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Mitigation of Acid Corrosion on Carbon Steel by Naturally Occurring Gum Exudate

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Gum exudates of *Azadirachta indica* (GAI) was tested as corrosion inhibitor for carbon steel in 1 N H_2SO_4 by means of different techniques *viz.*, gravimetric experiments, electrochemical polarization and impedance studies, IR and SEM techniques. Nature of adsorption is reported and it follows Langmuir isotherm. Polarization method indicated mixed mode behaviour of the inhibitor. AC impedance studies supported mitigation effects of gum exudates of *Azadirachta indica*. IR and SEM studies reveal the protection of carbon steel through adsorption.

Keywords: ***Azadirachta indica*** **gum, Corrosion inhibitor, Electrochemical studies, Chemisorption, SEM.**

INTRODUCTION

Acid in general is employed to eliminate the detrimental corrosion products from metals in industries. In that circumstances, inhibitors are the most common source to handle the metal dissolution in acids. Majority of the well identified acid corrosion inhibitors are organic compounds having N, S and/or O atoms [1-5]. Such inhibitors obstruct the active sites on the metal by adsorbing on the metal surface through which manner they trim down the corrosion rate. Maximum number of investigated inhibitor compounds is lethal and cause rigorous ecological and environmental vulnerability [6]. The lethal paraphernalia of maximum synthetic corrosion inhibitors have directed to utilize natural products that are biodegradable and harmless. The use of natural products as corrosion inhibitors is well documented [7-13].

Number of gum exudates were also studied as corrosion inhibitors [14-17]. Gums are considered excellent corrosion inhibitors as they form complexes with the metal ion, occupy large surface area, contain number of hetero atoms, non-toxic, green and eco-friendly [18]. A flurry of work is made using various gums in different aggressive media for studying the corrosion effects in mild steel. From a survey of literature, it was found that less work was carried out for sulphuric acid corrosion of carbon steel using gum exudates as inhibitors [6,14-17,19-22]. Table-1 shows that towards carbon steel corrosion, gum exudates of *Azadirachta indica* at very low concentration of 60 ppm itself stands good with time as well as temperature. So, in this present study, the inhibition potency of gum exudates of *Azadirachta indica* in 1 N H_2SO_4 medium is investigated through weight loss, electrochemical and SEM techniques.

EXPERIMENTAL

Carbon steel of composition 0.68 % Mn, 0.37 % C, 0.23 % Si, 0.16 % Cu, 0.077 % Cr, 0.0059 % Ni, 0.016 % S, 0.011 % Ti, 0.00 9 % Co (wt. %), rest being Fe was employed for the analysis. Each specimen of dimension 25 mm × 10 mm × 1 mm was preserved after degreasing with ethanol, cleaning with acetone and drying before the experiments. AnalaR grade sulphuric acid and purified gum exudates of *Azadirachta indica* of concentrations 10 to 60 ppm were used for the study.

Methods: The weight loss method was carried out affording to the ASTM practice standard G-31 [23]. Corrosion rate, inhibition efficiency and surface coverage were obtained from the formulae given in well-known equations (eqns. 1-3).

$$\text{Corrosion rate (mmpy)} = 87.6 \times \frac{W}{\rho A t} \quad (1)$$

TABLE-1
COMPARISON OF CARBON STEEL CORROSION INHIBITION PERFORMANCE OF GUM EXUDATES OF *Azadirachta indica* WITH PREVIOUSLY STUDIED GUM EXUDATES

Gum exudates	Corrosive media	Inhibitor concentration (ppm)	Temperature (°C)	Inhibition efficiency (%)	Ref.
Xanthum gum	1.0 M HCl	1000	30	82.31	[19]
Arabino galactan from gum tragacanth	1.0 M HCl	500	60	96.30	[20]
Guar gum	1.0 M H_2SO_4	1500	30	93.88	[21]
Gum exudates of *Azadirachta indica*	0.5 M H_2SO_4	60	60	83.71	Present work

$$\text{Inhibition efficiency (\%)} = \frac{W_o - W_i}{W_o} \times 100 \quad (2)$$

$$\text{Surface coverage } (\theta) = 1 - \frac{W_i}{W_o} \quad (3)$$

Polarization and impedance measurements were performed with the cell which consisted of a platinum and saturated calomel electrodes as counter and reference electrodes. The carbon steel electrode with 0.5 cm exposure area was made dipped in the test solutions. For the polarization experiments potential range used was +200 to –200 with 1 mV s^{-1} scan rate of OCP and for impedance studies frequency range of 10 KHz to 0.01 Hz was used with AC signals. The inhibition efficiency by polarization and impedance methods was calculated using eqns. 4 and 5, respectively.

$$\text{Inhibition efficiency} = \frac{i^{o}_{corr} - i_{corr}}{i_{corr}} \times 100 \quad (4)$$

$$\text{Inhibition efficiency (\%)} = \frac{R_{ct} - R^{o}_{ct}}{R_{ct}} \times 100 \quad (5)$$

where, i_{corr}, i°_{corr}, R_{ct} and R°_{ct} are the corrosion current density with inhibitor, corrosion current density without inhibitor, charge transfer resistance with inhibitor and charge transfer resistance without inhibitors respectively.

Shimadzu FT-IR 8000 spectrophotometer was utilized to record the IR spectra in order to determine the interaction of inhibitor with the carbon steel specimen. Scanning electron microscopy was employed to examine the surfaces of carbon steel specimens.

RESULTS AND DISCUSSION

Weight loss measurements

Corrosion inhibition performance of gum exudates of *Azadirachta indica*: The influence of gum exudates of *Azadirachta indica* on corrosion process of carbon steel in 1 N sulphuric acid for different immersion periods was studied using weight loss technique in the temperature range of 303-323 K. The corrosion rates, inhibition efficiency and surface coverage were determined using eqns. 1, 2 and 3, respectively. Table-2 shows that the inhibition efficiency is high in the presence of gum exudates of *Azadirachta indica* than in the free acid solution for all the immersion periods studied. Further with increase in concentration of gum exudates of *Azadirachta indica*, inhibition efficiency increases. 60 ppm gum exudates of *Azadirachta indica* was found as optimum concentration which shows maximum efficiency where optimal adsorption of gum exudates of *Azadirachta indica* on the metal took place [24] and thus reduction in area open for acid attack is attained. However above 60 ppm, the corrosion rate is found almost same with slight change which might be due to competitive adsorption [25]. Gum exudates of *Azadirachta indica* is a plant gum exudating from *Melia azadirachta.* Actually the gum is a complex polysaccharide complex [26]. Due to the complexity of the inhibitor compound, it is difficult to pronounce the specific mechanistic path of the corrosion process. The nature of inhibition process is well appreciated by analyzing the constituents of neem gum. The neem gum contains a 35 % of proteinaceous material which is mostly made of aspartic acid and significant proportions of threonine and serine and also it is a very complex carbohydrate component which constitutes of D-glucose, D-glucoronic acid, L-fucose, L-arabinose, mannose, xylose, rhamnose, glucosamine and aspartic acid. Aldobiuronic acid along with D-galactose is also present [27]. Hence, it can be ascribed that gum exudates of *Azadirachta indica* with its larger size, number of reactive functional groups and different hetero atoms present in the chemical structure can be anticipated to adsorb onto the metal surface in an extensive manner subsequently reducing the corrosion rate.

TABLE-2
CORROSION PARAMETERS OBTAINED FROM WEIGHT LOSS MEASUREMENTS FOR CARBON STEEL IN 1 N H_2SO_4 SOLUTION CONTAINING VARIOUS CONCENTRATIONS OF GUM EXUDATES OF *Azadirachta indica*

Immersion period (h)	Concentration (ppm)	Corrosion rate (mmpy)	Inhibition efficiency (%)	Surface coverage (θ)
1	Blank	57.8620	–	–
	5	44.3006	23.44	0.2344
	10	27.5749	52.34	0.5234
	20	23.9585	58.59	0.5859
	40	19.8901	65.63	0.6563
	60	18.0819	68.75	0.6875
2	Blank	51.9854	–	–
	5	39.7801	23.48	0.2348
	10	27.3489	47.39	0.4739
	20	25.9927	50.00	0.5000
	40	14.4655	72.17	0.7217
	60	12.6573	75.65	0.7565
4	Blank	56.5059	–	–
	5	13.9004	75.40	0.7540
	10	12.8833	77.20	0.7720
	20	11.3012	80.00	0.8000
	40	9.8320	82.60	0.8260
	60	8.3629	85.20	0.8520
6	Blank	64.3414	–	–
	5	22.9791	64.29	0.6429
	10	15.0682	76.58	0.7658
	20	11.4519	82.20	0.8220
	40	10.6231	83.49	0.8349
	60	10.0204	84.43	0.8443

Effect of immersion period: Gravimetric experiments were performed in sulphuric acid medium to assess the inhibitor stability on carbon steel surface with and without gum exudates of *Azadirachta indica* for 1-6 h of immersion time at room temperature. From the Table-2, it can be observed that with increase in immersion period the inhibition efficiency of gum exudates of *Azadirachta indica* increased upto 4 h which is indicative of strong adsorption of gum exudates of *Azadirachta indica* upon the carbon steel surface ensuing shielding deposit. It is suggestive of chemical adsorption when there is increase in inhibition efficiency with increase in time [28]. In the present case, efficiency of the inhibitor rises until 4 h. The efficiency of the inhibitor first increases with the immersion time, reaching a maximum at 4 h and showed a decrease with further increase in immersion time.

Effect of temperature: Effect of temperature was evaluated in the range 303-323 K using mass loss method for different concentrations of gum exudates of *Azadirachta indica* and corrosion parameters were tabulated in Tables-3a and 3b for immersion periods of 1 and 4 h, respectively. The temperature dependence can be expressed using the following Arrhenius equation:

TABLE-3a
CORROSION PARAMETERS FOR CARBON STEEL IN 1 N H_2SO_4 SOLUTION CONTAINING VARIOUS CONCENTRATIONS OF GUM EXUDATES OF *Azadirachta indica* AT DIFFERENT TEMPERATURES FOR 1 h IMMERSION PERIOD

Temp. (K)	Concentration (ppm)	Corrosion rate (mmpy)	Inhibition efficiency (%)	Surface coverage (θ)
303	Blank	57.8620	–	–
	10	27.5749	52.34	0.5234
	20	23.9585	58.59	0.5859
	40	19.8901	65.63	0.6563
	60	18.0819	68.75	0.6875
313	Blank	160.4767	–	–
	10	78.6562	50.99	0.5099
	20	56.5059	64.79	0.6479
	40	38.4240	76.06	0.7606
	60	33.9035	78.87	0.7887
323	Blank	277.5569	–	–
	10	91.7656	66.94	0.6694
	20	63.2866	77.20	0.7720
	40	49.2731	82.25	0.8225
	60	45.2047	83.71	0.8371

TABLE-3b
CORROSION PARAMETERS FOR CARBON STEEL IN 1 N H_2SO_4 SOLUTION CONTAINING VARIOUS CONCENTRATIONS OF GUM EXUDATES OF *Azadirachta indica* AT DIFFERENT TEMPERATURES FOR 4 h IMMERSION PERIOD

Temp. (K)	Concentration (ppm)	Corrosion rate (mmpy)	Inhibition efficiency (%)	Surface coverage (θ)
303	Blank	56.51	–	–
	10	12.88	77.20	0.7720
	20	11.30	80.00	0.8000
	40	9.83	82.60	0.8260
	60	8.36	85.20	0.8520
313	Blank	221.05	–	–
	10	124.20	43.81	0.4381
	20	99.56	54.96	0.5496
	40	69.95	68.35	0.6835
	60	64.02	71.04	0.7104
323	Blank	361.86	–	–
	10	226.36	37.45	0.3745
	20	209.30	42.16	0.4216
	40	166.81	53.90	0.5390
	60	135.50	62.55	0.6255

$$\log CR = \log A - \frac{E_a^*}{2.303RT} \quad (6)$$

where A is the frequency factor and E_a is the apparent activation energy.

It is said to be chemisorption when there is increase in inhibition efficiency with corresponding decrease in activation value [29]. Figs. 1a-b show the plot between log CR and 1/T from which slope gives ($-E_a$/2.303 R) while the intercept gives A. E_a values were presented in Table-4.

Kinetic data enthalpy (ΔH^*) and entropy (ΔS^*) of corrosion can be found using the alternate Arrhenius equation:

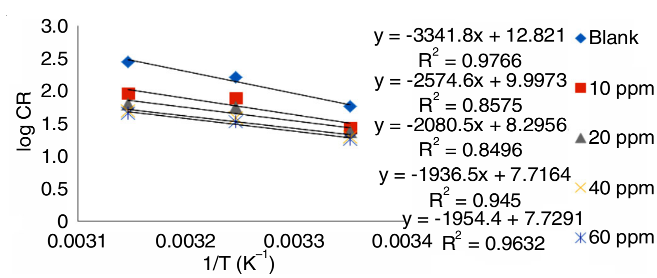

Fig. 1a. Arrhenius plot - GAI on carbon steel in 1 N H_2SO_4 for 1 h immersion time

TABLE-4
ACTIVATION PARAMETERS OBTAINED FROM WEIGHT LOSS MEASUREMENTS FOR CARBON STEEL IN 1 N H_2SO_4 SOLUTION CONTAINING VARIOUS CONCENTRATIONS OF GUM EXUDATES OF *Azadirachta indica* AT DIFFERENT TEMPERATURES

Immersion period (h)	Concentration (ppm)	E_a (kJ mol^{-1})	ΔH (kJ mol^{-1})	ΔS (J K^{-1} mol^{-1})	(E_a-ΔH)
1	Blank	65.1920	62.5344	-4.34961	2.6576
	10	49.9899	47.3323	-60.0950	2.6576
	20	40.3863	37.7287	-93.1629	2.6576
	40	37.7173	35.0597	-103.9820	2.6576
	60	38.0970	35.4394	-103.6170	2.6576
4	Blank	77.2061	74.5485	35.65281	2.6576
	10	119.1695	116.5119	162.9393	2.6576
	20	121.3585	118.7009	168.7507	2.6576
	40	117.7135	115.0559	155.0933	2.6576
	60	115.8007	113.1431	147.7020	2.6576

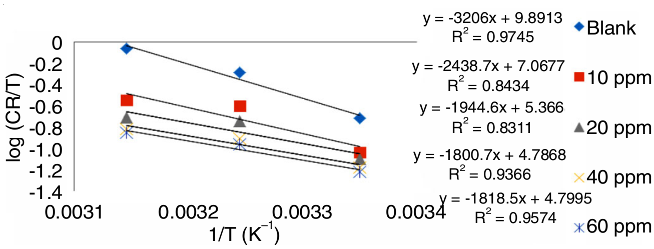

Fig. 1b. Transition state plot - GAI carbon steel 1 N H_2SO_4 for 1 h immersion time

$$CR = \left(\frac{RT}{Nh}\right)\exp\left(\frac{\Delta S^*}{R}\right)\exp\left(\frac{-\Delta H^*}{RT}\right) \tag{7}$$

Graph between log (CR/T) and 1/T was represented in Figs. 2a-b, whose slope and intercept was used to calculate ΔH^* and ΔS^*. E^*_a for uninhibited 1 N H_2SO_4 solution with an immersion period of 1 h was 65.19 kJ mol^{-1}. It is found that the E_a value in inhibited system is lower than that in the uninhibited system. The reduction of E_a in the presence of inhibitor may be attributed to the chemisorption of inhibitor on the steel surface [30,31]. The change in enthalpy (ΔH^*) for the inhibited solution containing various concentrations of gum exudates of *Azadirachta indica* are lower than the blank again supports the chemical mode of adsorption. Also, endothermic nature was reflected from positive values of enthalpy values [32,33]. For 1 h immersion study, the values of ΔS^* for uninhibited solution was -4.34 J K^{-1} mol^{-1} and it decreases towards more negative side with increase in concentration of gum exudates of *Azadirachta indica* up to maximum of -103.98 J K^{-1} mol^{-1}. The negative ΔS^* value with and without inhibitor indicated the association corrosion mechanism. Addition of gum exudates of *Azadirachta indica* to the free acid solution alters the ΔS^* which is indicative of decrease in corrosion rate.

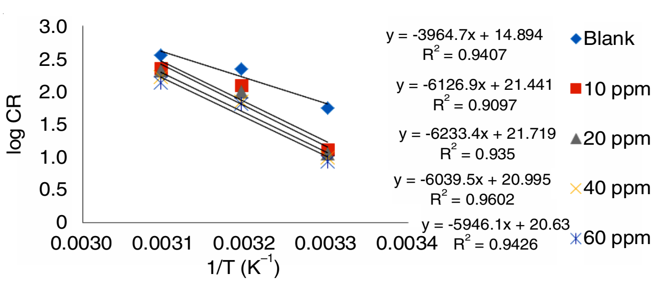

Fig. 2a. Arrhenius plot-GAI on carbon steel in 1 N H_2SO_4 for 4 h

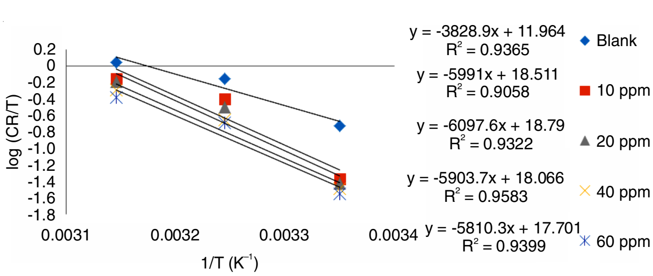

Fig. 2b. Transition state plot-GAI carbon steel 1 N H_2SO_4 for 4 h

To determine the stability of the inhibitor with time, the temperature studies are performed with 4 h immersion time also. E_a, ΔH^* and ΔS are calculated as explained above and the corresponding Arrhenius and transition state plots are given in Figs. 2a-b. From Table-4, contrary to 1 h studies, it is found that with 4 h immersion period, E_a value for blank solution is lower than that for the inhibited test solutions. The change in enthalpy (ΔH^*) for the inhibited solution containing 60 ppm gum exudates of *Azadirachta indica* (113.14 kJ mol^{-1}) is found to be higher than blank solution (74.54 kJ mol^{-1}) again supports the physical mode of adsorption. So the presence of inhibitor increases the energy barrier. On comparing the entropy activation values of uninhibited (35.65 J K^{-1} mol^{-1}) and inhibited solution, it is understood that disorderness is increased indicating the activated complex formation as well as signifying the inhibition action of gum exudates of *Azadirachta indica* [34].

Adsorption isotherm: Adsorption behaviour can be well understood from surface coverage of inhibitors. Adsorption isotherms can be tested using surface coverage values. In the present case, the best fit isotherm was found as Langmuir model. The following eqn. 8 was used to plot graph between concentration (C) and surface coverage (θ) from which equilibrium adsorption constant K_{ads} was evaluated.

$$C/\theta = 1/K_{ads} + C \tag{8}$$

Langmuir plots are characteristic of having slope of unity and intercept [35,36] (Fig. 3). Table-5 reveals that the slopes obtained for the Langmuir plots were close to unity and thus it implies that Langmuir isotherm was obeyed as strong correlation was also observed. Eqn. 9 shows the relation between Equilibrium constant and free energy of adsorption [37].

$$K = -\log C_{H_2O} - \left(\frac{\Delta G^o_{ads}}{2.303RT}\right) \tag{9}$$

where R is the universal gas constant, T is the absolute temperature and 55.5 is the concentration of H_2O in solution [38]. In general free energy of adsorption around -40 kJ/mol is indicative of chemisorption and that around -20 kJ/mol is physisorption [39]. The negative ΔG_{ads} obtained means that the adsorption of gum exudates of *Azadirachta indica* was spontaneous which was the direct evidence for strong adsorption of gum exudates of *Azadirachta indica* on carbon steel [40]. Analyses of the experimental results suggest that the inhibitor gum exudates of *Azadirachta indica* inhibited through both physical and chemical mode of adsorption onto the carbon steel substrate.

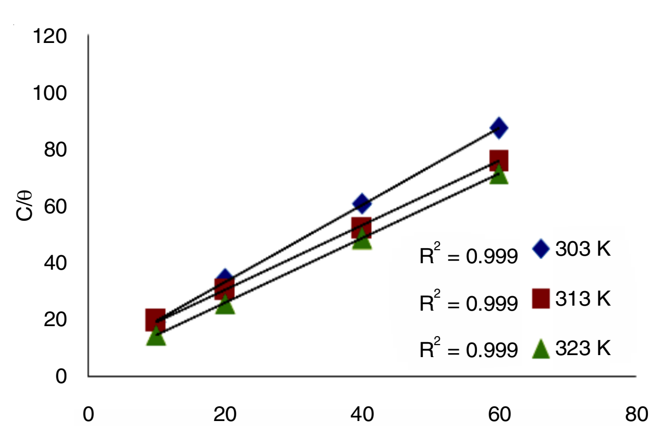

Fig. 3. Langmuir adsorption isotherm

TABLE-5
ADSORPTION PARAMETERS OBTAINED FROM TEMPERATURE AND ISOTHERM PLOTS OF THE CORROSION RATE VALUES OF CARBON STEEL IN GUM EXUDATES OF *Azadirachta indica*

Isotherm	Temp. (K)	R^2	Slope	K_{ads} (mol^{-1})	ΔG_{ads} (kJ/mol)
	303	0.999	1.3564	159.13	22.89
Langmuir	313	0.999	1.1249	121.55	22.21
	323	0.999	1.1361	297.26	24.47

Electrochemical polarization methods: Polarization curves for carbon steel in 1 N sulphuric acid in the absence and presence of various concentrations of gum exudates of *Azadirachta indica* was given in Fig. 4. The corrosion current density and potential were attained by the usual way of extrapolating the current and potential curves. The values of E_{corr}, I_{corr}, inhibition efficiency and Tafel slopes (b_a and b_c) were presented in Table-6. Addition of gum exudates of *Azadirachta indica* to 1 N H_2SO_4 solution brings about a change in anodic and cathodic Tafel slopes. The decrease in current density in the presence of inhibitor signifies gum exudates of *Azadirachta indica* was adsorbed on the metal substrate resulting in increase of inhibition efficiency. From Fig. 4, it was clear that the nature of polarization curves remained unaltered except for a shift in current density in the presence of gum exudates of *Azadirachta indica*. Thus, gum exudates of *Azadirachta indica* addition hinder the corrosion influence without changing the mechanism of corrosion process.

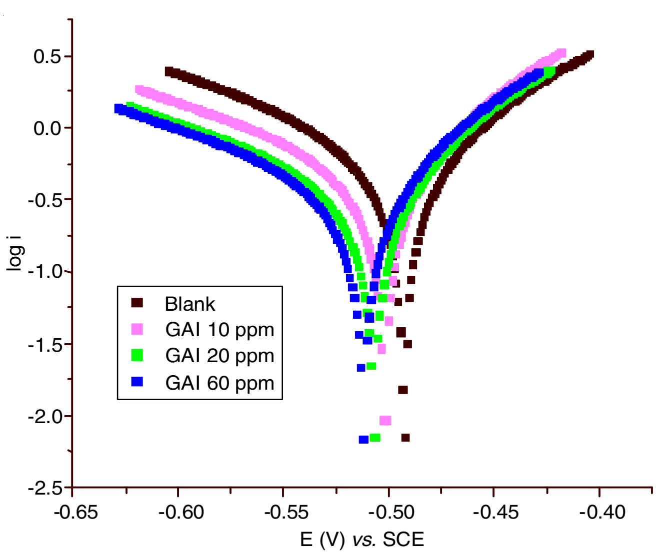

Fig. 4. Potentiodynamic polarization curves for carbon steel in 1 N H_2SO_4

The E_{corr} value in the presence of gum exudates of *Azadirachta indica* was changed a slight, which means gum exudates of *Azadirachta indica* was mixed mode type of inhibitor affecting both anodic and cathodic reactions [41]. An E_{corr} shift more than ± 85 mV from the free acid solution can be considered as cathodic or anodic type [42]. But in the present case, a maximum shift was found to be 23 mV, the inhibitor could be considered as mixed type [43]. The behaviour of Tafel slopes b_a and b_c also suggested mixed type of behaviour for the inhibitor.

AC impedance study: The inhibition performance of gum exudates of *Azadirachta indica* on carbon steel in sulphuric acid was investigated by electrochemical impedance spectroscopy. Fig. 5 exhibits the Nyquist plots for carbon steel in sulphuric acid with and without inhibitor. Imperfect semicircles were indicative of presence of charge transfer process. Also it was understood that corrosion dissolution mechanism was not altered by gum exudates of *Azadirachta indica* [44]. The values of impedance parameters were presented in Table-7. Double layer capacitance C_{dl} was calculated using eqn. 10:

$$C_{dl} = 1/2\pi\, f_{max}\, R_{ct} \quad (10)$$

where f_{max} is the maximum frequency.

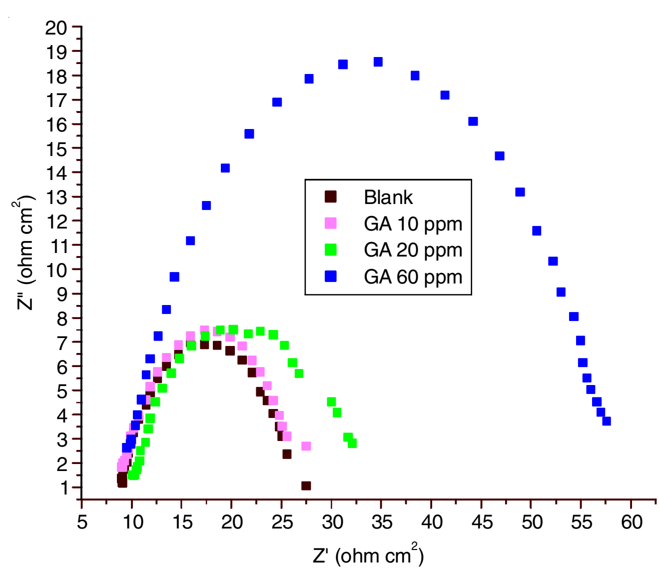

Fig. 5. Nyquist plots of carbon steel in 1 N H_2SO_4

It is obvious from Table-7 that the value of R_{ct} increased with increasing concentration of the inhibitor. This can be ascribed to the formation of protective film at the carbon steel-sulphuric acid interface [45]. The decrease in C_{dl} values shows

TABLE-6
ELECTROCHEMICAL POLARIZATION PARAMETERS FOR CARBON STEEL IN 1 N H_2SO_4 IN THE ABSENCE AND PRESENCE OF VARIOUS CONCENTRATIONS OF GUM EXUDATES OF *Azadirachta indica*

Concentration (ppm)	$-E_{corr}$ (V *vs*. SCE)	I_{corr} (mA/cm^2)	Tafel slope (mV/decade)		Inhibition efficiency (%)
			b_a	b_c	
Blank	490.1	410	85	137	-
10	493.4	410	89	140	44.63
20	505.8	227	90	150	50.97
60	513.6	201	74	160	55.60

TABLE-7
AC IMPEDANCE PARAMETERS FOR CARBON STEEL IN 1 N H_2SO_4 CONTAINING GUM EXUDATES OF *Azadirachta indica* GUM

Conc. (ppm)	R_{ct} (Ω cm^{-2})	C_{dl} (μF cm^{-2}) × 10^{-3}	Inhibition efficiency (%)
Blank	19.19	35.1	–
10	22.5	16.9	14.71
20	25.8	15.7	25.62
60	48.4	14.1	60.35

that the adsorption of gum exudates of *Azadirachta indica* has taken place at the carbon steel surface. According to Helmholtz model, the thickness of protective layer (d) is related to C_{dl} as given in eqn. 11:

$$C_{dl} = \frac{\varepsilon\varepsilon_o A}{d} \quad (11)$$

where ε, ε_o and A are dielectric constant, permittivity and surface area of the electrode respectively. From (eqn. 10), it is clear that C_{dl} will decrease with increase in adsorption. In our present study C_{dl} value is highest for uninhibited solution and it is found that the gum exudates of *Azadirachta indica* addition decreases the C_{dl} which in turn increase the thickness of the double layer. Eqn. 5 is used to obtain the inhibition efficiency from R_{ct} values. The R_{ct} was found highest for 60 ppm concentration of gum exudates of *Azadirachta indica*.

FT-IR spectra: Figs. 6a and 6b shows the FTIR spectra of gum exudates of *Azadirachta indica* solution and that of carbon steel immersed in 1 N H_2SO_4. Fig. 6a exhibits vibrant and resilient characteristics of polysaccharides in gum exudates of *Azadirachta indica*. It is characterized with its –OH characteristic stretching frequency in the region between 3540-3100 cm^{-1}. Absorption bands at 1639 and 1523 cm^{-1} are due to C-O bond of carboxyl group. The 856.39 cm^{-1} band was because of the presence of glycosides bond in gum exudates of *Azadirachta indica* alike in polysaccharides [46].

On comparing the intensities of major vibrational modes in Figs. 6a and 6b, adsorption mechanism can be followed. The missing of O-H bond stretching at 3540-3100 cm^{-1} and

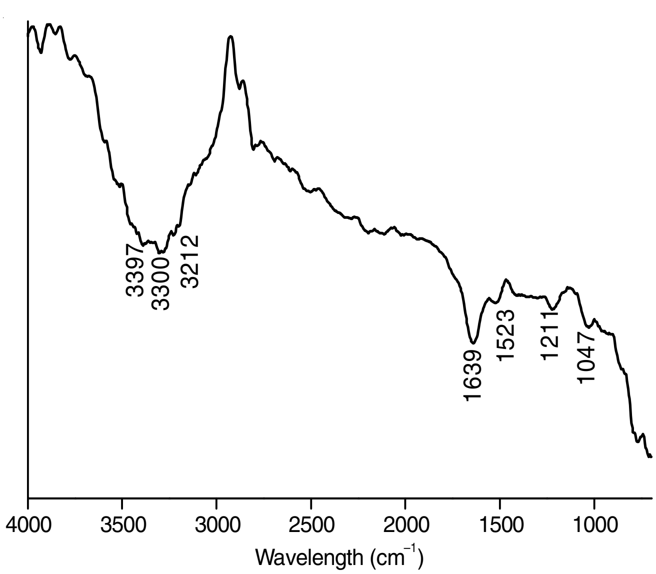

Fig. 6(a). FT-IR spectrum of gum exudates of *Azadirachta indica* solution

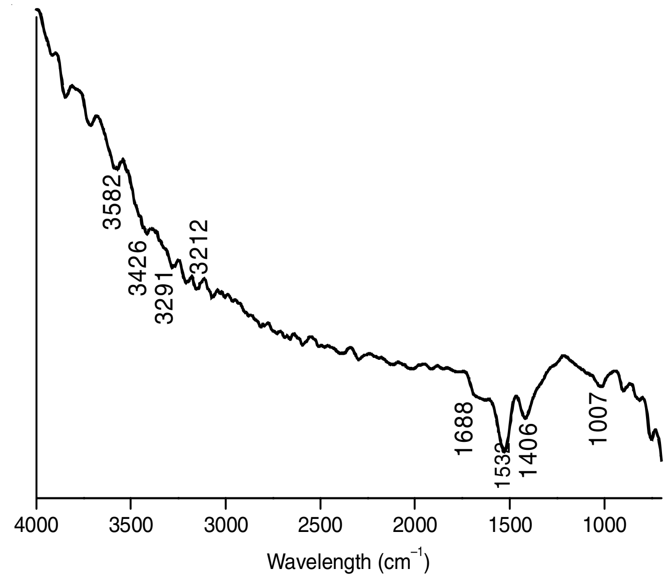

Fig. 6b. FT-IR spectrum of carbon steel immersed in 1 N H_2SO_4 in the presence of gum exudates of *Azadirachta indica* for 1 h

decrease of intensity for >C=O bond stretching of carboxylate group at 1639 and 1523 cm^{-1} observed in the Fig. 6(b) The above shifting in the characteristic peaks is ascribed to adsorption of gum exudates of *Azadirachta indica* on carbon steel surface. Disappearance of the peaks at 2877, 1300 and 1222 cm^{-1} clearly indicates that gum exudates of *Azadirachta indica* adsorption on carbon steel specimen was through these functional groups [47]. Formation of fresh bands around 1531, 1419 and 749 cm^{-1} were indicative of formation of new bonds [48]. So it can be ascertained that gum exudates of *Azadirachta indica* got adsorbed on the metal surface through the prominent functional groups.

Scanning electron microscopy: The above discussion makes it clear that gum exudates of *Azadirachta indica* is proved to be good inhibitor for carbon steel in 1 N H_2SO_4. To confirm the obtained results, electron microscope photographs of carbon steel specimen were taken before and after immersion in test solutions. The SEM photographs are shown in Figs. 7(a)–(c). Fig. 7(a) illustrates the polished surface of the carbon steel coupon before immersion in the solution, while Fig. 7(b) depicts the effect of 1 N H_2SO_4 solutions on the carbon steel specimen after 1 h immersion. It clearly shows large pits that are caused by the attack of 1 N H_2SO_4 solution. Fig. 7(c) shows surface of the carbon steel coupon immersed in 1 N H_2SO_4 solution along with 60 ppm gum exudates of *Azadirachta indica*. It can be seen that surface morphology entirely changed in the presence of gum exudates of *Azadirachta indica*. Adsorption of gum exudates of *Azadirachta indica* is evinced from disappearance of large pits in Fig.7(c). Thus SEM studies revealed that gum exudates of *Azadirachta indica* reduced the corrosion rate by adsorption.

Conclusion

• Gum exudates of *Azadirachta indica* is found to be an efficient inhibitor for carbon steel in 1 N H_2SO_4.

• With increase in both concentration and temperature, the inhibition efficiency found to increase.

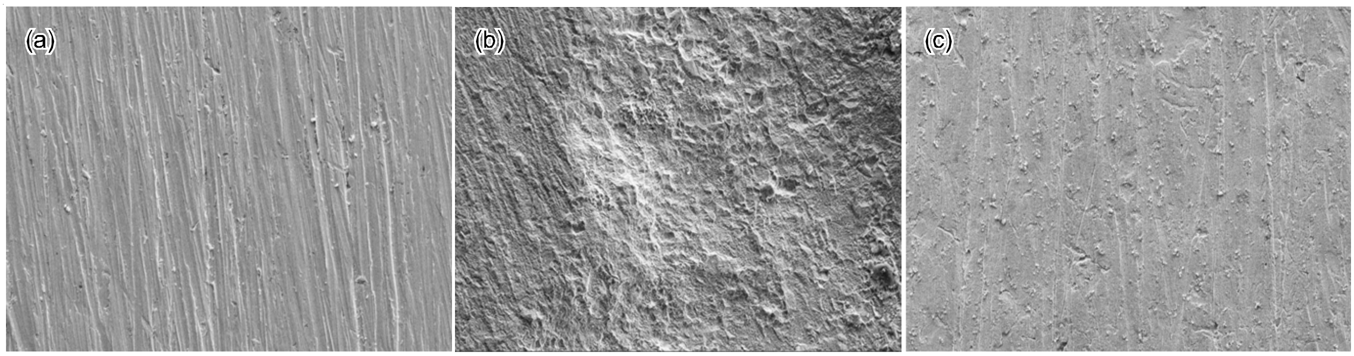

Fig. 7. SEM photographs of carbon steel sample (a) polished surface (b) after immersion in 1N H_2SO_4solution (c) in the presence of 60 ppm gum exudates of *Azadirachta indica*

• A stable increase in the inhibitor performance up to a reasonable amount of time.

• The activation energy values, enthalpy of activation and free energy of adsorption proposed chemisorption mechanism at 1 h immersion period and physisorption at 4 h immersion period.

• The adsorption behaviour of gum exudates of *Azadirachta indica* on carbon steel in sulphuric acid is confined to Langmuir adsorption isotherm.

• The polarization measurements indicate that the inhibitor is a mixed mode type.

• The protective layer formed is ascertained by FTIR and SEM studies.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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