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Eco-Friendly Corrosion Inhibition of Welded Mild Steel in Hydrochloric Acid Using Akee Apple (Blighia sapida) Seed Extract

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Abstract

An investigation was carried out regarding the corrosion inhibition properties of akee apple (Blighia sapida) seed extract on welded mild steel in hydrochloric acid solutions, utilizing mass loss and temperature-based measurement techniques. Tests took place under ambient conditions employing inhibitor concentrations of 0.1, 0.3, and 0.5 g/L within the acidic solution. Outcomes demonstrate the seed extract acts as a competent corrosion inhibitor for mild steel, showing effectiveness across all concentration ranges studied. Inhibition efficacy proved to increase proportionally with higher inhibitor concentrations, suggesting a clear concentration-dependent mechanism. Performance was notable, with inhibition reaching approximately 44.4% and 48% in mass loss and temperature measurements respectively. These observations imply akee apple seed extract holds promise as a viable, environmentally sustainable option for corrosion control in mild steel structures within acidic settings.

Keywords: Mild steel, Akee apple seed extract, corrosion inhibition, hydrochloric acid, weight loss, thermometric measurement, eco-friendly inhibitors.

1. INTRODUCTION

Corrosion fundamentally represents the degradation of metallic materials through chemical interactions with their external surroundings, remaining an ongoing concern within engineering implementations (Aslam et al., 2025; Bender et al., 2022). Following breakdown of the passive protective layer on metal surfaces, electrochemical processes begin, resulting in oxide formation, localized pH variations, and migration of metal ions into surface regions (Parangusan et al., 2021). Temperature has a great effect on corrosion rate. In fact, there seems to be a consensus that within a predetermined partial pressure of CO^2, corrosion increases with rising temperature until a predetermined temperature. Above that temperature, protective films are formed on the surface, thus corrosion decreases with a rise in temperature (Konovalova, 2021; Shuhayeu et al., 2025). These reactions ultimately degrade the structural integrity and performance of metallic components. Industrial processes such as acid cleaning, pickling, descaling, and oil-well acidizing frequently employ acidic media to achieve surface treatment objectives; however, these environments can significantly accelerate corrosion on metallic substrates. Inhibitors are chemical agents that can slow down metal corrosion if added in small quantities to fluids in contact with metal. In cases where environmental conditions pose a danger to unprotected carbon steels, the solution to corrosion does not lie in other methods but in using an inhibitor (Kadhim et al., 2021; Trabanelli, 2020). In corrosion inhibition in oil and gas industry, corrosion inhibitors are normally used in either continuous injections into produced fluids or in batch processes (Al-Janabi, 2020; Leal et al., 2020). In continuous injections used in oil or gas wells, there is continuous addition of a fluid inhibitor with a small concentration. Other methods involved are batch methods or squeeze methods. The use of corrosion inhibitors is therefore essential to mitigate acid-induced deterioration, particularly in welded steel components used in structural and industrial applications. The corrosion inhibitors, which nowadays can be categorized as green (eco-friendly corrosion inhibitors), are qualified to deliver sufficient protection in a CO2 environment especially for highly elevated wall shear stresses (Panchal et al., 2021).

Akee apple (Blighia sapida) belongs to the Sapindaceae family, the same as *lychee* and *longan*, and is indigenous to tropical West Africa. While its unripe portions contain toxins, the mature arils are widely consumed and valued for their nutritional and economic importance. Beyond its culinary value, *Akee apple* seed extract has drawn scientific attention due to its antioxidant properties and potential use in corrosion control. Given its natural origins, plentiful availability, and non-hazardous nature, the extract offers an ecological substitute for conventional synthetic corrosion inhibitors (Akinyemi et al., 2025). Welded mild steel finds extensive use in structural and industrial applications thanks to its accessibility, mechanical properties, and fabrication simplicity (Baloyi et al., 2021; Obura et al., 2025). Nevertheless, welded regions display amplified vulnerability to corrosion due to microstructural variations and residual stresses arising from welding procedures (Falodun et al., 2025), necessitating corrosion prevention measures for sustained functionality. Containing under 0.3% carbon content, mild steel is commonly joined through techniques like TIG or arc welding, producing consistent joints yet featuring microstructural disparities that can affect corrosion tendencies.

The current work endeavors to produce quantifiable experimental evidence concerning mitigation of material degradation caused by corrosion using environmentally conscious inhibitor approaches. This study examines corrosion rates for welded mild steel in hydrochloric acid with and without the inhibitor, assesses the inhibition effectiveness of akee apple seed extract, and conducts visual inspections of affected surfaces. Results offer insights into developing practical green corrosion inhibitors that balance ecological considerations, economic feasibility, and regional accessibility for industrial uses.

2. MATERIALS AND METHODS

2.1 Metal Specimen Preparation

The material selected for this investigation was welded mild steel, chosen because of its adaptability, robustness, and common employment in construction and industrial settings. It sees utility across sectors such as utilities, food production, chemicals, and petrochemicals, though it remains vulnerable to deterioration in harsh conditions. For the experiment, mild steel pieces were machine-cut to measurements of 2.0 × 0.2 × 2.5 cm, giving a combined exterior area of 11.8 cm^2. The specimens underwent mechanical polishing through progressively finer emery papers, from 400 to 1200 grit, followed by grinding to achieve an even, smooth finish before analysis.

2.2 Preparation of Akee Apple Seed Extract (Inhibitor)

Akee apple seeds were gathered from Aaye in Ekiti State, Nigeria. The seeds were detached from their pods, rinsed, and air-dried until reaching a steady mass. Once desiccated, they were pulverized and kept in airtight plastic sacks until extraction commenced. Roughly 70 grams of the powdered seeds were steeped in ethanol for 48 hours at ambient temperature to ensure thorough extraction. The liquid was strained, and the resulting filtrate condensed using a rotary evaporator to eliminate ethanol at 76°C for 20 minutes, producing the intended inhibitor extract. Figure 1 shows the measured grinded seed sample.

Figure 1: Measured grinded seed sample

2.3 Preparation of Acid Solution

Standard concentrated hydrochloric acid (HCl) with a density of 1.18 g/cm³ and purity of 35% was used. The molarity of the conc. HCl was calculated using the equation 1 below.

$$\text{Molarity} = \frac{Concentration}{Molar\ Mass} \quad (1)$$

Given molar mass of HCl to be 35.5 g/mol, the calculated molarity was 11.63 M.

In preparing 2 M HCl, the dilution formula $C_1V_1=C_2V_2$ was used, resulting in 85.99 cm³ of concentrated HCl diluted in 500 cm³ of distilled water. The prepared acidic solution served as the corrodent. The inhibitor extracts were then added to obtain varying concentrations of 0.1, 0.3, and 0.5 g/L, which were used for corrosion testing.

2.4 Weight Loss Measurement

The weight reduction approach was utilized to gauge the corrosion rate of the welded mild steel both without and with the Akee apple seed extract present. Steel samples were submerged in 2 M HCl solutions dosed with varying inhibitor amounts under room conditions. Each strip was hung using corrosion-resistant clamps and withdrawn at 3-hour marks over a cumulative span of 18 hours. Following every immersion phase, coupons were meticulously cleansed with distilled water, stripped of grease via acetone, dried, and then weighed anew. The mass deficit (W) was derived using Equation 2.

$$W = W_b - W_a \quad (2)$$

Where,
W_b = specimen weight before immersion, and
W_a = specimen weight after immersion

Corrosion rate (CR) was calculated using equation 3 below.

$$CR = \frac{\Delta W}{At} \quad (3)$$

Where, ΔW is weight loss (g), A is surface area (cm²), and t is the exposure time in hours.

The inhibition efficiency (IE%) was calculated using equation 4 below.

$$\text{IE}(\%) = \left(\frac{\text{CR}_1 - \text{CR}_2}{\text{CR}_1}\right) \times 100 \quad (4)$$

where CR_1 and CR_2 are the corrosion rates in the absence and presence of the inhibitor, respectively.

2.5 Thermometric Measurement

Thermometric technique was used to calculate corrosion reaction kinetics. Mild steel coupons were immersed in beakers containing inhibited and uninhibited HCl solutions. In measuring the temperature variation of the corroding system over time, a digital thermometer with a probe was inserted through the test tube stopper. The temperature readings were recorded at regular intervals until the maximum steady-state temperature was reached.

The reaction number (R), which reflects the rate of the corrosion process, was calculated using equation 5.

$$\text{R} = \frac{\text{T}_\text{m} - \text{T}_\text{i}}{\text{t}} \quad (5)$$

where T_m and T_i are the maximum and initial temperatures, respectively, and t is the time (minutes) required to reach the maximum temperature.

Inhibition efficiency (%I) for the thermometric measurement was gotten from the percentage reduction in reaction number shown in equation 6 below.

$$\%\text{I} = \frac{\text{R}_\text{aq} - \text{R}_\text{wi}}{\text{R}_\text{aq}} \times 100 \quad (6)$$

Where R_aq is the reaction number of the aqueous solution and R_wi is the reaction number in the presence of each inhibitor. Figure 2 shows the experimental setup of the thermometric measurement.

Figure 2: Experimental Setup of Thermometric Measurement

3. RESULTS AND DISCUSSION

3.1 Weight Loss Measurement

The weight loss technique still stands among the most dependable and frequented methods for evaluating metal corrosion in hostile settings. This approach computes degradation rate by tracking mass changes before and after metal exposure to corrosive agents over a preset interval. Here, welded steel coupons were dipped in undiluted (HCl) and diluted (2 M HCl) media, either lacking or containing Akee apple seed extract (AASE) in doses of 0.1, 0.3, and 0.5 g/L. Findings from the mass loss assessments, displayed in Tables 1 and 2, indicate greater weight loss climbing with prolonged immersion across all solutions. However, when AASE accompanied the medium, the decline diminished notably, underscoring the extract's efficacy.

Table 1: Corrosion values for concentrated HCl

Inhibitors			**Time(h)**			
Conc.	**3**	**6**	**9**	**12**	**15**	**18**
Conc. HCL + WMS	1.8167	2.0342	2.15025	2.40025	2.78525	3.01025
Conc. HCL + WMS + 0.1g Inhibitor	1.16140	1.59130	1.89130	2.09130	2.49130	2.79130
Conc. HCL + WMS + 0.3g Inhibitor	1.00200	1.38580	1.58580	1.68580	1.80065	2.18580
Conc. HCL + WMS + 0.5g Inhibitor	0.99540	1.48130	1.78130	1.98130	2.28130	2.38130

Table 2: Corrosion values for dilute HCl

Inhibitors				**Time(h)**		
Diluted	**3**	**6**	**9**	**12**	**15**	**18**
Dil. HCL(2m) + WMS	0.32515	0.39755	0.58755	0.64355	0.79355	0.89355
Dil. HCL(2m) + /WMS + 0.1g Inhibitor	0.18580	0.21850	0.26050	0.36050	0.68050	0.78050
Dil. HCL(2m) + WMS + 0.3g Inhibitor	0.22010	0.23850	0.26090	0.30620	0.40620	0.45870
Dil. HCL(2m) + WMS + 0.5g Inhibitor	0.19790	0.21830	0.24250	0.28700	0.38700	0.48700

The values obtained for the corrosion rates and inhibition efficiencies are presented in Table 3. From these results, there was a decline in corrosion rate with an increase in inhibitor concentration, thus suggesting that there was an improvement in corrosion protection efficiency due to increased concentrations. The maximum observed values in inhibition efficiency were 44.4% and 48% for 2M HCl solutions. These values show that there was an effective adsorption of inhibitor molecules onto the surface of mild steel to create a barrier against corrosion.

Table 3: Corrosion rate values and inhibitor efficiency obtained

	Exposure Time (hour)								
Inhibitor/Conc (g/l)	3	6	9	12	15	18	CR	IE (%)	ϴ
C + WMS + 0.1g Inhibitor	0.03281	0.02248	0.01781	0.01477	0.01408	0.01314	0.01918	21.8	0.218
C + WMS + 0.3g Inhibitor	0.02831	0.01957	0.01493	0.01191	0.00557	0.01029	0.0151	28.4	0.284
C + WMS + 0.5g Inhibitor	0.02812	0.02092	0.01677	0.01399	0.01289	0.01121	0.01432	29.4	0.294
2M + 0.1g + WMS1	0.00525	0.00309	0.00245	0.00255	0.00384	0.00367	0.00348	37.8	0.378
2M + 0.3g + WMS1	0.00622	0.00337	0.00246	0.00216	0.00229	0.00216	0.00311	44.4	0.444
2M + 0.5g + WMS1	0.00559	0.00308	0.00228	0.00203	0.00219	0.00229	0.00219	48	0.480

Figures 3 and 4 show the relationship between weight loss and exposure times for concentrated and dilute solutions of HCl, respectively. In both systems, there was an increased weight loss with an increase in exposure time, which shows corrosion but at a slower rate in inhibited systems.

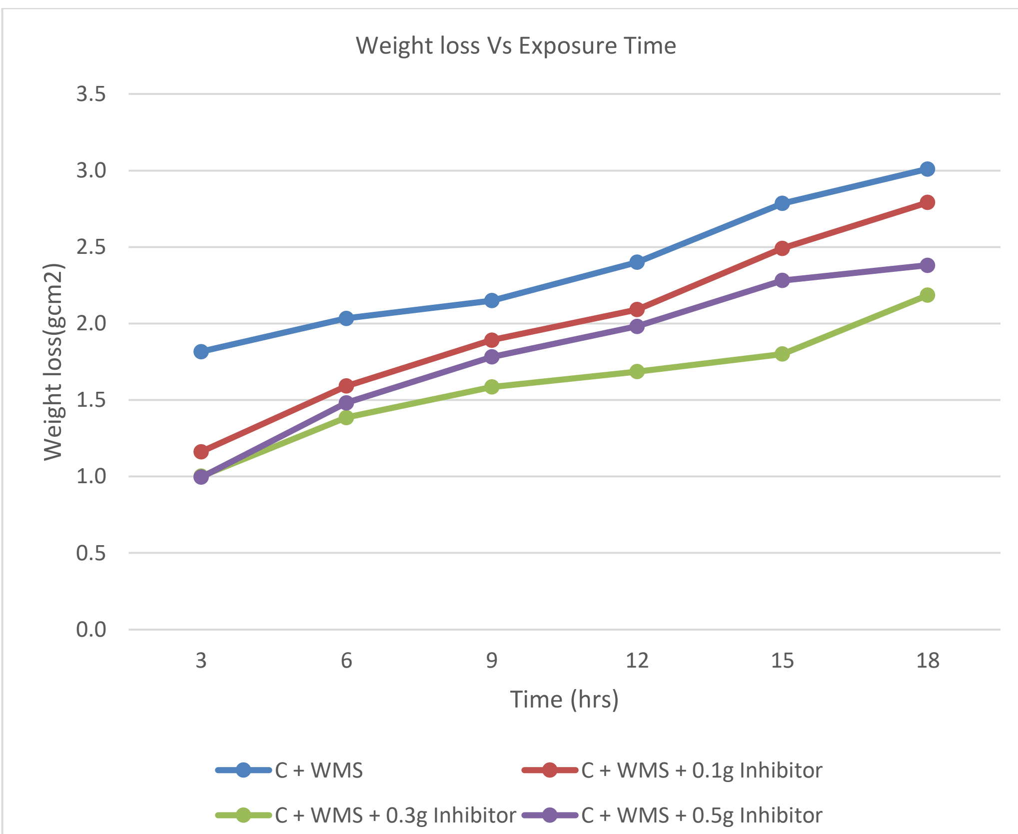

Figure 3: Graph of weight loss against time for concentrated inhibitor

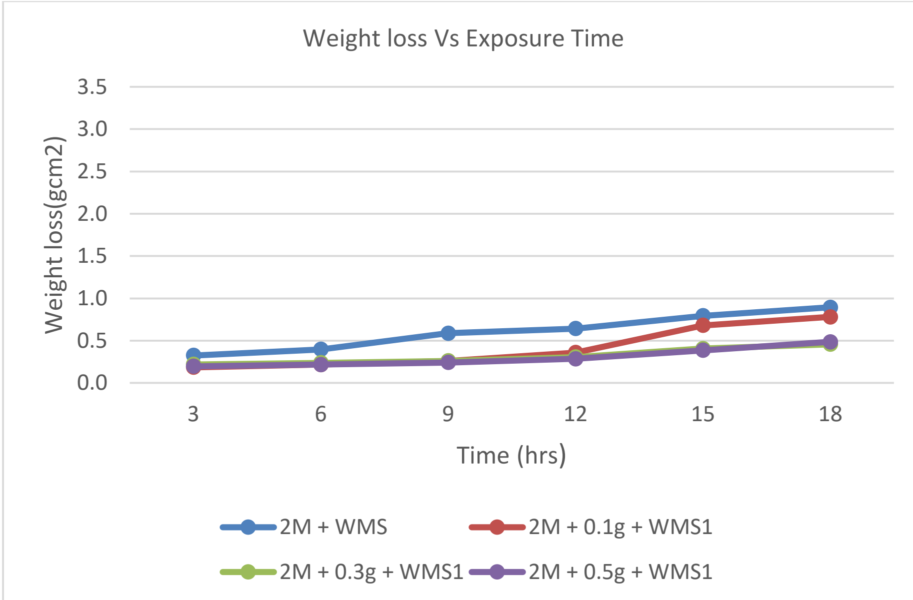

Figure 4: Graph of weight loss against time for diluted HCl

3.2 Inhibition Efficiency and Surface Coverage

Inhibition efficiency (IE%) and surface coverage (θ) values are calculated using data obtained for corrosion rate. From these results, there exists a direct relationship between inhibitor concentration and surface coverage. With an increasing number of inhibitor molecules occupying sites on the surface of the metal, there will be a consequent decrease in corrosion rate.

Based on data presented in Table 3, for the concentrated acid environment, inhibition efficiencies of 21.8%, 28.4%, and 29.4% were obtained at inhibitor concentrations of 0.1 g/L, 0.3 g/L, and 0.5 g/L, respectively. In the 2M HCl solution environment, increases in efficiency to 37.8%, 44.4%, and 48% were attained. It can thus be observed that there was increased inhibitive efficiency in the diluted acid environment. From Figures 5 and 6, there was a progressive increase in inhibition efficiency with increasing concentration for both concentrated and diluted HCl environments. These results validate assumptions made in both theories presented.

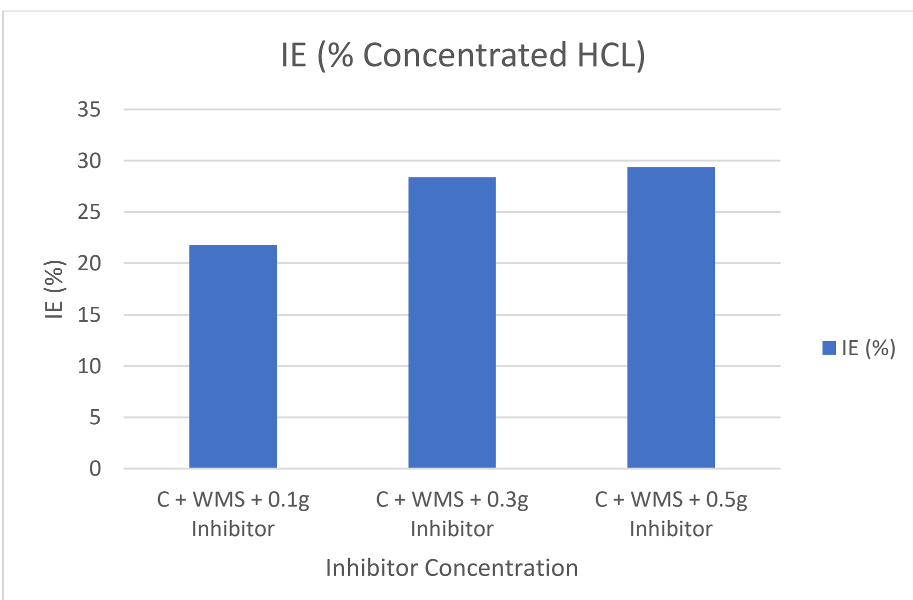

Figure 5: Graph of inhibition efficiency against inhibitor concentration for concentrated HCl

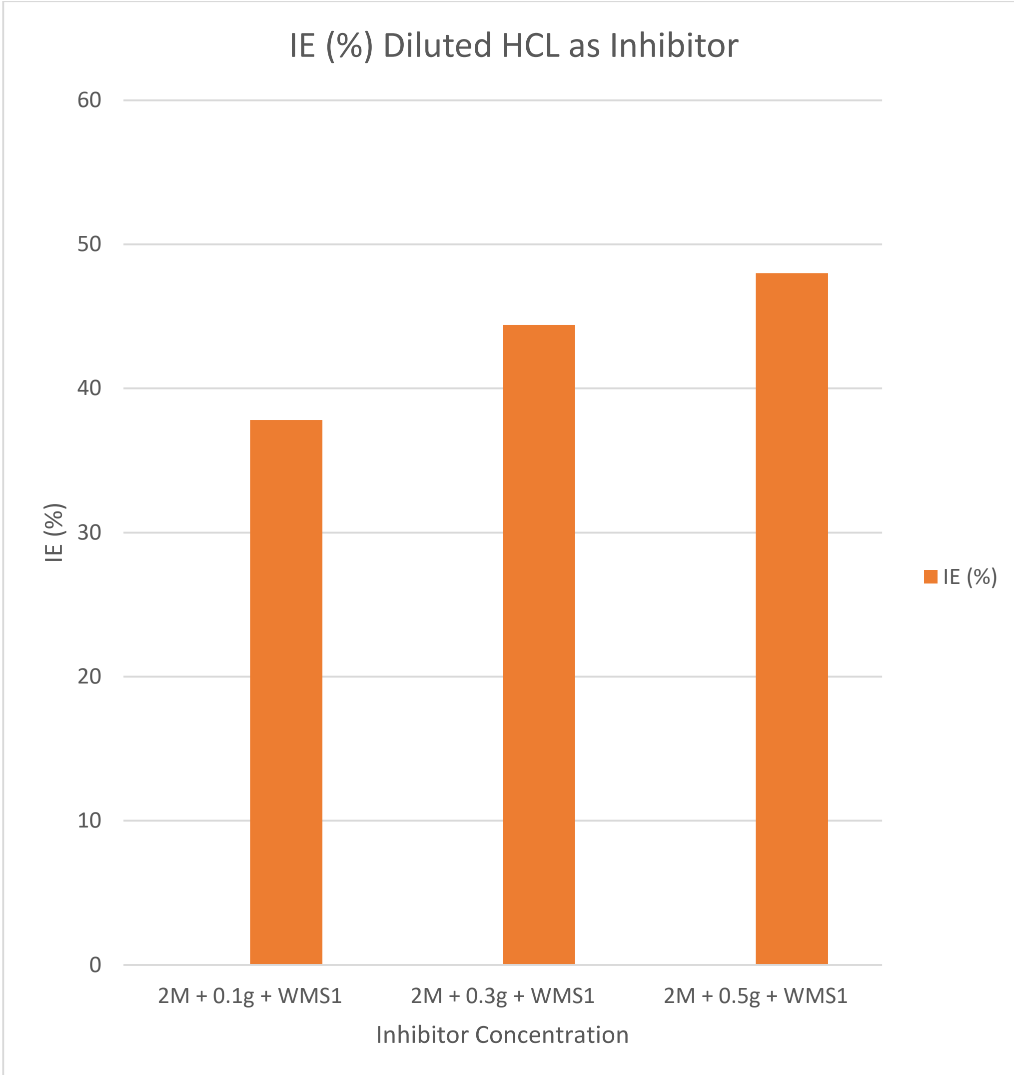

Figure 6: Graph of inhibition efficiency against inhibitor concentration for diluted HCl

3.3 Thermometric Measurement

The thermometric method was employed to analyze the kinetics of the corrosion reaction to ensure that the obtained data using the weight loss method are reliable. The values for temperature variation for both inhibited and uninhibited solutions are shown in Table 4.

Table 4: Thermometric values obtained in absence and presence of AASE

Time (min)	Conc + HCL + sample	Conc + HCl + sample	Conc HCL + 0.1g of inhibitor + sample	Conc HCL +0.3g of inhibitor + sample	Conc HCL +0.5g of inhibitor + sample	Dil HCL [2M] + sample	Dil HCL [2M]+ sample	Dil HCL [2M] + 0.1g of inhibitor + sample	Dil HCL [2M] + 0.3g of inhibitor + sample	Dil HCL [2M] + 0.5g of inhibitor + sample
0	27.6	26.7	26.9	26.9	27.2	27.5	27.4	27.1	26.9	27.1
15	28.8	28.5	28	27.6	27.8	27.4	27.6	27.1	26.9	27.1
30	29.7	29.3	28.4	28.1	28.1	27.4	27.6	27.1	26.9	27.1
45	30.1	30.1	28.8	28.5	28.4	27.2	28	27.1	26.8	27.1
60	30.9	30	29.1	28.6	28.5	27.5	27.3	27.1	26.7	26.9
75	31.1	30.8	29.3	28.8	28.5	27.1	27.2	27	26.7	26.9
90	31.3	30.9	29.4	28.8	28.6	27.1	27.1	27	26.7	26.9
105	31.2	30.8	29.5	28.8	28.5	27.1	27.1	27	26.6	26.9
120	31.8	30.9	29.5	28.9	28.7	27.1	27.1	27	26.6	26.9
135	31.5	30.8	29.6	28.9	28.9	27.1	27.1	27	26.6	26.9
150	31.1	30.6	29.8	28.9	29	27.2	27.1	27	26.7	26.9
165	30.8	30.4	29.8	28.9	29.2	27.3	27.2	27.1	26.7	26.9
180	30.5	30.2	29.9	29	29.3	27.4	27.3	27.1	26.8	27.1
195	30.8	29.5	29.1	28.8	28.8	27.5	29.1	27.3	27	27.2
210	30.7	28.2	29.1	28.8	28.8	27.5	28.5	27.4	27	27.2
225	32.1	29.1	29.3	29	28.9	27.6	28.1	27.5	27.1	27.3
240	31.3	29.5	29.3	29.1	29	27.8	27.9	27.6	27.2	27.4
255	30.2	29.6	29.3	29.2	29.1	27.8	27.9	27.6	27.3	27.3
270	29.6	29.4	29.3	29.2	29.1	27.8	28.5	27.7	27.3	27.5
285	29.5	29.4	29.4	29.2	29.1	27.8	28	27.8	27.1	27.4
300	29.3	29.3	30.2	29.2	29.1	27.9	27.9	27.8	27.3	27.2
315	29.3	29.3	30.5	29.3	29.1	27.9	27.9	27.9	27.2	27.3
330	29.3	29.3	29.8	29.3	29.1	27.9	27.9	27.9	27.3	27.4
345	29.3	29.3	29.8	29.3	29.1	27.9	27.9	27.9	27.3	27.4
360	29.4	29.3	29.5	29.6	29.1	27.9	27.9	27.8	27.4	27.3

As shown in Figure 7, the temperature of the corroding system increased with time until a steady-state value was reached. Without inhibitors, there was a greater temperature rise, which shows more aggressive corrosion reactions. On the other hand, when Akee apple seed extract was used as an inhibitor, there was less temperature rise, especially with increased concentrations. The lower temperature rise shows that there was a lower exothermic reaction between the surface of the steel material and the acid medium due to the use of the inhibitor.

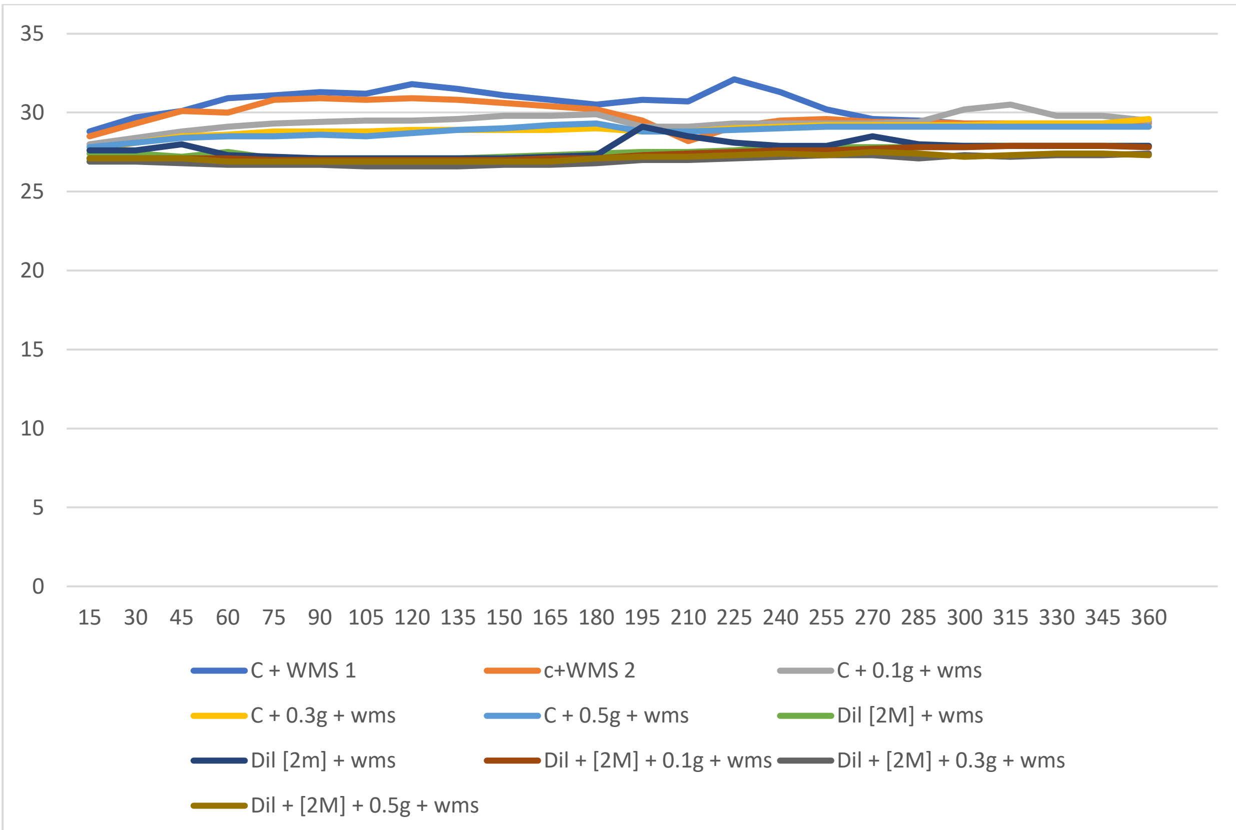

Figure 7: Graph of Temperature against time in inhibitive system

Inhibition efficiency based on thermometric readings confirms the values obtained using the weight loss method. The maximum inhibition efficiency of 48% was found to occur when the inhibitor dosage was 0.5 g/L for 2M HCl solution. Again, these results authenticate that corrosion inhibition occurs due to surface adsorption or both surface and chemical interactions between Akee Apple seed extract and mild steel.

In general, the experimental outcome shows that Akee apple seed extract is found to possess great potential to function as an effective natural corrosion inhibitor for welded mild steel in an acidic solution. The result suggests that corrosion can be more effectively inhibited in a dilute acid solution since fewer hydrogen ions are involved. These ions possess a major role in speeding up corrosion.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

In this study, the corrosion inhibition properties of Akee Apple Seed Extract (AASE) for welded mild steel in hydrochloric acid solutions using both weight loss methods and thermometric analysis are presented. From the experimental data obtained, there was a progressive decrease in corrosion rate with increasing inhibitor concentration. The data obtained confirms that Akee Apple Seed Extract has impressive corrosion inhibition properties in both concentrated and diluted (2M) HCl solutions. It can be concluded that there was a 44.4% to 48% improvement in corrosion inhibition properties in the 2M HCl solution system. Based on these observations made in this study, there was a sharp decline in both weight loss values and reaction temperatures for inhibited systems. Overall analysis shows that Akee Apple Seed Extract functions as an effective green and economic corrosion inhibitor.

4.2 Recommendations

The application of Akee apple seed extract is advised for corrosion protection for mild steel-based equipment when working in an environment influenced by acids. Other areas to explore include analyzing the mechanism involved in the adsorption phenomenon of the extract on the mild steel surface using electrochemical impedance spectroscopy (EIS), or other surface analysis techniques (such as SEM and FTIR). Other environmental conditions like temperature effects, immersion period, or pH changes should also be considered to improve the functionality of the inhibitor. Research into the combination therapy with other natural corrosion inhibitors based on Akee apple seed extract to maximize benefits not achievable when used alone should be explored. Scaling-up procedures to test scientific laboratory analysis based on the long-term stability or safety to the environment should also be considered.

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