion rate. Despite this, the metal loss for all concentrations of the corrosive medium tended to reach a saturation point at higher immersion times. The decrease in corrosion rate with increased immersion time could be due to the reduced solubility of the electrolyte as it gradually becomes saturated with the corrosion product, or it may indicate the formation of a surface film that slows the corrosion of mild steel. This observation is consistent with findings from other researchers [14]. Additionally, a rapid decrease in corrosion rate during the initial phase of corrosion was observed with increased immersion time in 4M HCl compared to other concentrations (fig.3) suggesting that most of the corrosion of mild steel occurs at a faster rate during the initial immersion hours in 4M HCl. In contrast, corrosion in 1M, 2M, and 3M HCl solutions occurred at a nearly uniform but gradually decreasing rate. Furthermore, the reduction in corrosion rate may be attributed to a decrease in the mobility of ions within the solution. The experimental results are illustrated in the plot of corrosion rate (mpy) versus HCl concentration in figure 4. From this it is observed that the corrosion rate increases with concentration of corrosion medium however it decreases with the time of immersion.

**Table 3:** metal loss (mils) at regular immersion time intervals in different HCl concentrations

| HCl concentration | metal loss/area (mils) | | | | | | |
|---|---|---|---|---|---|---|---|
| | **2 hrs** | **4 hrs** | **6 hrs** | **8 hrs** | **10 hrs** | **12 hrs** | **14 hrs** |
| 1M | 1.8758 | 2.4584 | 3.0749 | 3.7944 | 4.3961 | 4.7584 | 5.6156 |
| 2M | 2.7192 | 4.5291 | 5.7041 | 6.4979 | 7.2913 | 8.0073 | 8.5130 |
| 3M | 4.7586 | 8.8019 | 12.1683 | 14.5664 | 16.4020 | 17.4206 | 17.8568 |
| 4M | 5.9891 | 9.3166 | 12.3902 | 14.3373 | 15.6954 | 16.9272 | 17.4755 |

**Table 4:** corrosion rate (mpy) at regular immersion time intervals in different HCl solutions

| HCl concentration | corrosion rate (mpy) | | | | | | |
|---|---|---|---|---|---|---|---|
| | **2 hrs** | **4 hrs** | **6 hrs** | **8 hrs** | **10 hrs** | **12 hrs** | **14 hrs** |
| 1M | 8218.77 | 5385.77 | 4490.84 | 4156.33 | 3852.35 | 3474.86 | 3514.99 |
| 2M | 11914.12 | 9922.09 | 8330.79 | 7117.62 | 6389.41 | 5847.36 | 5328.55 |
| 3M | 20849.71 | 19282.73 | 17771.79 | 15955.67 | 14373.07 | 12721.40 | 11177.08 |
| 4M | 26241.44 | 20410.44 | 18095.87 | 15704.70 | 13753.89 | 12361.14 | 10938.44 |
| mean | 16806.01 | 13750.26 | 12172.32 | 10733.58 | 9592.18 | 8601.19 | 7739.76 |
| | **11342.19** | | | | | | |

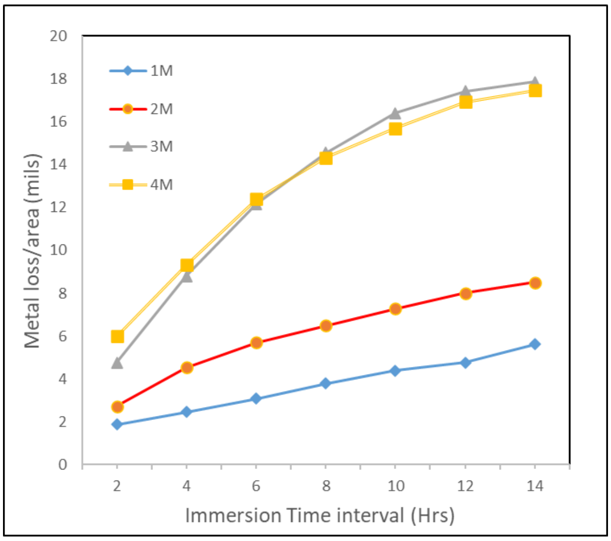

**Fig.2:** Plot of metal loss (mils) against immersion time

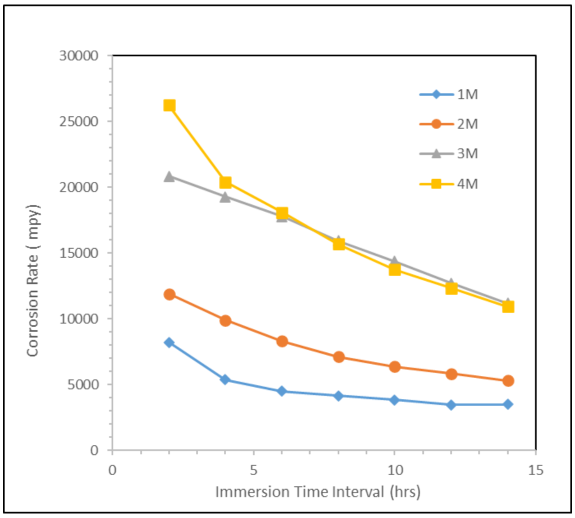

**Fig.3:** Plot of corrosion rate (mpy) against immersion time

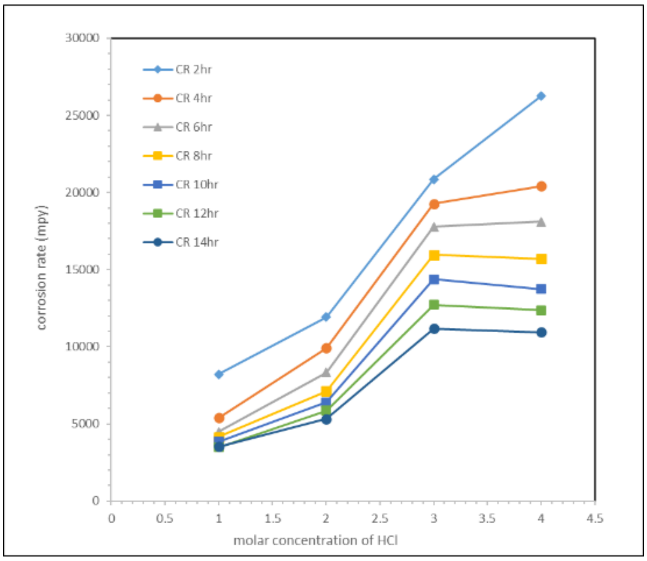

**Fig.4:** Plot of corrosion rate (mpy) against molar concentration of HCl

### 3.3 Corrosion Kinetics

The corrosion of mild steel in aqueous solutions of HCl corrosion medium with concentrations of 1M, 2M, 3M, and 4M was examined to determine if the process follows first-order kinetics. This was achieved using equation 3, and the half-life period of mild steel coupons was calculated using equation 4. The resulting values for the rate constant and half-life period are presented in Table 5. It was found that, the corrosion process in the HCl solution followed first-order kinetics with mean rate constant of 0.0248 $hr^{-1}$ and mean half-life period of 37.86 hrs. This was confirmed by the linear relationship observed in the plot of Log ($Wi/W_t$) versus immersion time, which is shown in figure 5.

**Table 5:** mean corrosion rate constant & mean half-life period of mild steel coupons in aqueous HCl corroding medium

| Time interval (hrs) | corrosion rate constant, K ($hr^{-1}$) | | | | mean rate constant ($hr^{-1}$) | mean half-life period (hrs) |
|---|---|---|---|---|---|---|
| | 1M | 2M | 3M | 4M | | |
| 2 | 0.0171 | 0.0231 | 0.0425 | 0.0564 | **0.0248** | **37.8640** |
| 4 | 0.0113 | 0.0195 | 0.0409 | 0.0454 | | |
| 6 | 0.0095 | 0.0166 | 0.0390 | 0.0416 | | |
| 8 | 0.0088 | 0.0143 | 0.0359 | 0.0369 | | |
| 10 | 0.0082 | 0.0129 | 0.0330 | 0.0328 | | |
| 12 | 0.0074 | 0.0119 | 0.0295 | 0.0299 | | |
| 14 | 0.0076 | 0.0109 | 0.0261 | 0.0267 | | |

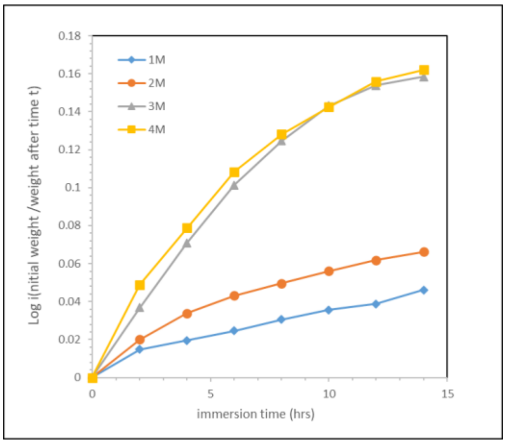

**Fig.5:** Plot of Log ($W_i/W_t$) against immersion time

## 4. Conclusion

The findings of this study provide a comprehensive understanding of the corrosion behaviour of mild steel in aqueous HCl solutions of varying concentrations. The experimental results demonstrated a continuous decrease in the weight of mild steel coupons as the immersion time increased, indicating ongoing corrosion over time. This suggests that, the steel undergoes gradual deterioration as it interacts with the acidic environment. The corrosion behaviour was further found to be highly dependent on the concentration of the HCl solution. As the concentration of the corrosive medium increased, the corrosion rate initially high but then showed a decrease when the steel was immersed in higher concentrations of HCl. This suggests a complex interaction where, at higher acid concentrations, certain protective or inhibitive factors may play a role in reducing the corrosion rate. Furthermore, the corrosion process of mild steel in these aqueous HCl solutions was shown to follow first-order kinetics, as evidenced by the linear relationship between the logarithm of the ratio of initial weight ($W_i$) to the final weight ($W_t$) and immersion time. This indicates that the rate of corrosion is proportional to the concentration of the corrosive species in the solution. Together, these results offer valuable insight into how immersion time, acid concentration, and kinetic principles interact to affect the corrosion of mild steel in acidic environments.

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## Conflict of interest

The authors have no conflict of interest regarding the publication of this research paper.

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