TRENDS IN SCIENCES 2022; 19(20): 6237 RESEARCH ARTICLE
https://doi.org/10.48048/tis.2022.6237

Investigation of Mild Steel Corrosion in Hydrochloric Acid Solutions by Sodium carboxymethyl Cellulose and Polyethylene Glycol

Uchenna Itodoh[1,*], Innocent Madufor[1], Martin Obidiegwu[1] and Emeka Oguzie[2]

[1]*Department of Polymer and Textile Engineering, Federal University of Technology, Imo State, Nigeria*
[2]*Electrochemistry and Materials Science Research Laboratory, Department of Chemistry,*
Federal University of Technology, Imo State, Nigeria

([*]Corresponding author's e-mail: uchennaitodoh@yahoo.com)

Received: 6 August 2021, Revised: 13 September 2021, Accepted: 20 September 2021

Abstract

Investigation of mild steel (MS) submerged into 2 M HCl solution alongside sodium carboxymethyl cellulose (SCMC) and its mixtures with polyethylene glycol (PEG) and potassium iodide (KI) respectively was investigated by weight loss measurements, potentiodynamic polarization measurements and scanning electron microscopy (SEM). SCMC was not-good-enough at low concentration of 0.5 g/L of 2 M HCl solution at 30 °C as its inhibition efficiency (IE) stood at 42.73 and 40 % for 24 and 120 h immersion, respectively. However, increasing content of SCMC to 2 g/L of 2 M HCl solution at 30 °C, rose IE to 61.64 and 57.60 % at 24 and 120 h immersion, respectively. Effect of 0.5 g KI and PEG, respectively on 2 g SCMC/L of 2 M HCl solution at 30 °C for 24 h immersion improved IE to 70.91 and 83.64 %, respectively. Conversely, increasing temperature reduced IE of SCMC from 57.60 % at 30 °C to 46.30 % at 60 °C for 120 h immersion within 2 g/L of 2 M HCl solution; whereas 67.20 and 51.85 % at 30 and 60 °C as well as 69.60 and 55.56 % at 30 and 60 °C, respectively were obtained on adding 0.5 g KI as well as PEG, respectively to the 2 g/L SCMC. It was shown that SCMC-KI and SCMC-PEG mixtures show better IEs than SCMC alone, while the best IE of 83.64 % was found for SCMC-PEG mixture after 1 day of MS exposure to 2 M HCl solution. All inhibitor compounds were of mixed-type and obey Langmuir adsorption isotherm. Corrosion inhibition was afforded by physisorption of inhibitor compounds on the MS, while the good synergistic effect was owing to competitive adsorption of inhibitive combinations and thus enhanced inhibitor coverages on the MS. SEM gave visual evidence of adsorption by the compounds on MS.

Keywords: Mild steel, Corrosion, Adsorption, Inhibition, Isotherm, Hydrochloric acid

Introduction

Steel corrosion is a primary concern in oil and gas industry. It is interfacial effect between steel and environmental influences. It can alter material microstructure; thus, making it breakable and blistering. Gradually, it loses its mechanical strength and elasticity alongside attendant shortening in shelf life. It can also cause severe failures and expensive damage to structures and industrial equipment [1]. However, in order to minimize mild steel dissolution exposed to acid solutions, corrosion inhibitors are usually introduced especially where steel structure pickle is required. Hydrochloric acid is the most important pickling acid and it is used at temperature up to 80 °C [2]. Most inhibitors utilized are either cost-ineffective or toxic to humans and their environment [3]. Most common inhibitors are organic compounds having electronegative functional groups and π-electrons in conjugated double or triple bonds and consequently show good inhibitory behaviours [4]. Compounds with functional groups containing nitrogen, sulfur and oxygen are known to demonstrate corrosion inhibitory behaviours through specific adsorption. Both mechanisms can afford enhanced anticorrosive performance [5]. Use of organic compounds as inhibitive additives for mild steel in HCl solutions can be found in the literature [6-27]. Those of synthetic origin are scarce and costly possibly owing to synthesis course while those of natural origin are susceptible to biodegradation.

Meanwhile, among those of polymeric origin, those of cellulosic origin got our attention because of their demonstrated inhibitive potentials. Sodium carboxymethyl cellulose (SCMC) is an anionic water-soluble linear polymer derived from the partial substitution of 2, 3 and 6 hydroxyl groups of cellulose by hydrophilic carboxymethyl groups. SCMC contains Na^+, -OH and $-CH_2COO^-$ groups in its molecular structure, fulfilling an important criterion to work as a corrosion inhibitor. Use of SCMC as inhibitor is particularly important because it is cheap, soluble in water, non-toxic and eco-friendly [27]. Polyethylene glycol (PEG) is a flexible, water-soluble polymer. It contains oxygen atoms in its molecular structure having lone pair of electrons. Adsorption is achieved on mild steel by the interface between the lone pair of the electrons of the oxygen atoms and mild steel surface. The interaction may be eased by the presence of d-vacant orbital of iron constituent of the steel as noted in the d-group transition metals. Molecularly, PEG in acid solution may be protonated. Through electrostatic interface, the positively charged protonated species eases adsorption of the PEG on the mild steel surface [28]. On the other hand, KI added into the acid solution functions as inhibitive compound by ready chemisorption of iodide ion (I^-) on the mild steel surface as I^- displaces chlorine ion (Cl^-) of HCl solution from the mild steel surface given larger atomic radius and higher electronegativity of I^- over Cl^- and thus predisposes the mild steel to be negatively charged in acid solution which eases adsorption of polycation from protonated carbonyl oxygen of CMC through coulomb interface; thus, resulting in enhanced surface coverage and invariably improved inhibitory performance. Moreover, SCMC comprised carboxymethyl ($-CH_2-COO^-$) and hydroxyl (-OH) functional groups, plus sodium ion. Sodium ion has high affinity for Cl^- and will swiftly react chemically to reduce the number of anions (Cl^-) present in the acid solution. The feebly adsorbed hydrated ions of chloride on mild steel predisposed mild steel to be negatively charged in the HCl solution rather than being positively charged, thereby easing adsorption by polycation from the protonated carbonyl oxygen (C=O) of CMC through coulomb interface [29]. The inhibitive mechanisms employed by SCMC alone combined with that adopted by PEG alone on mild steel submerged into HCl solution led to synergistic effect between the two compounds (SCMC+PEG). Although, possible crosslinking reaction might have taken place between SCMC and PEG in the test solution, but that possibility is usually known to occur under specialized conditions meant for such synthesis.

From literature review, (sodium) carboxymethyl cellulose has been reported to have minimized mild steel corrosion in acidic medium [30]. Solomon *et al.* [26], studied the inhibitive effect of CMC on mild steel exposed to 2 M H_2SO_4 solution for 10 h immersion at temperatures 30 - 60 °C using chemical methods. CMC afforded a modest performance of 64.8 % at 500 ppm at 30 °C. Subsequently, the authors studied synergistic influence of halide ions on inhibitive performance of CMC under the same experimental conditions. Findings showed that effect of 5 mM KCl, lowered protective performance to 51 % while 5 mM KBr and KI improved inhibitory performance to 67 and 89 %, respectively. Another study had it that adsorption behaviour and corrosion inhibiting effect of SCMC investigated in 1 mol/L HCl for 24 h gave inhibition efficiency of 72 % at 400 ppm at 298 K, which decreased to 58 % at 328 K [25]. Aslam *et al.* [27] studied anticorrosive performance of SCMC-surfactants system composed of combined solutions of varying concentrations (10 - 700 ppm) of sodium salt of carboxymethylcellulose (SCMC) and fixed concentration (1 ppm) of synthesized oppositely charged biodegradable cationic di-ester bonded gemini surfactants i.e., ethane-1,2-diylbis(*N*,*N*-dimethyl-*N*-alkylammoniumacetoxy)dichloride, referred as m-E2-m, (where m = 12, 14, 16, the number of carbon atoms in alkyl chain and E2 is the di-ester group in gemini's spacer part), for mild steel submerged into 1 M HCl solution for 6 h exposure period. Inhibiting effect of SCMC-gemini surfactant system was examined by mass reduction measurement, potentiodynamic polarization technique, electrochemical impedance spectroscopy, scanning electron microscopy and molecular dynamic simulation. SCMC afforded moderate inhibition efficiency of 57.3 % at 500 ppm, which was synergistically enhanced in presence of very small amount of synthesized gemini surfactants. Inhibitory improvement was highly dependent on surfactant tail length; maximum improvement in inhibition efficiency of 90.1 % was observed in presence of 16-E2-16. Conversely, use of (S)CMC for mild steel corrosion inhibition in acidic solutions never exceeded 24 h exposure period from literature review. Consequently, this work is aimed at exploring inhibitive potentials of SCMC in curbing mild steel corrosion in not only 2 M HCl, but also at 120-h immersion period at temperatures between 30 and 60 °C, focusing on effects of SCMC content, exposure period and temperature and synergistic effect of KI and PEG, respectively on SCMC.

Materials and methods

Metal preparation

Mild steel sheet with the following weight-percentage composition (C (0.04 %)), (Mn (0.04 %)), (Cu (0.06 %)), (Cr (0.05 %)), (Si (0.02 %)) along with (Fe (balance %)) was machined into 4×2.5 cm^2 coupons. Coupons were drilled at one end to allow for insertion of nylon thread through the opening for suspension of coupons during immersion in solutions. Coupons were polished with emery papers of 240 and 320 grits to smoothen the surface of the coupons and remove any possible burrs at the edges, rinsed alongside acetone, washed alongside double-distilled water, dried under a shade and then weighed before being immersed into 2 M HCl solutions.

Solution preparation

BDH analytical grade hydrochloric acid (37 %) purchased from Sigma-Aldrich, USA was used to prepare stock solution of 2 M HCl alongside double-distilled water. Sodium carboxymethyl cellulose (Mw ~ 250,000; degree of substitution 0.9) obtained from Sigma-Aldrich, USA was used to prepare various SCMC concentrations by measuring alongside weighing balance (GF-6100 Precision Scale): 500, 1000, 1500 and 2000 mg SCMC into separate measuring cylinders and filled to the calibrated mark of 1000 mL by 2 M HCl solution, respectively. Test solutions containing 500 mg KI and PEG, respectively in 1 L of 2 M HCl were prepared, accordingly. 500 mg KI and PEG, respectively were introduced into each concentration of SCMC for synergistic study. All the reagents used were obtained from Sigma-Aldrich, USA.

Weight loss measurements

Weighed mild steel coupons were suspended into 300 mL solutions contained in 500 mL beakers at room temperature (30 °C). Coupons were removed after 24 h interval, which kept on continuously for 120 h. The coupons were rinsed alongside double-distilled water as well as allowed to dry under shade before being reweighed. Measurement was taken in triplicate for accurate determination. Similar approach was followed in investigating thermal effect on the corrosion control process from 30 - 60 °C using thermostatic water bath (thermostatic controlled-STD/GMP models) and in determining synergistic effect of 500 mg KI and PEG, respectively on each concentration of SCMC. Average weight-loss values taken from weight difference before-and-after exposure of the mild steel coupons to 2 M HCl solutions were used to calculate:

$$Corrosion\ rate\ \left(\frac{mm}{yr}\right) = \frac{876W}{\rho At} \tag{1}$$

where W, A, t and ρ denote weight loss (g), area of coupon (cm^2), exposure period (h) and mild steel density (g.cm^{-3}), respectively.

$$Inhibition\ efficiency, IE\ (\%) = 1 - \frac{W_i}{W_o} \times 100 \tag{2}$$

where W_o and W_i are weight losses without as well as alongside inhibitive compounds at same temperature, accordingly.

$$Surface\ coverage, \theta = 1 - \frac{W_i}{W_o} \times 100 \tag{3}$$

where W_o and W_i are weight losses without as well as alongside inhibitive compounds at same temperature, correspondingly.

Potentiodynamic polarization measurements

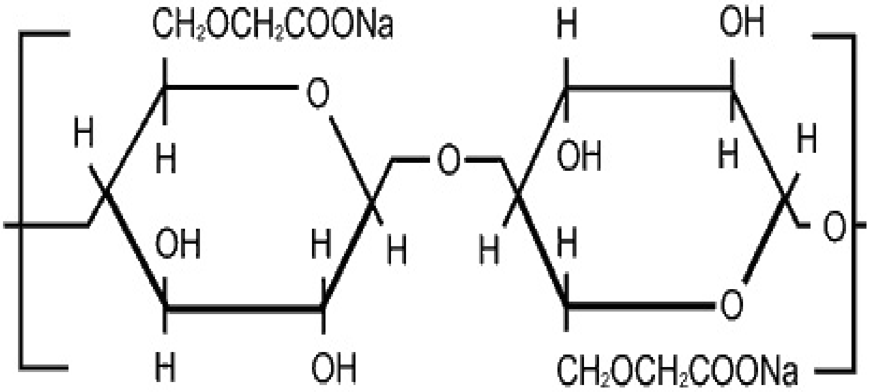
This technique was utilized in the assessment of electrochemical corrosion of mild steel submerged into 2 M HCl solution without as well as alongside inhibitive compounds at 30 °C. It was performed in glass electrolytic cell consisted of three electrodes connected to computer-controlled electrochemical workstation (*VERSASTAT3 Model*). The glass cell assembly comprised: graphite rod (99.9 %, Aldrich) as counter electrode, the saturated calomel electrode (Ag/AgCl (3 M KCl, Gamry)) as reference electrode and mild steel (MS) coupon of wt. % composition (C (0.04 %)), (Mn (0.04 %)), (Cu (0.06 %)), (Cr (0.05 %)), (Si (0.02 %)) as well as (Fe (balance%)) as working electrodes, respectively. Working electrode of 2 cm^2 was prepared as in weight loss measurements. The working electrode was attached to copper wire and submerged into 2 M HCl solution without as well as alongside inhibitive compounds, respectively for 30 min for electric current to pass through and set open-circuit potential from which reading began. Exposed into test solutions for corrosion to take place without agitations was uninsulated 1 cm^2 working electrode while the other half was insulated with epoxy resin. Measurement was taken at a range of potentials –250 to +250 mV at scan rate of 0.5 mV/s. Calculated using Eq. (4) was inhibition efficiency of the inhibitive compounds:

$$Inhibition\ efficiency\ (\%) = 1 - \frac{I_i}{I_o} \times 100 \quad (4)$$

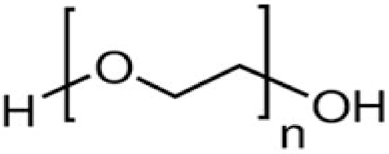
where I_o and I_i denote corrosion current densities without as well as alongside the inhibitive compounds, accordingly.

Scanning electron microscopy

SEM (model JSM-5600 LV) was utilized to examine surface morphology of mild steel coupons of dimension 4×2.5 cm^2 before-and-after exposure to 2 M HCl solution without as well as alongside inhibitive compounds for corrosion attack and adsorbed inhibitive compounds. This was done by having the mild steel submerged into 2 M HCl solution without as well as alongside the inhibitive compounds for 5 days at room temperature (30 °C). Then, the coupons were removed, rinsed alongside double-distilled water as well as dried under shade before being placed for observation under the microscope at accelerating voltage of 15 kV.



(a)



(b)

Figure 1 Schematic structure of (a) SCMC and (b) PEG.

Results and discussion

Effect of immersion time on corrosion rate of mild steel

The proportion of metal loss over time in an aggressive environment is commonly known as *corrosion rate*. Effect of immersion time on corrosion rate of mild steel dipped into 2 M HCl solution without as well as alongside various concentrations of inhibitive compounds for 120 h, respectively is illustrated (**Figure 2**).

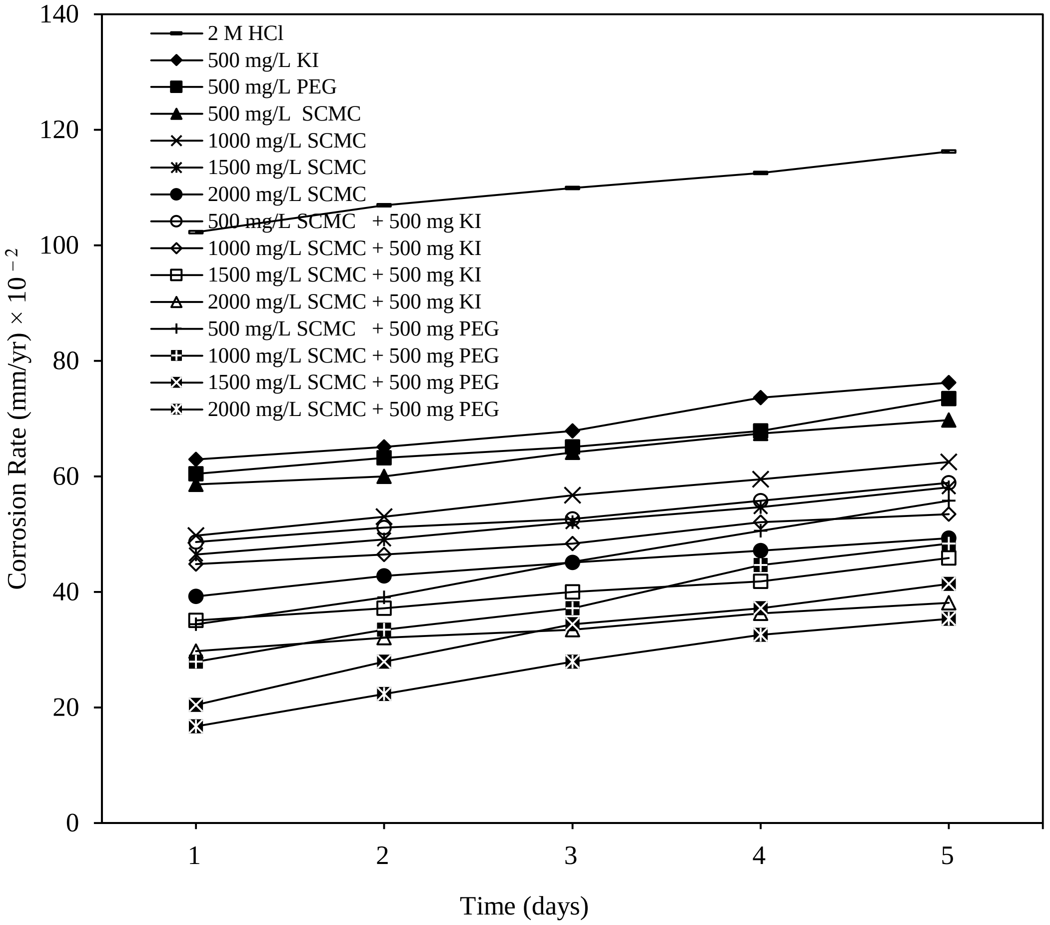


Figure 2 Corrosion rate over time for mild steel submerged into 2 M HCl without as well as alongside inhibitive compounds

From the figure, mild steel dissolution increased alongside time without as well as alongside inhibitive compounds. From **Table 1**, corrosion rate increased from 1.0229 mm/yr at day 1 to 1.0992 mm/yr at day 3 and then to 1.1624 mm/yr at day 5 (without inhibitive compounds). The reason being that when mild steel is exposed to acid solution, it releases electrons which interface alongside hydrogen ions already adsorbed on the steel surface in solution leading to spontaneous forming and effervescing of gaseous hydrogen from the steel surface which typifies anodic dissolution of the mild steel in solution [31]. As far as the metal remains in solution coupled with influence of corrosion product which predisposes the metal to be more anodic in orientation through polarization effect, the mild steel loses weight over time which is accompanied alongside simultaneous increase in corrosion rate. Reaction of iron in acid solution is given thus [32]:

$$Fe + OH^- \rightarrow FeOH_{ads} + H^+ + e^- \tag{5}$$

$$Fe\ OH_{ads} \rightarrow FeOH^+ + e^- \tag{6}$$

$$Fe\ OH\ + H^+ \rightarrow\ Fe^{2+} + H_2O \tag{7}$$

$$2H^+_{ads} + 2e^- \ \rightarrow H_{2\,(g)} \qquad \text{(cathodic reaction)} \tag{8}$$

$$O_2 + 2H_2O + 4e^- \quad \rightarrow 4OH^- \ \ \text{(cathodic reaction with } H_2O\text{)} \tag{9}$$

However, corrosion rate was lessened in presence of SCMC comparative to its absence in solution. From **Table 1**, at 500 mg/L SCMC, corrosion rate reduced to 0.5859 mm/yr at day 1, 0.6417 mm/yr at day 3 and then 0.6975 mm/yr at day 5. This shows that SCMC blocked corrosion prone sites on the mild steel surface by stifling release of electrons from the mild steel through adsorption. Then, within 2000 mg/L SCMC, corrosion rate was further reduced to 0.3924 mm/yr at day 1, 0.4510 mm/yr at day 3 and then 0.4929 mm/yr at day 5. This was because more corrosion prone sites were overlaid by increasing presence of SCMC which shows that inhibitory performance of SCMC is concentration-dependent. Nevertheless, much further reduction in corrosion rate was observed of SCMC-KI and SCMC-PEG mixtures over SCMC alone and is ascribed to synergistic effect to which it was revealed that PEG had more synergistic influence on SCMC than KI for mechanisms accounted for earlier. Shown in **Table 1** are calculated corrosion rate and inhibition efficiency for mild steel submerged into 2 M HCl solution without as well as alongside inhibitive compounds at varying days.

Comparative to what was obtained in the work of Solomon *et al.* [26], where inhibitive effect of carboxymethyl cellulose (CMC) on mild steel exposed to 2 M H_2SO_4 solution for 10 h immersion at temperatures 30 - 60 °C using chemical methods (weight loss measurements) afforded a modest performance of 64.8 % at 500 ppm at 30 °C. Then, later, the authors studied synergistic influence of halide ions on inhibitive performance by CMC under the same experimental conditions to which findings showed that effect of 5 mM KCl lowered protective performance to 51 % while 5 mM KBr and KI improved inhibitory performance to 67 and 89 %, respectively. In ours, inhibitive effect of SCMC on mild steel exposed to 2 M HCl solution for 24 h immersion at 30 °C using chemical approach as weight loss measurement afforded 42.73 % at 500 mg SCMC/L of 2 M HCl solution at 30 °C. Although, stronger acid (H_2SO_4) was used in theirs compared to HCl employed in ours, but exposure time of 10 h made use of in theirs compared to 24 h employed in ours made a huge difference. The difference of 14 h immersion to which SCMC was exposed to in ours was enough to dampen its inhibitory efficiency which led to lower inhibition efficiency obtained in ours relative to theirs on that note. By extension, synergistic effect by (S)CMC with potassium iodide (KI) was also influenced for the same reason as 89 % was obtained in theirs relative to 52.46 % obtained in ours, though 0.005 M KI employed in theirs is not equivalent/comparable to 500 mg KI used in ours. On adding 500 mg PEG to 500 mg SCMC/L of 2 M HCl solution, 66.36 % was obtained. This is an indication that immersion time plays critical role in the assessment of performance of inhibitive compounds. However, inhibitory performance of SCMC was improved at higher concentration under the same experimental conditions as shown in **Table 1** to which 61.64, 70.91 and 83.64 % were obtained within 2000 mg SCMC, 2000 mg SCMC + 500 mg KI and 2000 mg SCMC + 500 mg PEG/L of 2 M HCl solutions, respectively.

On the other hand, comparative to what was obtained in literature [25], we had 42.73 % inhibition efficiency (IE) when mild steel was submerged into 0.5 g SCMC/L of 2 M HCl solution for 24 h at 30 °C; while 72 % IE was obtained in the study of adsorption behaviour and corrosion inhibiting effect of SCMC on mild steel submerged into 0.4 g SCMC/L of 1 M HCl solution for 24 h at 25 °C. Obviously, the greater inhibition efficiency obtained in theirs was owing to lower acid concentration of 1 M HCl solution in which 0.4 g SCMC was added at 25 °C for 24 h immersion compared to higher acid concentration of 2 M HCl solution in which 0.5 g SCMC was added at 30 °C for 24-h immersion employed in ours. Also, ours had 5 °C greater than temperature employed in theirs of which everything being equal will have significant effect and truly did in this context notwithstanding disparity in other variable conditions which even made greater by 0.1 g SCMC content in ours relative to theirs insignificant. Nevertheless, complicated disparity in variable conditions coupled with relevantly scanty literature on which to premise comparative analysis between what was obtained in ours and in other literature as it concerns synergistic effect of SCMC and PEG mixture on mild steel exposed to hydrochloric acid solution left us no room for accounts in that regard.

Table 1 Calculated corrosion rate and inhibition efficiency for mild steel submerged into 2 M HCl without as well as alongside inhibitive compounds at varying days.

System/Day	**Corrosion Rate (mm/yr)×10^{-2}**					**Inhibition Efficiency (%)**				
	1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
2 M HCl	102.29	106.94	109.92	112.52	116.24	-	-	-	-	-
500 mg/L KI	62.96	65.10	67.89	73.65	76.26	38.46	39.13	38.24	34.55	34.40
500 mg/L PEG	60.45	63.24	65.10	67.89	73.47	40.91	40.87	40.78	39.67	36.80

System/Day	**Corrosion Rate (mm/yr)$\times 10^{-2}$**					**Inhibition Efficiency (%)**				
	1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
500 mg/L SCMC	58.59	59.98	64.17	67.42	69.75	42.73	43.91	41.62	40.08	40.00
1000 mg/L SCMC	49.75	53.01	56.73	59.52	62.49	51.36	50.44	48.39	47.11	46.24
1500 mg/L SCMC	46.50	49.10	52.08	54.68	58.12	54.55	54.09	52.62	51.41	50.00
2000 mg/L SCMC	39.24	42.78	45.10	47.15	49.29	61.64	60.00	58.97	58.10	57.60
500 mg/L SCMC + 500 mg KI	48.64	51.15	52.63	55.80	58.87	52.46	52.17	52.12	50.41	49.36
1000 mg/L SCMC + 500 mg KI	44.82	46.50	48.36	52.08	53.47	56.18	56.52	56.01	53.72	54.00
1500 mg/L SCMC + 500 mg KI	35.06	37.20	39.99	41.85	45.85	65.73	65.22	63.62	62.81	60.56
2000 mg/L SCMC + 500 mg KI	29.76	32.08	33.48	36.27	38.13	70.91	70.00	69.54	67.77	67.20
500 mg/L SCMC + 500 mg PEG	34.41	39.06	45.20	50.59	55.80	66.36	63.48	58.88	55.04	52.00
1000 mg/L SCMC + 500 mg PEG	27.90	33.48	37.20	44.64	48.36	72.73	68.70	66.16	60.33	58.40
1500 mg/L SCMC + 500 mg PEG	20.46	27.90	34.41	37.20	41.38	80.00	73.91	68.70	66.94	64.40
2000 mg/L SCMC + 500 mg PEG	16.74	22.32	27.90	32.55	35.34	83.64	79.13	74.62	71.07	69.60

Effect of temperature on mild steel corrosion

Thermal effect on mild steel corrosion is a common concern given that increase in temperature increases corrosion rate just like in any chemical reaction. Consequently, there is need to study metallurgical behaviour of mild steel exposed to 2 M HCl solution at a range of temperatures 30 - 60 °C for 120 h immersion without as well as alongside inhibitive compounds, respectively; which is illustrated in **Figure 3**.

Figure 3 shows that increasing temperature increased corrosion rate of mild steel submerged into 2 M HCl solution. Presented in **Table 2** are calculated corrosion rate and inhibition efficiency for mild steel submerged into 2 M HCl solution without as well as alongside inhibitive compounds at varying temperatures. From the table, without inhibitive compounds, corrosion rate increased from 1.1624 mm/yr at 30 °C to 1.6925 mm/yr at 40 °C, 2.0459 mm/yr at 50 °C and then 2.5108 mm/yr at 60 °C. The reason is that, at high temperature, microstructure of mild steel is distorted leading to defective lattice structure from which mild steel dissolution is initiated. Moreover, at elevated temperature in solution, anions are known to be more energized according to kinetic theory of matter. These energized anions are known to go frenetic in solution thereby make their impingement quite swift at corrosion vulnerable sites on the mild steel surface which eventually results in further disintegration of the lattice structure made manifest as corrosion. However, dissolution rate is minimized by adsorption of inhibitive compounds on mild steel surface. From **Table 2**, within 500 mg/L SCMC, corrosion rate reduced to 0.6975 mm/yr at 30 °C, 1.0508 mm/yr at 40 °C, 1.3717 mm/yr at 50 °C and then 1.7390 mm/yr at 60 °C, respectively; while within 2000 mg/L SCMC, further reduction in corrosion rate was observed to be 0.4929 mm/yr at 30 °C, 0.7579 mm/yr at 40 °C, 1.0601 mm/yr at 50 °C and then 1.3484 mm/yr at 60 °C, respectively. This shows that increasing concentration of SCMC dampens better effect of temperature on mild steel corrosion within 2 M HCl solution. Nevertheless, much further reduction in corrosion rate was observed of SCMC-KI and SCMC-PEG mixtures over SCMC alone and is ascribed to synergistic effect to which it was revealed that PEG had better synergistic influence on SCMC than KI as shown in **Table 2**.

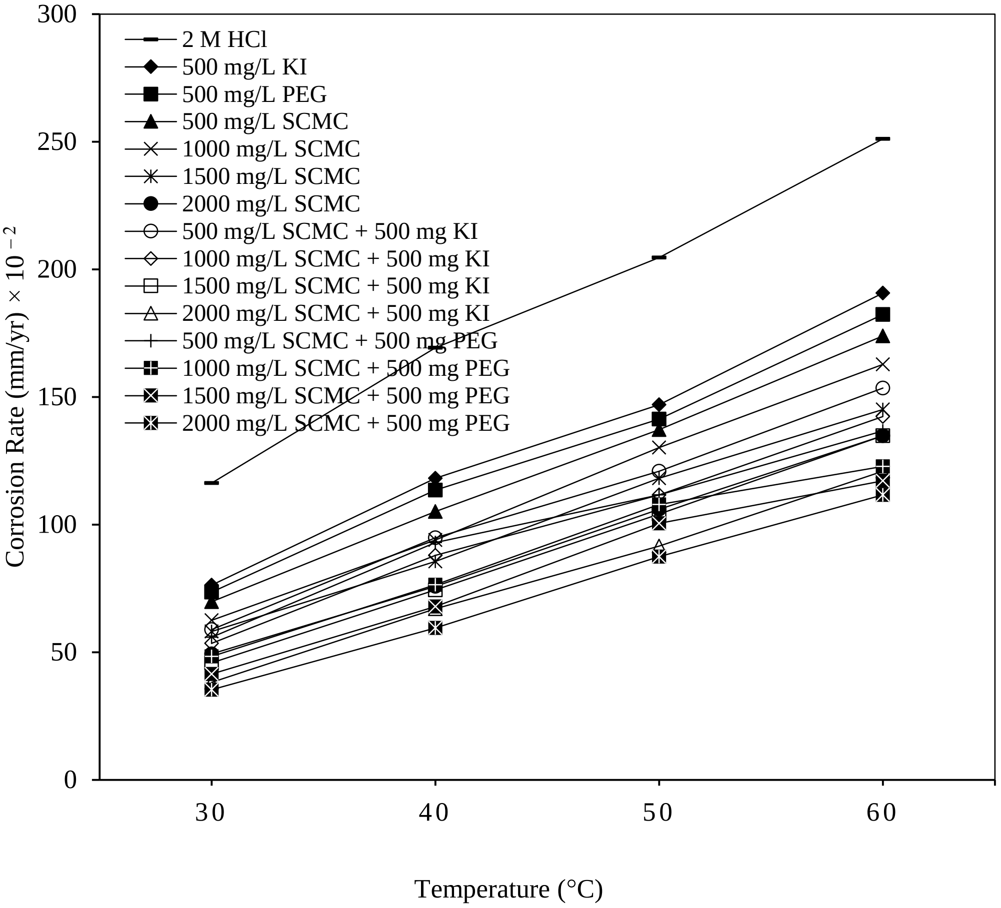


Figure 3 Corrosion rate against temperature for mild steel submerged into 2 M HCl without as well as alongside inhibitive compounds

Table 2 Calculated corrosion rate and inhibition efficiency for mild steel submerged into 2 M HCl without as well as alongside inhibitive compounds at varying temperatures.

System	**Corrosion Rate (mm/yr)×10 $^{-2}$**				**Inhibition Efficiency (%)**			
	30 °C	**40 °C**	**50 °C**	**60 °C**	**30 °C**	**40 °C**	**50 °C**	**60 °C**
2 M HCl	116.24	169.25	204.59	251.08	-	-	-	-
500 mg/L KI	76.26	118.10	146.93	190.64	34.40	30.22	28.18	24.07
500 mg/L PEG	73.47	113.45	141.35	182.27	36.80	32.97	30.91	27.41
500 mg/L SCMC	69.75	105.08	137.17	173.90	40.00	37.91	32.96	30.74
1000 mg/L SCMC	62.49	93.92	130.19	162.74	46.24	44.51	36.36	35.19
1500 mg/L SCMC	58.12	85.55	118.10	145.07	50.00	49.45	42.27	42.22
2000 mg/L SCMC	49.29	75.79	106.01	134.84	57.60	55.22	48.18	46.30
500 mg/L SCMC + 500 mg KI	58.87	94.85	120.89	153.44	49.36	43.96	40.91	38.89
1000 mg/L SCMC + 500 mg KI	53.47	87.88	111.59	142.28	54.00	48.08	45.46	43.33
1500 mg/L SCMC + 500 mg KI	45.85	74.40	104.15	134.84	60.56	56.04	49.09	46.30

System	**Corrosion Rate (mm/yr)×10 $^{-2}$**				**Inhibition Efficiency (%)**			
	30 °C	**40 °C**	**50 °C**	**60 °C**	**30 °C**	**40 °C**	**50 °C**	**60 °C**
2000 mg/L SCMC + 500 mg KI	38.13	66.96	91.60	120.89	67.20	60.44	55.23	51.85
500 mg/L SCMC + 500 mg PEG	55.80	92.99	111.59	136.70	52.00	45.06	45.46	45.56
1000 mg/L SCMC + 500 mg PEG	48.36	76.44	107.87	122.75	58.40	54.84	47.27	51.11
1500 mg/L SCMC + 500 mg PEG	41.38	67.89	100.43	117.17	64.40	59.89	50.91	53.33
2000 mg/L SCMC + 500 mg PEG	35.34	59.52	87.41	111.59	69.60	64.84	57.27	55.56

Effect of immersion time on inhibition efficiency

This is a measure of durability of adsorbed inhibitive compounds on mild steel over a period of time from the sway of anions at adsorbed compounds–mild steel interface in solution. Also, it is one of the ways to assess cost effectiveness of inhibitive compounds in practice as it aims at reducing frequency of application of inhibitive compounds and invariably its cost of procurement. **Figure 4** demonstrates effect of immersion time on inhibitory performance of the compounds on mild steel exposed to 2 M HCl solution at room temperature, 30 °C.

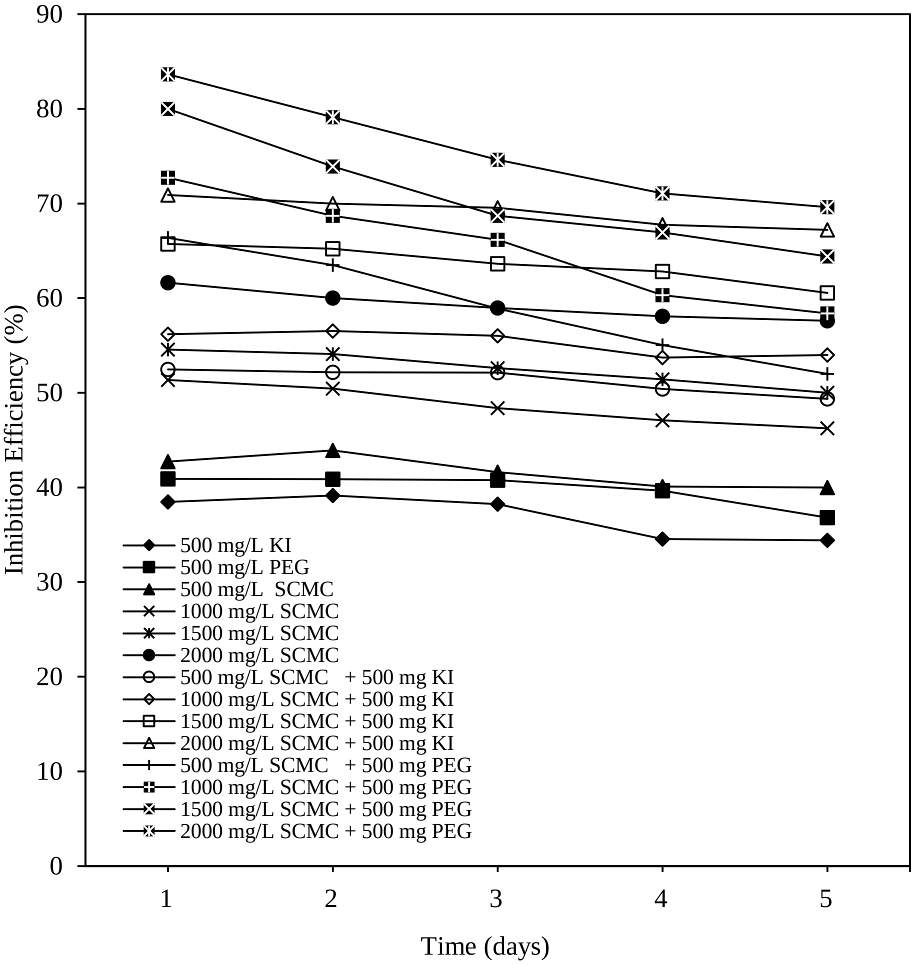


Figure 4 Inhibition efficiency of the compounds over time on mild steel submerged into 2 M HCl.

Figure 4 shows that inhibitory performance of the compounds on mild steel waned with increasing immersion time as inhibition efficiency reduced from 42.73 % at day 1 to 41.62 % at day 3 and then 40.00 % at day 5 within 500 mg/L SCMC. This was owing to impinging action of the anions at the adsorbed compounds–mild steel interface over time in a bid to dislodge the adsorbed compounds from the mild steel surface. However, on increasing content of SCMC to 2000 mg/L, inhibition efficiency increased to 61.64 % at day 1, 58.97 % at day 3 and then 57.60 % at day 5, respectively. This shows that increasing content of SCMC ameliorates its inhibitory performance. Nevertheless, adding 500 mg KI as well as PEG, respectively to 2000 mg/L SCMC, improved inhibition efficiency to 70.91 % at day 1, 69.54 % at day 3 and then 67.20 % at day 5 as well as 83.64 % at day 1, 74.62 % at day 3 and then 69.60 % at day 5, respectively. This shows that synergistic effects of SCMC+PEG and SCMC+KI mixtures have greater inhibitory performances over time than SCMC alone to which SCMC+PEG mixtures outperformed SCMC+KI mixtures for mechanisms accounted for earlier. Also, it was observed from **Figure 4** that the compounds resiliently declined in inhibition efficiency over time. This suggests that adsorption by the compounds on mild steel is relatively firm. Presented in **Table 1** are calculated inhibition efficiency of the compounds on mild steel submerged into 2 M HCl solution at varying days.

Effect of temperature on inhibition efficiency

To evaluate thermal influence on inhibitory performance of the compounds on mild steel submerged into 2 M HCl solution without as well as alongside various contents of the compounds; plot of inhibition efficiency against temperature is illustrated in **Figure 5**.

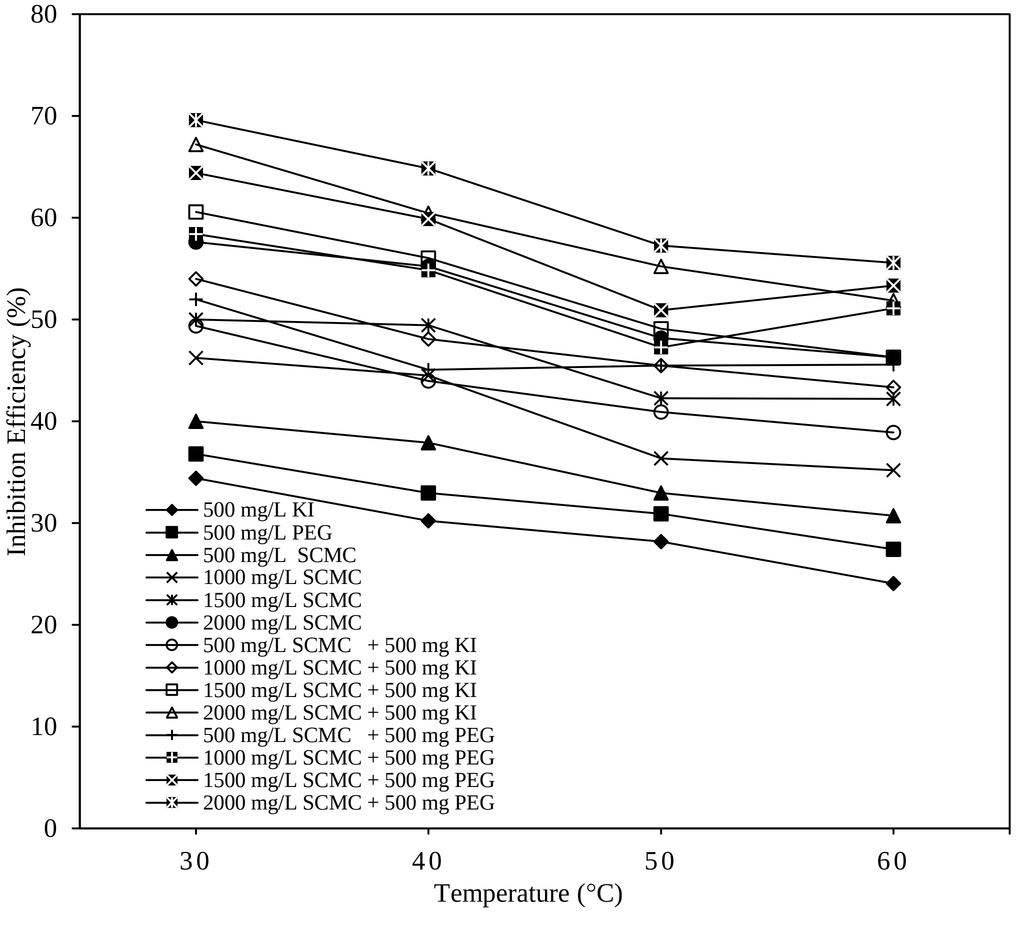


Figure 5 Inhibition efficiency of the compounds against temperature on mild steel submerged into 2 M HCl.

Figure 5 shows that increasing temperature unfavourably affected inhibitory performance of the compounds as inhibition efficiency reduced from 57.60 % at 30 °C to 46.30 % at 60 °C for 120 h immersion within 2000 mg/L SCMC; while it decreased from 67.20 % at 30 °C to 51.85 % at 60 °C within 2000 mg/L SCMC+KI and 69.60 % at 30 °C to 55.56 % at 60 °C within 2000 mg/L SCMC+PEG for 120 h immersion, respectively. This decline in inhibitory performance alongside rise in temperature is linked to softening and desorbing of adsorbed compounds from the mild steel surface. This scenario also supports the idea that adsorption by the compounds on mild steel is physical, not chemical [33]. Presented in **Table 2** are calculated inhibition efficiency of the compounds on mild steel submerged into 2 M HCl solution at varying temperatures.

Adsorption consideration

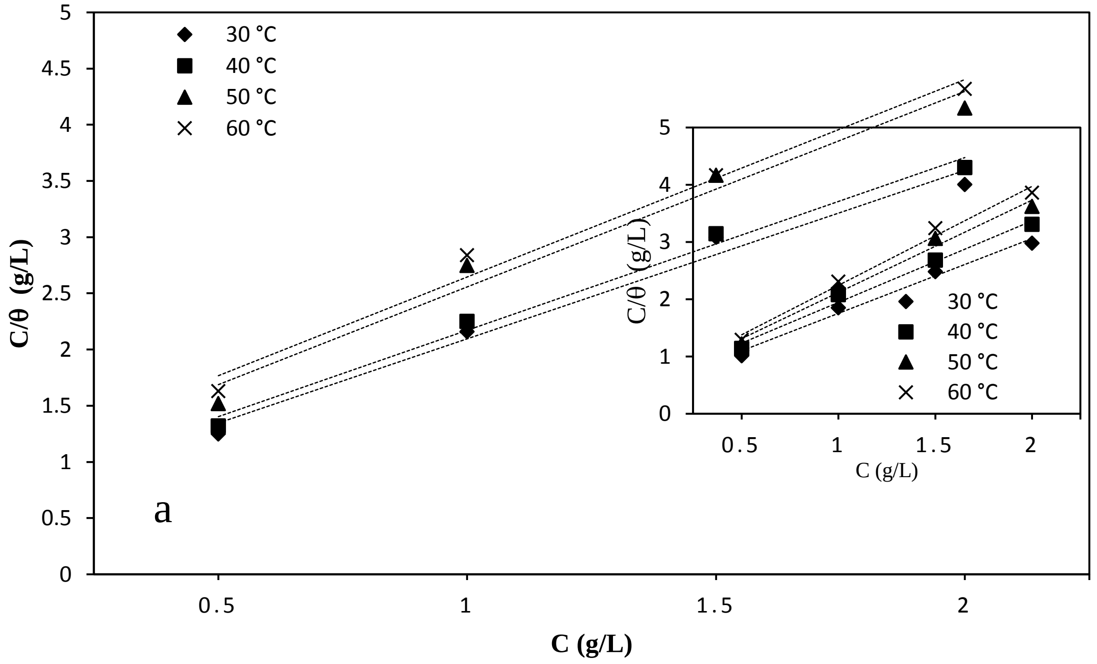
Adsorption is the molecular accumulation of the inhibitive compounds at the metal-electrolyte interface. Adsorption isotherms are used to picture the interface between adsorbed compounds and metal surface. The appropriate adsorption isotherm suitable for adsorptive pattern followed by the inhibitive compounds on mild steel was ascertained by fitting values of surface coverage (IE% = 100θ) obtained from weight loss measurement into different adsorption isotherm equations such as Langmuir, Freundlich and Temkin, and evaluated from their graphs the one whose values of correlation coefficient (R^2) approximated to unity the most. Hence, Langmuir adsorption isotherm became the one appropriate for the occasion. Langmuir isotherm equation is given thus:

$$\frac{C}{\theta} = \frac{1}{K_{ads}} + C \tag{10}$$

where θ, C and K_{ads} denote proportion of surface coverage, content of compounds and binding strength of compounds, respectively. K_{ads} is associated with $\triangle G_{ads}$ (Gibb's free energy) by Eq. (11):

$$K_{ads} = \frac{1}{55.5} exp^{\left[\frac{-\Delta G_{ads}}{RT}\right]} \tag{11}$$

The plots of C/θ against C for mild steel dipped into 2 M HCl solution alongside various contents of SCMC, SCMC-KI and SCMC-PEG at varying temperatures, respectively are shown in **Figure 6**. From the linearised plots, very good correlation coefficients were obtained and values of slope were unity which imply that adsorption of SCMC, SCMC-KI and SCMC-PEG, respectively on mild steel obeys Langmuir isotherm. K_{ads} values took the trend SCMC-PEG > SCMC-KI > SCMC. Higher values of K_{ads} imply better adsorption efficiency; hence, better inhibitory performance [34]. This scenario concurs with inhibitory performance presented in **Tables 1** and **2**, respectively. Calculated ΔG_{ads} from Eq. (11) were all negative and lay between the range (–11.12 to –14.45) KJ/mol which confirms our early proposed prompt physisorption by the compounds on mild steel [35]. **Table 3** shows calculated Langmuir adsorption parameters.



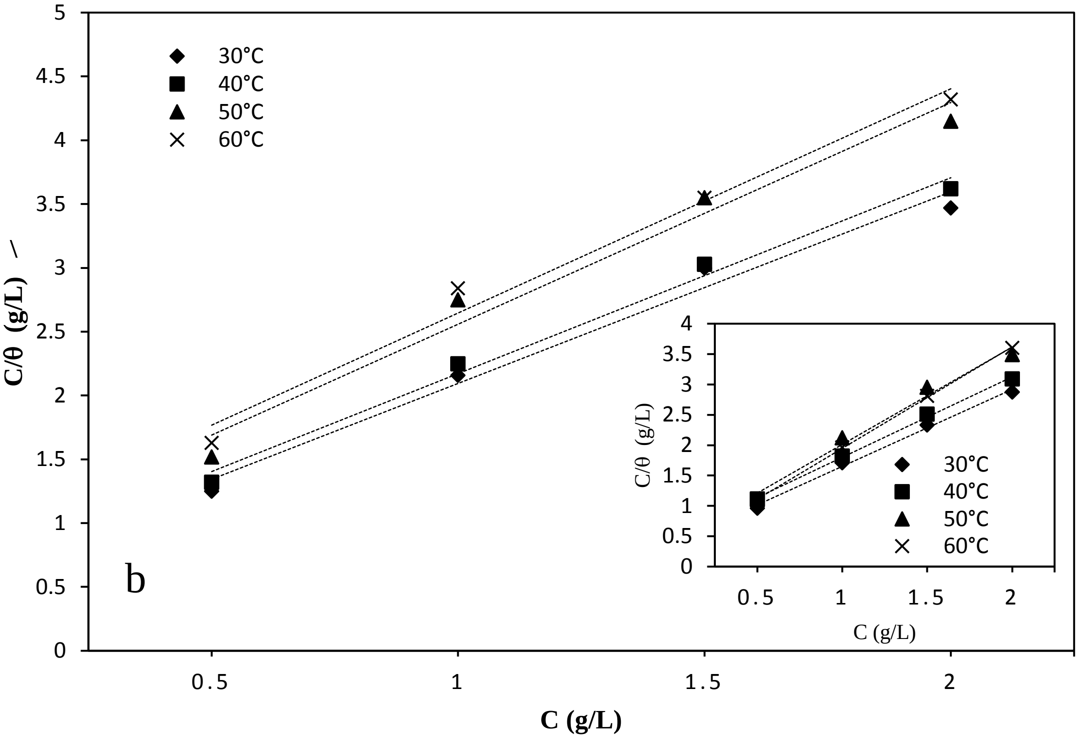


Figure 6 Langmuir isotherm for the adsorption of various concentrations of (a) SCMC and SCMC-KI (inset) and (b) SCMC and SCMC-PEG (inset) at different temperatures on mild steel submerged into 2 M HCl.

Table 3 Adsorption parameters for SCMC, SCMC−KI and SCMC−PEG on mild steel submerged into 2 M HCl at varying temperatures.

System	**Temp. (°C)**	**Langmuir Adsorption Isotherm (C/θ vs C)**				
		Slope	**R^2**	**Intercept**	**K_{ads}**	**ΔG^{o}_{ads} (KJ mol^{-1})**
SCMC	30	1.5000	0.9815	0.6000	1.667	–11.41
	40	1.5400	0.9903	0.6250	1.600	–11.68
	50	1.7231	0.9737	0.8750	1.143	–11.14
	60	1.7067	0.9837	1.0000	1.000	–11.12
SCMC–KI	30	1.2833	0.9865	0.4750	2.105	–11.99
	40	1.4167	0.9879	0.5000	2.000	–12.26
	50	1.6320	0.9861	0.5200	1.923	–12.54
	60	1.7143	0.9888	0.5000	2.000	–13.04
SCMC–PEG	30	1.2667	0.9945	0.3750	2.667	–12.59
	40	1.3133	0.9979	0.5000	2.000	–12.26
	50	1.6000	0.9822	0.4000	2.500	–13.25
	60	1.6667	0.9996	0.3000	3.333	–14.45

Thermodynamic considerations

Energy changes on exposure of mild steel to 2 M HCl solution at temperatures 30 - 60 °C without as well as alongside inhibitive compounds were ascertained by evaluating the following:

Energy of activation, E_a

Mild steel is made more vulnerable to the influence of anions in acid solution when the energy of activation is lowered at high temperature. Arrhenius equation expresses this phenomenon by highlighting that increasing temperature lowers energy of activation (E_a) which invariably increases corrosion rate of metal as delineated in Eq. (12). **Figure 7** shows Arrhenius plot for mild steel submerged into 2 M HCl solution at temperatures 30 - 60 °C without as well as alongside inhibitive compounds, respectively.

$$\mathrm{LogCR} = \left(\frac{-E_a}{2.303RT}\right) + \mathrm{LogA} \tag{12}$$

where E_a, R and A denote activation energy (KJ/mol), universal gas constant (J/mol. K) and pre-exponential factor, respectively.

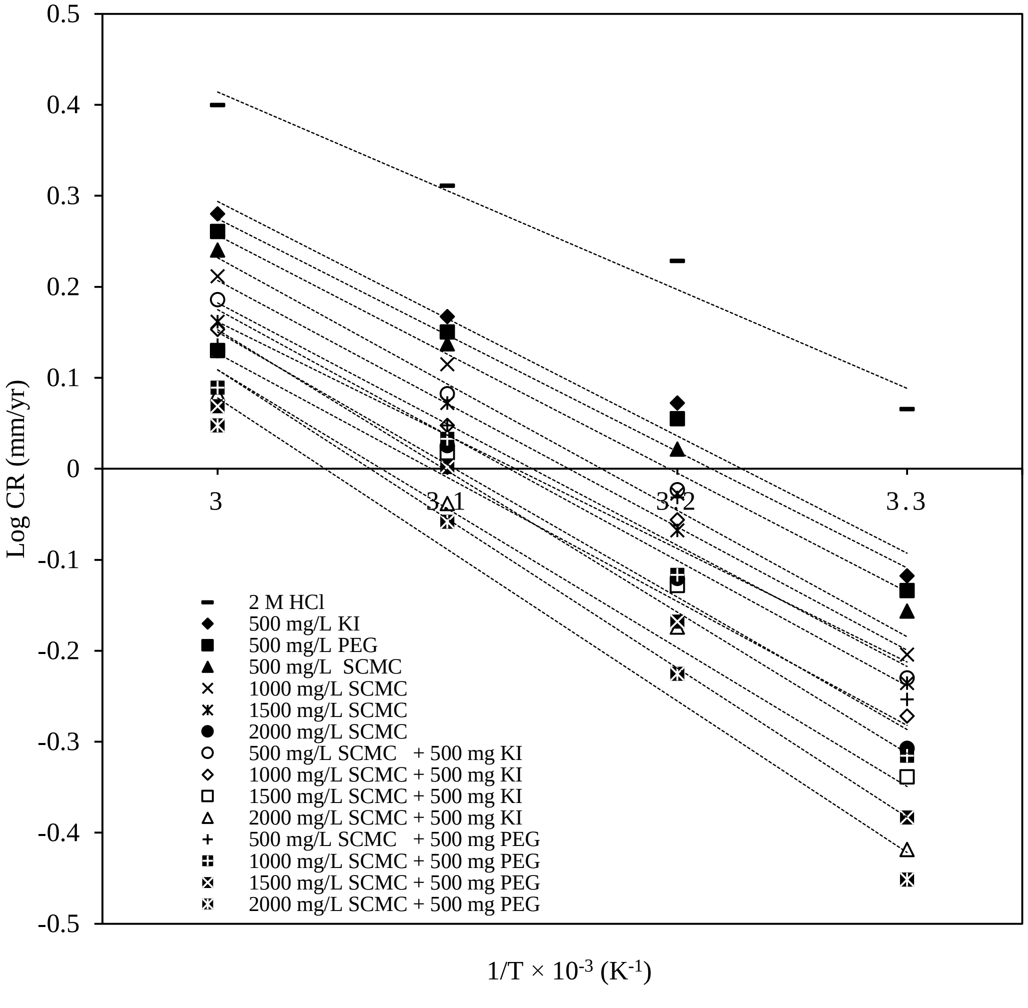


Figure 7 Log CR against 1/T without as well as alongside inhibitive compounds for mild steel submerged into 2 M HCl.

E_a values derived from slope ($-E_a$ / 2.303R) of the linearised plot from the figure and presented in **Table 4** were greater alongside the compounds comparative to their absence which indicates that energy threshold required for corrosion to ensue is amplified in presence of the compounds [36]. The fluctuation in E_a values alongside increasing content of the compounds is associated to adsorption-desorption behaviour of the adsorbed compounds alongside increasing temperature.

Heat of adsorption, Q_{ads}

One of the crucial thermodynamic considerations is *heat of adsorption.* Heat of adsorption is raised in a metal at high temperature which makes the metal susceptible to the sway of anions easily which in effect accelerates rate of corrosion. However, it is important to know that it is also used to ascertain the adsorptive mechanism employed by the adsorbed compounds on the metal surface by taking into account the effect of temperature on inhibitory performance of the compounds. Q_{ads} was calculated using Eq. (13) given thus:

$$Q_{ads} = 2.303R\left[\log\left(\frac{\theta_2}{1-\theta_2}\right) - \log\left(\frac{\theta_1}{1-\theta_1}\right)\right] * \left(\frac{T_1T_2}{T_2-T_1}\right) \quad (13)$$

where Q_{ads}, θ_1 and θ_2 at T_1 and T_2 denote heat of adsorption, proportion of surface coverages at lowest and highest temperatures, respectively. Presented in **Table 4** are calculated values of $Q_{ads.}$ The negative Q_{ads} values show that the compounds physically adsorb on the mild steel. This is further substantiated by the less than –40 KJ/mol obtained in all the systems [37]. Additionally, the fluctuation in Q_{ads} values alongside increasing content of the inhibitive compounds is indicative of adsorption-desorption behaviour of the adsorbed compounds alongside increasing temperature.

Enthalpy(ΔH_{ads}) and entropy (ΔS_{ads}) of adsorption

Energy requirement for corrosion activity to take place is denoted *enthalpy of adsorption* while how the energy is expended connotes *entropy of adsorption.* **Figure 8** shows the transition state plot for mild steel dipped into 2 M HCl solution without as well as alongside inhibitive compounds at varying temperatures derived from Eq. (14):

$$\text{Log}\left(\frac{\text{CR}}{T}\right) = \left[\log\left(\frac{R}{Nh}\right) + \left(\frac{\Delta S_{ads}}{2.303R}\right) - \left(\frac{\Delta H_{ads}}{2.303RT}\right)\right] \quad (14)$$

where h, N, R and T denote Planck's constant, Avogadro's number, universal gas constant and absolute temperature, respectively.

From slope ($-\Delta H_{ads}$ / 2.303R) and intercept [(log (R/Nh) + ΔS_{ads} /2.303R)] of the linearised plot, ΔH_{ads} and ΔS_{ads} values were derived, respectively and presented in **Table 4**. The enthalpy values being positive in the acid solution without as well as alongside the inhibitive compounds, respectively reveal that mild steel corrosion is endothermic. ΔH_{ads} values being greater alongside inhibitive compounds in 2 M HCl solution than their absence show that the compounds physically adsorb on the mild steel surface. The variation in ΔH_{ads} values alongside increasing content of the inhibitive compounds is suggestive of adsorption-desorption behaviour of the adsorbed compounds alongside increasing temperature. ΔS_{ads} values being negative in all the systems imply that molecules of the inhibitive compounds move about in solution without disturbances; and its low values show that adsorption of the compounds on mild steel led to decline in the degree of disarray of the system [38].

Table 4 Thermodynamic parameters for mild steel submerged into 2 M HCl without as well as alongside inhibitive compounds

System	ΔH$_{ads}$ (KJ mol^{-1})	ΔS$_{ads}$ (KJ mol^{-1} K^{-1})	E_a (KJ mol^{-1})	Q$_{ads}$ (KJ mol^{-1})
2 M HCl	17.87	–0.2363	19.79	-
500 mg/L KI	21.37	–0.2379	24.25	–13.69
500 mg/L PEG	21.69	–0.2379	22.98	–12.93
500 mg/L SCMC	21.69	–0.2388	25.21	–11.04
1000 mg/L SCMC	22.34	–0.2393	26.81	–12.83
1500 mg/L SCMC	22.98	–0.2400	25.53	–9.03

System	ΔH_{ads} (KJ mol^{-1})	ΔS_{ads} (KJ mol^{-1} K^{-1})	E_a (KJ mol^{-1})	Q_{ads} (KJ mol^{-1})
2000 mg/L SCMC	26.16	–0.2402	32.23	–13.51
500 mg/L SCMC + 500 mg KI	21.69	–0.2400	24.89	–11.39
1000 mg/L SCMC + 500 mg KI	22.34	–0.2404	25.21	–12.36
1500 mg/L SCMC + 500 mg KI	27.29	–0.2400	29.68	–17.00
2000 mg/L SCMC + 500 mg KI	27.45	–0.2411	30.32	–17.57
500 mg/L SCMC + 500 mg PEG	20.91	–0.2407	22.34	–6.72
1000 mg/L SCMC + 500 mg PEG	23.61	–0.2407	26.81	–7.91
1500 mg/L SCMC + 500 mg PEG	28.07	–0.2404	29.36	–12.73
2000 mg/L SCMC + 500 mg PEG	28.07	–0.2414	31.59	–16.95

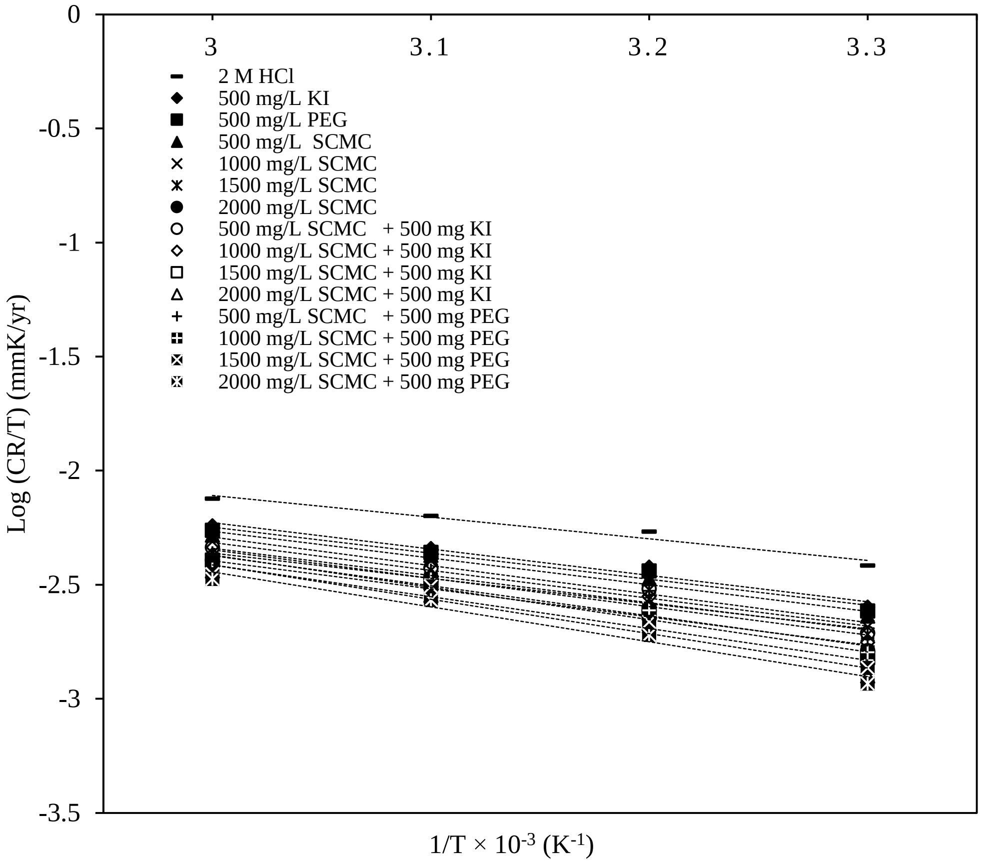


Figure 8 Log (CR/T) against 1/T without as well as alongside inhibitive compounds for mild steel submerged into 2 M HCl

Synergistic consideration

Table 5 shows the calculated synergism parameter, S_1 obtained by the relation between inhibitory efficiency of the inhibitive compounds as well as inhibitory efficiency of the inhibitive combinations [39] using Eq. (15):

$$S_1 = \frac{1-I_{1+2}}{1-I'_{1+2}} \tag{15}$$

where $I_{1+2} = (I_1 + I_2)$; I_1 is inhibitory efficiency of KI and PEG, respectively; I_2 is inhibitory efficiency of SCMC while I'_{1+2} is inhibitory efficiency of SCMC with KI and PEG, respectively.

S_1 proceeds towards unity when there are no interactions between compounds; whereas $S_1 > 1$ denotes synergistic interface while $S_1 < 1$ antagonistic interface (competitive adsorption). Hence, synergistic mechanism occasioned by SCMC-KI and SCMC-PEG mixtures, respectively on mild steel submerged into 2 M HCl solution has been explained earlier. From the calculated values of synergistic parameter for mild steel submerged into 2 M HCl solution for 5 days alongside inhibitive combinations at temperatures 30 and 60 °C presented in **Table 5**, synergistic adsorption was competitive. This was probably because large number of molecules of inhibitive combinations approached promptly the charged mild steel surface almost at the same time given their relatively equal binding energy on introduction into the acid solution, but certainly not at the same pace as the molecules obstructed one another during the course of their prompt approach towards the mild steel surface, leading to competition among molecules of inhibitive combinations towards the mild steel surface for adsorption, which gave little or no room for full sway of anions on corrosion vulnerable spots on mild steel in the acid solution.

Table 5 Calculated synergistic parameter for mild steel submerged into 2 M HCl alongside inhibitive combinations.

System	Temp. (°C)	Day				
		1	2	3	4	5
500 mg/L SCMC + KI	30	0.71	0.71	0.75	0.79	0.78
1000 mg/L SCMC + KI		0.59	0.69	0.73	0.75	0.77
1500 mg/L SCMC + KI		0.68	0.80	0.80	0.86	0.83
2000 mg/L SCMC + KI		0.64	0.81	0.83	0.85	0.85
500 mg/L SCMC + PEG		1.01	0.91	0.84	0.80	0.79
1000 mg/L SCMC + PEG		1.05	0.94	0.90	0.80	0.82
1500 mg/L SCMC + PEG		1.34	1.04	0.90	0.89	0.89
2000 mg/L SCMC + PEG		1.39	1.13	0.96	0.87	0.88
500 mg/L SCMC + KI	60	0.88	0.88	0.87	0.87	0.86
1000 mg/L SCMC + KI		0.90	0.90	0.89	0.87	0.87
1500 mg/L SCMC + KI		0.84	0.84	0.82	0.83	0.82
2000 mg/L SCMC + KI		0.89	0.87	0.85	0.86	0.85
500 mg/L SCMC + PEG		0.99	1.00	0.96	0.95	0.92
1000 mg/L SCMC + PEG		0.96	0.93	0.90	1.00	0.96
1500 mg/L SCMC + PEG		0.98	0.90	0.92	0.92	0.90
2000 mg/L SCMC + PEG		0.98	0.92	0.91	0.87	0.88

Potentiodynamic polarization study

Potentiodynamic polarization plot for mild steel submerged into 2 M HCl solution at 30 °C without as well as alongside inhibitive compounds is illustrated in **Figure 9**. The potentiodynamic polarization parameters derived from **Figure 9** are presented in **Table 6**. From the polarization plot, comparative to the blank experiment (without inhibitive compounds), anodic and cathodic parts of the polarization curves were shifted to the lower current density region in presence of the inhibitive compounds from 921.30 $\mu A/cm^2$ (without inhibitive compounds) to 487.60 $\mu A/cm^2$ in 0.5 g/L SCMC, 443.60 $\mu A/cm^2$ in 0.5 g/L SCMC + KI, 434.70 $\mu A/cm^2$ in 0.5 g/L SCMC + PEG and then 368.20 $\mu A/cm^2$ in 2 g/L SCMC, accordingly. This shows that introduction of the inhibitive compounds mitigates corrosion rate of mild steel by suppressing anodic dissolution and cathodic hydrogen evolution reactions. It was also found that corrosion current density decreased alongside increase in content of the inhibitive compounds while synergistic effect was observed to follow the trend SCMC + PEG > SCMC + KI > SCMC as observed in weight loss measurements results for mechanisms accounted earlier on this note. Also, it was observed that presence of inhibitive compounds shifted corrosion potential in a noble sense to anodic course within 500 mg/L SCMC and 500 mg/L SCMC+KI and cathodic course within 500 mg/L SCMC+PEG and 2000 mg/L SCMC with reference to E_{corr} of blank experiment. This shows that cathodic reaction is more effective in corrosion inhibition process of mild steel by more efficient inhibitive compounds. This scenario not only shows the corrosion inhibiting ability of the compounds but also shows the inhibitive compounds mitigated both anodic and cathodic reactions on mild steel within 2 M HCl solution and thus are regarded as mixed type inhibitors [40].

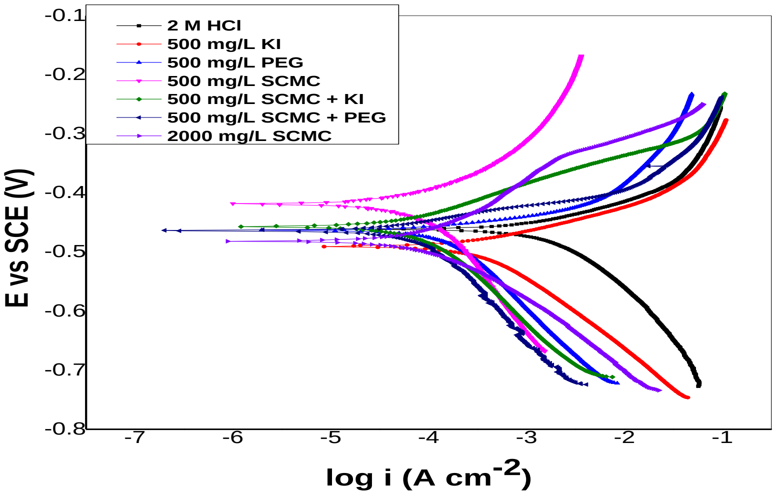


Figure 9 Polarization plot for mild steel submerged into 2 M HCl without as well as alongside inhibitive compounds at 30 °C

Table 6 Polarization parameters for mild steel submerged into 2 M HCl without as well as alongside inhibitive compounds at 30 ℃

System	I_{corr} (μA/cm^2)	E_{corr} (mV vs SCE)	IE (%)
2 M HCl	921.30	–453.40	-
500 mg/L KI	536.80	–497.90	41.74
500 mg/L PEG	523.40	–464.50	43.19
500 mg/L SCMC	487.60	–423.20	47.08
500 mg/L SCMC + KI	443.60	–449.60	51.85
500 mg/L SCMC + PEG	434.70	–466.80	52.82
2000 mg/L SCMC	368.20	–474.80	60.04

Scanning characterization

Surfaces of mild steel coupons were investigated by scanning electron microscope (model JSM-5600 LV) following a 5-day submersion into 2 M HCl solution without as well as alongside 500 mg KI, 500 mg PEG, 500 mg SCMC, 500 mg SCMC + KI and 500 mg SCMC + PEG, respectively. **Figure 10** clearly showed that sample (i) had no corrosion attack as the mild steel was not exposed to test solutions and thus, served as the control. The sample (ii), in the free acid solution, showed a significant attack resulting in severe surface roughness of the coupon owing to direct contact with the acid solution. Sample (iii) showed a moderate surface protection by KI adsorption; while sample (iv) showed a significant protection than that afforded by KI as a result of PEG adsorption. Then, sample (v), in 500 mg/L SCMC, showed a better surface protection occasioned by adsorption of SCMC and sample (vi) showed a much better protection as a result of co-adsorption by SCMC+KI mixture on the mild steel surface through coulomb interface. Finally, sample (vii) in presence of 500 mg/L SCMC+PEG mixture, showed the best protection owing to co-adsorption of SCMC+PEG mixture on the surface of mild steel for mechanisms accounted for earlier. These results evidently showed that the compounds served as corrosion inhibitors of mild steel within 2 M HCl solution and concurred with the results obtained in the weight loss and potentiodynamic polarization measurements.

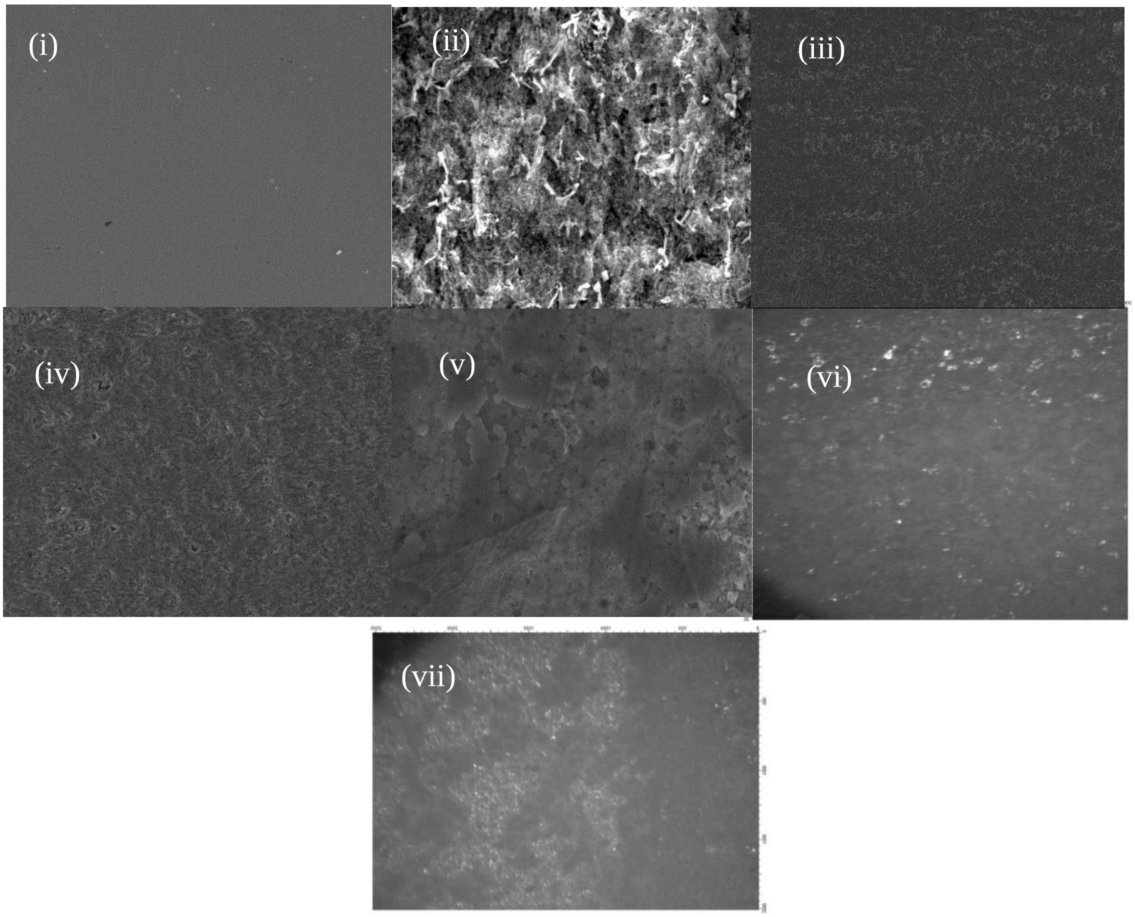


Figure 10 SEM microphotographs of (i) unexposed mild steel sample (ii) mild steel immersed into 2 M HCl solution without (iii) alongside 500 mg KI (iv) 500 mg PEG (v) 500 mg SCMC (vi) 500 mg SCMC+KI and (vii) 500 mg SCMC + PEG.

Conclusions

Investigation of mild steel corrosion within 2 M HCl solution without as well as alongside sodium carboxymethyl cellulose (SCMC) and its mixtures with potassium iodide (KI) and polyethylene glycol (PEG), respectively at temperatures between 30 and 60 °C was conducted using weight loss measurements while potentiodynamic polarization measurements were performed at 30 °C. SCMC significantly reduced corrosion rate of mild steel within 2 M HCl solution from 1.0229 mm/yr (without inhibitive compounds) to 0.5859 mm/yr within 0.5 g SCMC/L of 2 M HCl solution at 30 °C for 24 h immersion while corrosion rate stood from 1.1624 mm/yr (without inhibitive compounds) to 0.6975 mm/yr under the same conditions for 120 h immersion. SCMC showed maximum inhibition efficiency of 61.64 % on mild steel submerged into 2 g SCMC/L of 2 M HCl solution at 30 °C for 24 h immersion whereas effect of 0.5 g KI and PEG, respectively on the 2 g SCMC/L of 2 M HCl solution under the same conditions enhanced inhibition efficiency from 61.64 to 70.91 and 83.64 %, respectively by competitive adsorption on mild steel. Inhibition efficiency of SCMC on mild steel was lessened by increasing temperature from 57.60 % at 30 °C to 46.30 % at 60 °C within 2 g SCMC/L of 2 M HCl solution for 120 h immersion while effect of 0.5 g KI as well as PEG, respectively on the 2 g SCMC/L of 2 M HCl solution for 120 h immersion improved inhibition efficiency to 67.20 % at 30 °C and 51.85 % at 60 °C as well as 69.60 % at 30 °C and 55.56 % at 60 °C, respectively. Physical adsorption of inhibitive compounds on the mild steel surface afforded corrosion inhibition phenomenon by thermodynamic considerations. Polarization study conveyed that the inhibitor compounds behaved as mixed type inhibitors and obeyed Langmuir adsorption isotherm with inhibition efficiency of 47.08 % within 0.5 g SCMC/L of 2 M HCl solution, 51.85 % within 0.5 g SCMC + KI/L of 2 M HCl solution, 52.82 % within 0.5 g SCMC + PEG/L of 2 M HCl solution and 60.04 % within 2 g SCMC/L of 2 M HCl solution at 30 °C, respectively. Visual accounts of inhibitory performance by the compounds were portrayed by scanning electron microscopy. Lastly, inhibitory efficacy of the compounds rested on concentration of inhibitor compounds, immersion time, temperature and possibly synergistic effect.

Acknowledgements

The authors are appreciative for the equipment provided by both Polymer and Textile Engineering and Chemistry Departments of Federal University of Technology Owerri, Imo State, Nigeria.

References

[1] Corrosionpedia. Steel corrosion, Available at: https://www.coprrosionpedia, accessed May 2021.
[2] G Schmitt. Application of inhibitors for acid media: Report prepared for the European federation of corrosion working party on inhibitors. *Br. Corrosion J.* 1984; **19**, 165-76.
[3] F Bentiss, M Lagrenee, M Traisnel and JC Hornez. Corrosion inhibition of mild steel in 1 M hydrochloric acid by 2,5-bis(2-aminophenyl)-1,3,4-oxadiazole. *Corrosion* 1999; **55**, 968-76.
[4] M Yadav, L Gope, N Kumari and P Yadav. Corrosion inhibition performance of pyranopyrazole derivatives for mild steel in HCl solution: gravimetric, electrochemical and DFT studies. *J. Mol. Liq.* 2016; **216**, 78-86.
[5] A Dutta, SK Saha, P Banerjee and D Sukul. Correlating electronic structure with corrosion inhibition potentiality of some bis-benzimidazole derivatives for mild steel in hydrochloric acid: Combined experimental and theoretical studies. *Corrosion Sci.* 2015; **98**, 541-50.
[6] DK Singh, S Kumar, G Udayabhanu and RP John. 4(N, N-dimethylamino) benzaldehyde nicotinic hydrazone as corrosion inhibitor for mild steel in 1 M HCl solution: An experimental and theoretical study. *J. Mol. Liq.* 2016; **216**, 738-46.
[7] G Sığırcık, T Tüken and M Erbil. Assessment of the inhibition efficiency of 3,4-diaminobenzonitrile against the corrosion of steel. *Corrosion Sci.* 2016; **102**, 437-45.
[8] MM Solomon and SA Umoren. Enhanced corrosion inhibition effect of polypropylene glycol in the presence of iodide ions at mild steel/sulphuric acid interface. *J. Environ. Chem. Eng.* 2015; **3**, 1812-26.
[9] N Kıcır, G Tansuğ, M Erbil and T Tüken. Investigation of ammonium (2,4-dimethylphenyl)-dithiocarbamate as a new, effective corrosion inhibitor for mild steel. *Corrosion Sci.* 2016; **105**, 88-99.
[10] A Dutta, SK Saha, P Banerjee and D Sukul. Correlating electronic structure with corrosion inhibition potentiality of some bis-benzimidazole derivatives for mild steel in hydrochloric acid: Combined experimental and theoretical studies. *Corrosion Sci.* 2015; **98**, 541-50.
[11] A Popova, M Christov and A Vasilev. Mono- and dicationic benzothiazolic quaternary ammonium bromides as mild steel corrosion inhibitors. Part III: influence of the temperature on the inhibition process. *Corros. Sci.* 2015; **94**, 70-8.
[12] J Saranya, P Sounthari, K Parameswari and S Chitra. Acenaphtho[1,2-b] quinoxaline and acenaphtho[1,2-b] pyrazine as corrosion inhibitors for mild steel in acid medium. *Measurement.* 2016; **77**, 175-86.
[13] B Xu, Y Ji, X Zhang, X Jin, W Yang and Y Chen. Experimental and theoretical evaluation of N, N-Bis(2-pyridylmethyl) aniline as a novel corrosion inhibitor for mild steel in hydrochloric acid. *J. Taiwan Inst. Chem. E.* 2016; **59**, 526-35.
[14] P Mourya, P Singh, RB Rastogi and MM Singh. Inhibition of mild steel corrosion by 1,4,6-trimethyl-2-oxo-1,2-dihydropyridine-3-carbonitrile and synergistic effect of halide ion in 0.5 M H_2SO_4. *Appl. Surf. Sci.* 2016; **380**, 141-50.

[15] D Zhang, Y Tang, S Qi, D Dong, H Cang and G Lu. The inhibition performance of long-chain alkyl-substituted benzimidazole derivatives for corrosion of mild steel in HCl. *Corros. Sci.* 2016; **102**, 517-22.

[16] A Chetouani, B Hammouti and M Benkaddour. Corrosion inhibition of iron in hydrochloric acid solution by jojoba oil. *Pigm. Resin Tech.* 2004; **33**, 26-31.

[17] A Bouyanzer and B Hammouti. A study of anti-corrosive effects of Artemisia oil on steel. *Pigm. Resin Technol.* 2004; **33**, 287-92.

[18] EE Oguzie. Inhibition of acid corrosion of mild steel by Telfaria occidentalis extract. *Pigm. Resin Technol.* 2005; **34**, 321-26.

[19] EE Oguzie. Studies on the inhibitive effect of *Occimum viridis* extract on the acid corrosion of mild steel. *Mater. Chem. Phys.* 2006; **99**, 441-6.

[20] SA Umoren and EE Ebenso. Studies of the anti-corrosive effect of Raphia hookeri exudate gum-halide mixtures for aluminium corrosion in acidic medium. *Pigm. Resin Technol.* 2008; **37**, 173-82.

[21] M Abdallah. Guar gum as corrosion inhibitor for carbon steel in sulphuric acid solutions. *Port. Electrochim. Acta* 2004; **22**, 161-75.

[22] PC Okafor, UJ Ekpe, EE Ebenso, EM Umoren and KE Leizou. Inhibition of mild steel corrosion in acidic medium by Allium sativum extracts. *Bull. Electrochem.* 2005; **21**, 347-52.

[23] PC Okafor and EE Ebenso. Inhibitive action of Carica papaya extracts on the corrosion of mild steel in acidic media and their adsorption characteristics. *Pigm. Resin Tech.* 2007; **36**, 134-40.

[24] AAF Sabirneeza, R Geethanjali and S Subhashini. Polymeric corrosion inhibitors for iron and its alloys: A review. *Chem. Eng. Comm.* 2015; **202**, 232-44.

[25] E Bayol, AA Gürten, M Dursun and K Kayakirilmaz. Adsorption behaviour and inhibition corrosion effect of sodium carboxymethyl cellulose on mild steel in acidic medium. *Acta Physico-Chimica Sinica* 2008; **24**, 2236-43.

[26] MM Solomon, SA Umoren, II Udosoro and AP Udoh. Inhibitive and adsorption behaviour of carboxymethyl cellulose on mild steel corrosion in sulphuric acid solution. *Corrosion Sci.* 2010; **52**, 1317-25.

[27] R Aslam, M Mobin, J Aslam, H Lgaz and Ill-M Chung. Inhibitory effect of sodium carboxymethylcellulose and synergistic biodegradable gemini surfactants as effective inhibitors for mild steel corrosion in 1 M HCl. *J. Mater. Res. Tech.* 2019; **8**, 4521-33.

[28] SA Umoren, O Ogbobe, IO Igwe and EE Ebenso. Inhibition of mild steel corrosion in acidic medium using synthetic and naturally occurring polymers and synergistic halide additives. *Corrosion Sci.* 2008; **50**, 1998-2006.

[29] SA Abd El-Maksoud. The effect of organic compounds on the electrochemical behaviour of steel in acidic media - a review. *Int. J. Electrochem. Sci.* 2008; **3**, 528-55.

[30] SA Umoren and MM Solomon. Effect of halide ions on the corrosion inhibition efficiency of different organic species: A review. *J. Ind. Eng. Chem.* 2015; **21**, 81-100.

[31] EE Oguzie. Corrosion inhibition of aluminium in acidic and alkaline media by Sansevieria trifaciata extract. *Corrosion Sci.* 2007; **49**, 1527-39.

[32] JOM Bockris D Drazi, A Despic. The electrode kinetics of the deposition and dissolution of iron. *Electrochim. Acta* 1961; **4**, 325-61.

[33] A Singh, AK Singh and MA Quraishi. Dapsone: A novel corrosion inhibitor for mild steel in acid media. *Open Electrochem. J.* 2010; **2**, 43-51.

[34] SAM Refaey, F Taha and AMA El-Malak. Inhibition of stainless-steel pitting corrosion in acidic medium by 2-mercaptobenzoxazole. *Appl. Surf. Sci.* 2004; **236**, 175-85.

[35] IB Obot, NO Obi-Egbedi and SA Umoren. Antifungal drugs as corrosion inhibitors for aluminium in 0.1 M HCl. *Corrosion Sci.* 2009; **51**, 1868-75.

[36] EE Oguzie. Inhibition of acid corrosion of mild steel by Telfaria occidentalis extract. *Pigm. Resin Technol.* 2005; **34**, 321-26.

[37] A Bouyanzer, B Hammouti and L Majidi. Pennyroyal oil from Mentha pulegium as corrosion inhibitor for steel in 1 M HCl. *Mater. Lett.* 2006; **60**, 2840-3.

[38] AY El-Etre. Inhibition of aluminum corrosion using opuntia extract. *Corrosion Sci.* 2003; **45**, 2485-95.

[39] K Aramaki and N Hackermann. Inhibition mechanism of medium-sized polymethyleneimine. *J. Electrochem. Soc.* 1969; **116**, 568-74.

[40] W Li, Q He, S Zhang, B Pei and B Hou. Some new triazole derivatives as inhibitors for mild steel corrosion in acid medium. *J. Appl. Electrochem.* 2008; **38**, 289-95.