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Analyzing the Effect of Environments on the Corrosion Behavior of Grade (B) A372 Mild Steel

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ABSTRACT

Corrosion testing aims to evaluate how materials behave under simulated service conditions, helping to confirm that they will achieve their expected design lifespan. This research aims to explore the impact of environmental conditions on the corrosion behavior of GRADE B A372 mild steel. The mild steel was commercially obtained and cut into pieces of the same length called coupons. The initial weight of the coupons was measured and recorded. The coupons were then exposed to the specified corrosive environments for a predetermined duration of 21 days. The corrosion rate and weight loss of the samples were analyzed. An observation of the surface morphology of the corroded samples was conducted. The result obtained revealed that the samples exposed to atmospheric environment corroded very slowly within 21 days duration. The corrosion rate of the samples exposed in Tiga dam environment increases with the increase in exposure time. The corrosion rate of the samples exposed to the underground soil of KUST WUDIL exhibited a slower rate during the first week compared to the rates observed in the second and third weeks. The exposed samples reveal a significant corrosion rate for the second and third weeks of exposure. However, the (SEM) images show the presence of some lamellar shaped phases in samples exposed to atmosphere, larger needle shaped phases in samples exposed to the Tiga dam and the presence of some smaller needle shaped phases in the buried samples. It was determined that the corrosion rates of the mild steel samples had been examined. Notably, the corrosion rates among the different specimens exhibited significant variation according to the following trend: underground (soil), Tiga dam water and atmosphere. The findings imply that mild steel could be more suitable for use under atmospheric environment.

Keywords: Analyzing, Environment effect, Corrosion behavior, Grade B A372 and Mild steel.

INTRODUCTION

Corrosion remains a costly issue globally, contributing to financial impacts that equate to about 3.4% of the world's GDP, or around $2.5 trillion annually. These costs encompass not only immediate expenses like repairs and replacements but also indirect effects, including lost productivity from operational shutdowns. According to NACE International's image study, enhancing corrosion management strategies could cut these expenses by as much as 15-35%, potentially saving between $375 billion and $875 billion across various industries (NACE, 2016).

Recent research highlights the significance of evaluating metal performance through their compositions, structures, and the thermal and mechanical treatments they undergo, as these factors are vital in determining how metals behave in high-performance scenarios.

A comprehensive understanding of intrinsic properties, such as thermal stability and tensile strength, enables engineers to forecast how metals will perform under various conditions. Studies have shown that employing advanced

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thermomechanical treatments and carefully tailored alloy compositions can enhance metal characteristics, which is particularly important in sectors like aerospace, automotive, and electronics. This accumulating evidence underscores the value of thorough assessments to improve the predictability and durability of metals in industrial applications (Baigonakova et al., 2022; Metals, 2023)

Mild steel constitutes about 85% of global annual steel production and is recognized as the most utilized engineering material. Despite its susceptibility to corrosion, it finds wide-ranging applications in numerous sectors, such as marine engineering, nuclear and fossil fuel power plants, transportation, and chemical processing. Its cost-effectiveness and versatility render it particularly advantageous in scenarios where financial efficiency is critical (The Piping Mart, n.d.; Industrial Metal Service, 2021). Furthermore, mild steel's ductility and ease of machining promote straightforward fabrication and welding, establishing it as a favored option for structural components and equipment in the construction and manufacturing industries (Industrial Metal Service, 2021).

The economic impact of metallic corrosion is estimated to reach hundreds of millions of dollars (or euros) annually, as mild steels represent the largest category of alloys utilized in industry, both in terms of weight and cost. Therefore, corrosion in carbon steels presents considerable practical challenges. Addressing this problem is critical due to the widespread use of these materials across various applications, where their degradation can lead to substantial financial losses and operational disruptions (NACE, 2016; The Piping Mart, n.d.). This necessity has led to the development of entire industries focused on creating protective solutions for iron and steel materials. The importance of safeguarding these metals against corrosion is underscored by the economic and operational implications associated with their degradation (NACE, 2016; The Piping Mart, n.d.). Various protective systems, including coatings and cathodic protection, are essential for enhancing the longevity and performance of these widely used materials.

Corrosion is such a multifaceted phenomenon; it is useful to attempt to categorize various types. This is usually done on an environmental basis. Numerous studies have reported that exposure to the environment during service period affects the corrosion behavior of mild steel (R. E. Lowental, 2004). However, this is why; the most frequently used environments which are underground soil, water, and atmospheric were investigated. A372 Mild Steel is an extensively used engineering material celebrated for its adaptability and cost-effectiveness in numerous sectors, including construction and manufacturing. Nevertheless, understanding its corrosion behavior is critical, as mild steel is notably prone to various corrosive conditions. Investigating the corrosive characteristics of A372 Mild Steel is essential due to its widespread application, making effective corrosion management crucial for maintaining the integrity and safety of structures that utilize this alloy (Davis, 2021; Tiwari et al., 2022).

The corrosion susceptibility of A372 Mild Steel is influenced by multiple factors, such as environmental conditions, humidity, and exposure to electrolytes. Research indicates that under humid conditions, thin electrolyte films can form on metal surfaces, triggering electrochemical corrosion processes. Studies show that critical humidity levels can heighten corrosion rates across different environments (Jiang et al., 2022). Furthermore, various surface treatments and coatings can significantly affect A372's performance in corrosive settings, emphasizing the necessity

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for specific corrosion management techniques (Ahmed et al., 2023). Despite the general understanding of mild steel's corrosive properties, there remains a significant lack of focused research on A372 Mild Steel. Many existing studies tend to address broader corrosion phenomena without delving into the specific interactions and failures associated with this alloy. Gaining insights into these distinct behaviors can enhance the development of effective protective measures and maintenance strategies (Zhou et al., 2023).

MATERIALS AND METHODS

Materials Selection

The Grade B A372 mild steel was selected due to its mechanical attributes, resistance to corrosion, ease of fabrication, and overall cost-effectiveness. Its technical specifications, including its tensile and yield strength, favorable chemical composition, and compatibility with fabrication processes, make it a reliable choice for engineering applications such as pressure vessels and structural components.

These qualities ensure dependable performance, ease of manufacturing, and longevity, making Grade B A372 an optimal material for projects requiring both durability and economic efficiency.

X-ray fluorescence machine (XRF) was utilized to determine the elemental compositions of the mild steel samples, including the accuracy and detection limits as summarized in Table 1.

Table 1. Grade B A372xrf Result Analysis

S/N	ELEMENTS	CONTENTS (%)	±2δ (Error range factor)
1.	TIN (**Sn**)	0.051	0.018
2.	CUPPER (**Cu**)	0.201	0.074
3.	IRON (**Fe**)	98.67	0.34
4.	MANGANESE (**Mn**)	0.915	0.142
5.	CARBON (**C**)	0.163	_

Source: Authors Compilation

The analysis was conducted based on the ISO 14284 standard, which outlines sampling and sample preparation methods for determining the chemical composition of steels. This standard aligns with the requirements for XRF testing to ensure the acquisition of representative samples.

The surface morphology of the corroded mild steel samples was determined using a Scanning Electron Microscope (SEM), model JEOL JSM-IT300. The analysis was conducted in accordance with the ASTM G46 standard, utilizing a magnification of 1000x.

Sample Preparation

The Grade B A372 mild steel was commercially obtained and cut into cylindrical disc sizes of 7mm X 10mm called coupons. The coupons were initially mechanically grinded with abrasive papers, starting from coarser down to the finest one (400,800, and 1200 grits) to remove chips and scratch from the surface of the coupons. This will provide a shine flat surface with an appropriate surface roughness based on the grit paper used.

No etching was done, in this context only a mechanical method of abrasive grit paper was used to achieve the surface smoothing and roughness adjustment, rather than etching in the chemical sense.

A vernier caliper was used to measure the length, and the diameter of the coupons. Figure 1(a) shows the picture of the cutting operation of the mild steel samples. Fig 1(b) shows the final sizes of the mild steel (coupons) obtained after grinding operation. Figure 1(c) shows the measurement coming out on the mild steel coupons to obtain the sample.

(a) (b) (c)

Figure 1: represents how the samples were prepared from cutting the samples up to the stage where the samples were finally made to standard required sizes.

Methodology and Experimental Setup

1. The Grade B A372mild steel which is commercially available was obtained and cuts into pieces of same length and thickness called coupons.
2. The initial weight of each coupon was recorded.
3. Nine coupons were used for experimental setup conditions.
4. The coupons were subjected to selected corrosive environments and allowed to remain exposed for a designated period of three weeks (21 Days).
5. Weight loss of samples in various corrosive environments were recorded. The weight loss method is of different standards such as NACE RP-0775, ASTM-G1, ASTM-G4, ASTM G31 and many others, but as far as this research is concerned the ASTM-G31 standard practice is utilized.
6. The pH values of Tiga dam environment were monitored and recorded daily.
7. Corrosion rates of samples exposed to various corrosive media were analyzed.
8. The surface morphology of the samples was examined using a scanning electron microscope (SEM) machine.

Experimental Setup

The method adopted in this research is a weight loss method in accordance with ASTM G31 standard practice. Firstly, the initial weight of each coupon was measured and recorded before immersion. The coupons were then exposed to the respective corrosive mediums as discussed under the experimental setup of each environment:

Tiga Dam Water Environment: The average temperature of the Tiga dam water was measured using a thermometer and found to be 24.7°C. A pH meter was employed to determine the initial pH level of the water. The coupons were then immersed in a quantity of 150ml of Tiga dam water and the temperature of 24.7°C was obtained and maintained using water bath for the duration of three weeks.

Fig 2 shows the experimental setup of samples exposed to Tiga dam environment. Figure (a) and Figure (b) shows a water bath where the coupons were exposed, Figure (c) indicates a digital weighing balance used to measure the weight loss of the coupons and Figure (d) highlights a hot plate for heating the corroded coupons in HCL solution for removal of the corrosion particles.

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(a)

(c)

(b)

(d)

Figure 2: (a), (b), (c) and (d) clearly depict the experimental setup of Tiga Dam water Environment.

- KUST atmospheric environment: For this medium, the average temperature of the environment was recorded to be 38.2°C. The data were obtained from Kano University Metrological Records of Geography Department. The coupons were exposed to the atmospheric environment for three weeks.
- Underground (soil) Environment: Civil engineers were consulted to know the depth usually a mild used to be buried in column construction and found to be 1m and above depending upon the design and soil conditions. In this work, a depth of1m was dug on the ground and then the coupons were then buried and maintained for the duration of 3 weeks. The 1m depth was achieved using auger apparatus as shown in Figure below.

All the coupons from the various media were then taken out after a weekly interval, re-weighted and recorded and then re-immersed back to their respective corrosive environments.

Cleaning of Corrosion Product

As stated by ASTM G31 standard practice guide, hydrochloric acid (HCl) should be used as the cleaning solution for the removal of corrosion products after the test. In accordance with standard practice the samples were immersed in the hydrochloric acid solution HCl of 200 milliliters quantity heated up to a temperature of 20-25°C for the duration of 2-3 mins, the samples were then air dried, cleaned, and weighed using digital weighing machine. This cleaning method has been found satisfactory for most corrosion tests in many practical applications. Finally, the weight loss and the corrosion rate were determined.

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Figure 3: The Underground Environmental Setup.

RESULTS AND DISCUSSION

Equations (1), (2), and (3) illustrate the relationships used to calculate the surface area of the coupons, weight loss, and corrosion rate.

The calculation of Specimens Area

The area of the cylindrical specimen with 7mm length and 10mm diameter which was used for this study is calculated using the following relation.

$A = 2\pi r^2 + 2\pi rl$ …………………(1)

Where,

A = Specimen Area (cm^2)

r = Specimen radius (mm)

l = Length of the specimen (mm)

From the equation above

$A = 2\pi r^2 + 2\pi rL$

r = Specimen Radius (mm) = 5 mm

L = Specimen length (mm) = 7 mm

Now,

$A=2 \times \pi \times (5mm)^2 + 2 \times \pi \times (5mm) \times (7 mm)$

$A=157.1 + 219.94 = 377.04 mm^2$

Therefore,

$A = 3.77 cm^2$

Relationship for the Calculation of Weight Loss in Specimens

We obtained the weight loss by calculating the variation in weight between the initial and final measurements of the samples, using the relation below.

$W_L = W_I - W_F$……………… (2)

Where,

W_L = weight loss (g)

W_I = The initial weight of the coupons (grams)

W_F = The final weight of the coupons (grams)

Relationship of Corrosion Rate Calculation

The corrosion rate, which refers to the rate at which material is removed due to chemical action, is a crucial parameter in corrosion studies. It can be expressed as the corrosion penetration rate (CPR), measured in either miles per year (m/py) or millimeters per year (mm/py). In this study, the corrosion rate was

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measured in millimeters per year (mm/py) using the following relationship:

$$\text{Corrosion Penetration Rate}\left(\frac{\text{mm}}{\text{yr}}\right) = \frac{k*\Delta w}{\rho * A * T} \quad (3)$$

. = Corrosion) Penetration Rate (/), Δ = Weight loss in grams, A = Exposed surface area of Coupon = 3.77 x 10^{-2} 2, = Density of mild steel (/ 3) T = Exposure time in hours, k = Unit conversion constant.

Recorded Weight Loss Values of Samples

Table 2 represents the weight loss values of coupons recorded during the experimental test. These values were graphically represented in Figure 4.

Table 2: Recorded Weight Loss Values of Coupons

S/N	Exposure Environments	Samples	Initial weight (g)	First week (7 days)	Second week (14 days)	Third week (21 days)
		Sample A	4.635	4.628	4.559	3.922
1.	Tiga Dam Environment	Sample B	4.562	4.553	4.482	3.865
		Sample C	4.651	4.644	4.573	3.945
		Average	**-**	**4.644**	**4.590**	**3.971**
		Sample A	4.602	4.598	4.582	4.555
2.	Atmospheric Environment	Sample B	4.561	4.559	4.542	4.517
		Sample C	4.625	4.620	4.603	4.583
		Average	-	**4.592**	**4.575**	**4.125**
		Sample A	4.605	4.593	4.517	3.465
3.	Underground (soil) Environment	Sample B	4.656	4.648	4.571	3.519
		Sample C	4.571	4.561	4.484	3.431
		Average	**-**	**4.615**	**4.524**	**3.483**

Source: Authors Compilation

Fig 4. shows the graphical representation of weight loss of samples (in grams) for three different environments against the exposure time (days).

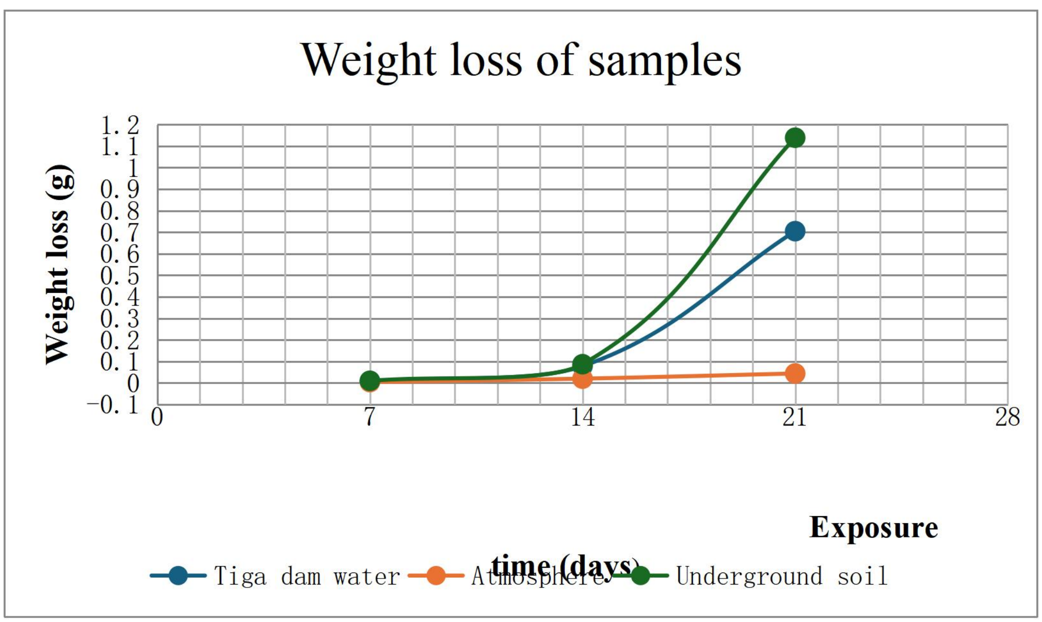

Figure 4: Weight loss of coupons against time.

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The calculation of Coupons Weight Loss

From the equation (2)

$W_L = W_I - W_F$

For sample (A) of Tiga dam environment at the first week

$W_{I=}$ 4.635g

$W_{F=}$ 4.638g

Now,

$W_{L=}$ 4.635g - 4.628g = 0.007g

Similarly, all the remaining values in shown Table 3 were computed using the same method.

Table 3: Calculated values of weight loss of the samples:

S/N	Exposure Environments	Samples	First week weight loss (g) (7 days)	Second week weight loss (g) (14 days)	Third week weight loss (g) (24 days)
1.	Tiga dam water Environment	Sample A	0.007	0.076	0.713
		Sample B	0.009	0.080	0.697
		Sample C	0.007	0.078	0.706
		Average	**0.008**	**0.078**	**0.705**
2.	Atmospheric Environment	Sample A	0.004	0.020	0.047
		Sample B	0.002	0.019	0.044
		Sample C	0.005	0.022	0.042
		Average	**0.004**	**0.020**	**0.044**
3.	Underground (soil) Environment	Sample A	0.012	0.088	1.140
		Sample B	0.008	0.085	1.137
		Sample C	0.010	0.087	1.140
		Average	**0.010**	**0.087**	**1.139**

Figure 4 indicates the graphical representation of weight loss of samples in grams (g) for the three different environments against samples exposure time for 21 days.

Calculation of Corrosion Penetration Rate of Samples

From the equation (3)

$$\text{Corrosion Penetration Rate}\left(\frac{\text{mm}}{\text{yr}}\right) = \frac{k*\Delta w}{\rho*A*T}$$

For Tiga dam water at the first week the corrosion rate was computed as:

$k = 8.76 \times 10^4$ $\Delta w = 0.007g$, $\rho = 7.86g/cm^3$, $A = 3.77\ cm^3$, $T = 168hrs$

$$\text{Corrosion penetration rate} = \frac{8.76 \times 104 \times 0.007g}{7.86g/cm3 \times 3.77 \times 168hrs} = 0.141mm/yr$$

Similarly, all the corrosion penetration rates were calculated using the same method shown below:

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Table 4: Rate of corrosion of samples in three different environments

S/N	Environments	Corrosion rate (mm/yr) week 1 (7 days)	Corrosion rate (mm/yr) week 2 (14 days)	Corrosion rate (mm/yr) week 3 (21 days)
1.	Tiga dam water Environment	0.141	0.686	0.835
2.	Atmospheric Environment	0.070	0.176	0.198
3.	Underground (soil) Environment	0.176	0.765	1.081

The graph in Figure 5 indicates the rate of corrosion for samples subjected to exposure in three environments. The corrosion rate usually shows the speed at which the sample in each environment deteriorates or the amount of material loss per year.

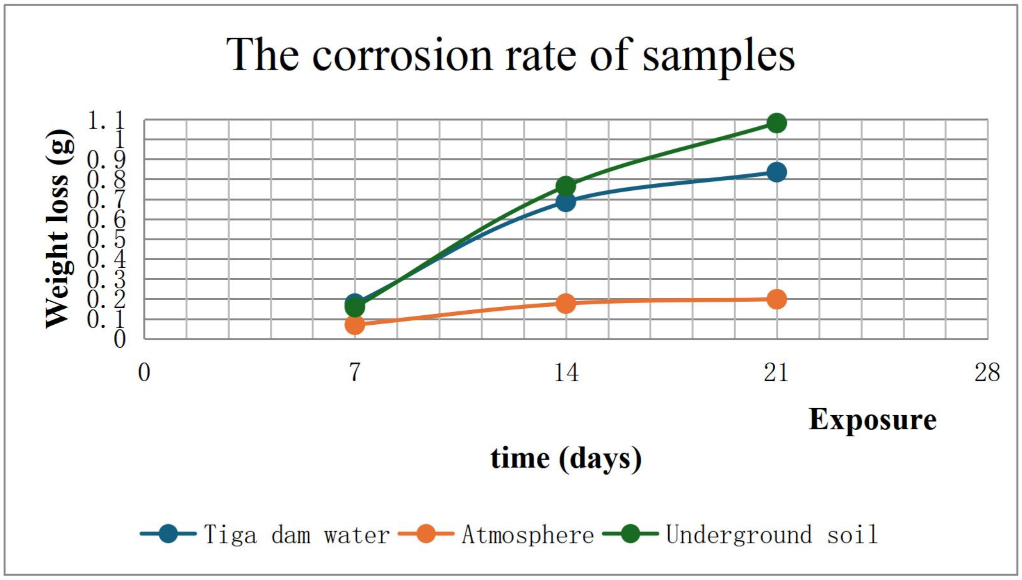

Figure 5: The corrosion rate of samples in the three different environments.

Recorded pH Values of Tiga Dam Environment

Table 5: Tiga Dam Water Environment Recorded pH Values.

Week	Day One	Day Two	Day Three	Day Four	Day Five	Day Six	Day Seven
First week	8.12 (initial)	8.09	8.08	8.05	8.03	8.01	8.01
Second week	8.00	7.98	7.97	7.96	7.96	7.96	7.95
Third week	7.93	7.91	7.91	7.90	7.87	7.87	7.87

Figure 6 graphically represents the recorded pH values of Tiga dam water showing the drop in pH of the environment upon immersion of the mild steel coupons.

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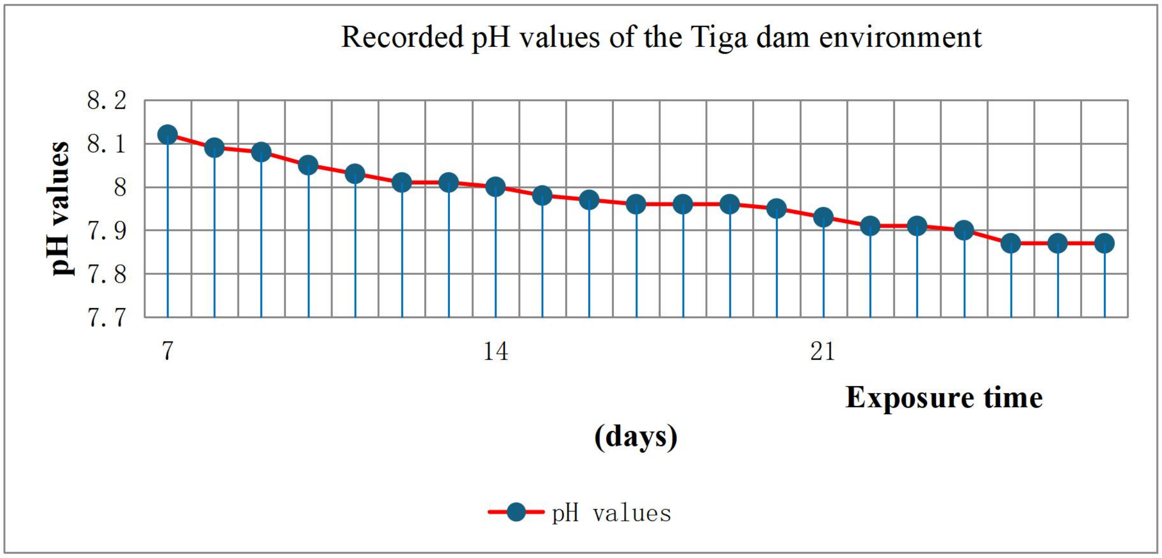

Figure 6: Recorded pH values of Tiga dam environment.

Figure 7 shows, the corroded samples in the atmosphere, the underground soil and the Tiga dam environment.

(a)

(b)

(c)

Figure 7: (a) Samples exposed to underground soil (b) Samples exposed to atmospheric environment (c) Samples exposed to Tiga dam environment.

DISCUSSION

- **KUST WUDIL Atmospheric Condition**

Table 6 represents the corrosion rate of mild exposed in the KUST WUDIL atmospheric condition. The result reveals that the sample exposed to the atmospheric environment corroded very slowly within 21 days duration. This is because of the absence of industries around the area which can result in the emission of corrosion into the atmospheric environment where the mild steel sample was exposed. However, a significant increase of corrosion rate per week was noticed for the atmospheric-exposed samples.

Table 6: The corrosion rate of mild exposed in the KUST WUDIL atmospheric condition.

S/N	Environments	Corrosion rate (mm/yr) week 1 (7 days)	Corrosion rate (mm/yr) week 2 (14 days)	Corrosion rate (mm/yr) week 3 (21 days)
1.	Atmospheric Environment	0.070	0.176	0.198

- **Tiga Dam Water**

Table 7 highlighted the corrosion rate of samples in the Tiga dam environment. The result reveals that the rate of corrosion of the samples exposed in Tiga dam environment increases with the increase in exposure time. A remarkable increase was noticed between the first and second weeks of exposure. However, the corrosion rate shows a slight increase between the second and third week which is because of the increase in the exposure time.

Table 7: Rate of corrosion of samples in Tiga dam environment

S/N	Environments	Corrosion rate (mm/yr) week 1 (7 days)	Corrosion rate (mm/yr) week 2 (14 days)	Corrosion rate (mm/yr) week 3 (21 days)
2.	Tiga dam water Environment	0.141	0.686	0.835

- **KUST WUDIL underground soil condition**

Table 8 portrays the corrosion rate of mild steel exposed to KUST Wudil underground soil. Samples exposed within the first week show slower corrosion rate compared to the second and third week. Exposed samples reveal a significant corrosion rate for the second and third weeks of exposure.

Table 8: Rate of mild steel corrosion in KUST WUDIL underground soil

S/N	Environments	Corrosion rate (mm/yr)week 1 (7 days)	Corrosion rate (mm/yr) week 2 (14 days)	Corrosion rate (mm/yr) week 3 (21 days)
3.	Underground (soil) Environment	0.176	0.765	1.081

The specimen in the soil experienced high corrosion rates towards the third week because of the presence of anaerobic bacteria and available oxygen accounted. It is believed that in the first two weeks the micro-organisms present were making available the necessary corrosive media combined with the available oxygen, hence corrosion increased at a rapid rate.

However, for the first week, the corrosion rate was slow, it then became intense in the second week and more intense in the third week. This occurred because the passive films that were formed within the first week broke down and thus corrosion became aggressive.

The result from Figure 5 above shows the trend in variation of the corrosion rate with respect to time which implies that the corrosion was proportional to the exposure time.

Scanning Electron Microscope (SEM) Machine Results.

For both underground soils, Tiga dam water and atmospheric environment the result obtained from the scanning electron

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microscope (SEM) machine shows a uniform corroded surface of the samples and presence of some dendrites and porosity was observed.

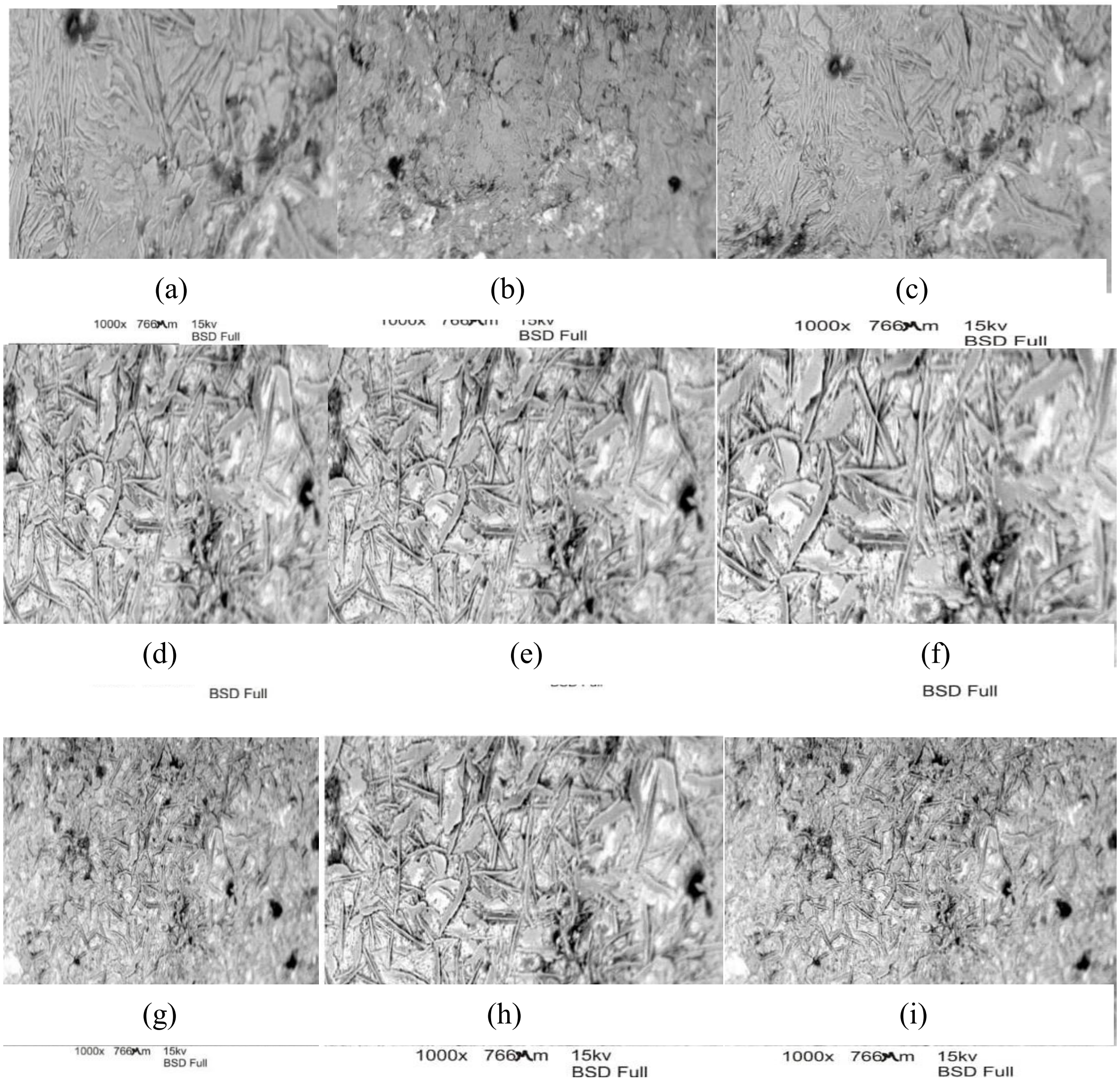

Figure 8: (a-c) samples exposed to KUST Wudil atmosphere (d-f) samples exposed to Tiga Dam Water (g-i) samples buried in KUST Wudil underground soil.

However, on comparison of the three environments using the images obtained from the scanning electron microscope (SEM) machine Figure 9(a) revealed the surface morphological sample exposed to atmospheric condition which shows the presence of lamellar shape Phases microstructure and some smaller holes. The laminar phases are more compact in such a way as it does not allow the metal to get into contact with the exposed environment. The SEM image in Figure 9(b) shows that the sample exposed to the Tiga dam environment shows larger needle shaped microstructural phases and some porosities. The larger shaped needle microstructural phases are very brittle

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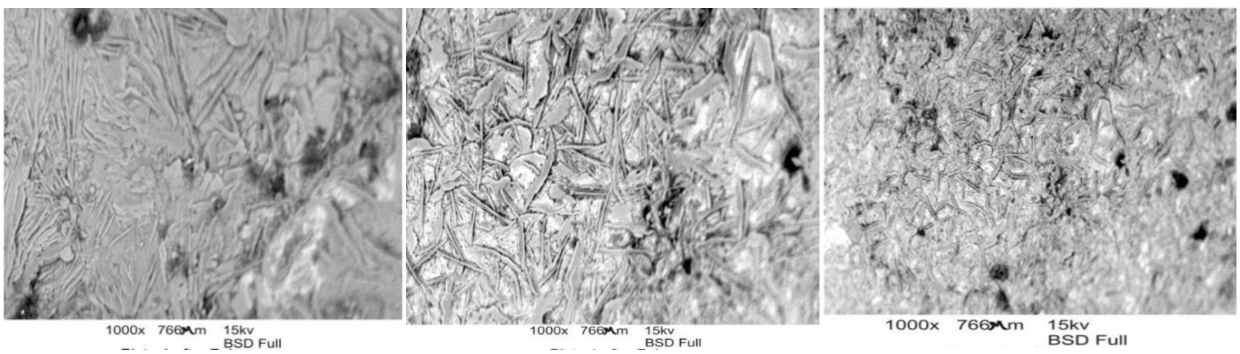
compared to the laminar ones present in Figure 9(a).

It signifies that Tiga dam environment has more contact with the sample surface than the atmospheric environment due to the presence of the needle shape phase microstructure and increase in porosity. Figure 9(c) reveals the presence of some smaller needle shape phases and larger porosities than that of the Tiga dam environment.

This indicates that the underground environment was more aggressive compared with the atmospheric and Tiga dam environments. Furthermore, the analysis of the corrosion rate indicates that the underground environment exhibits a higher corrosion rate than the other environments.

This may be attributed to factors such as moisture content, soil pH levels, the presence of oxygen, and the activities of bacteria and microbes. The result is in good agreement with the SEM image in Figure 9(c). This is because the corrosion rate analysis supports the observation of the SEM images, with the underground environment exhibiting a higher corrosion rate.

The SEM images reveals that underground environments introduce more aggressive corrosion mechanisms due to the surrounding conditions, resulting in a more severely degraded material structure, which aligns well with the surface features highlighted in Figure 9(c).



(a) (b) (c)

Figure 9: (a) Surface morphological samples exposed to KUST Wudil atmosphere (b) Samples exposed to Tiga Dam water (c) Samples buried in KUST Wudil underground soil.

This finding is in good agreement to the previous research by Sinebe J.E conducted on corrosion testing in various environments that indicates underground soil environments has more corrosion attack compared to the other environments unless in aggressive condition such as in an acidic medium (Sinebe J. E., 2014).

However, unlike Sinebe's conclusion that higher corrosion rates in other environments occur under acidic conditions, this study found significant corrosion in the Tiga dam environment even without acidity, suggesting that water environments can be highly corrosive under non-acidic conditions as well.

CONCLUSION

The effect of three different environments on the corrosion behavior of GRADE B A372 mild steel was investigated. The following conclusions were drawn from the research:

I. The corrosion rate of mild steel exposed to KUST WUDIL atmospheric condition increases with an increase in time.

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The result revealed the lowest corrosion rate obtained as 0.198mm/yr at the duration of 21 days after being exposed to atmospheric environment.

II. Corrosion penetration rate of mild steel in Tiga Dam environment varies with an increase in time. The corrosion rate of 0.835mm/yr was obtained for a duration of 21 days.

III. The corrosion rate of samples in KUST WUDIL underground soil environment increases with time, with the highest rate of corrosion recorded at 1.081mm/yr at the duration of 21 days.

It can be inferred that the corrosion rates of the different specimens showed a progressive trend: samples exposed to KUST Wudil underground soil, samples subjected to Tiga dam water, and samples exposed to the KUST Wudil atmosphere. These findings suggest that mild steel may be more appropriate for use in atmospheric environments.

Recommendations

The results obtained from the experiment conducted hence arrived at the following recommendations:

1. Our research indicates the need for an investigation into the impact of surface roughness on mild steel corrosion to assess how surface roughness affects corroded mild steel.
2. We recommend that research should be conducted on the thermodynamic properties and kinetics of mild steel corrosion.

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