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ORIGINAL ARTICLE

Inhibitive action of ethanol extracts from *Nauclea latifolia* on the corrosion of mild steel in H_2SO_4 solutions and their adsorption characteristics

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Abstract The inhibitive action of ethanol extracts from leaves (LV), bark (BK) and roots (RT) of *Nauclea latifolia* on mild steel corrosion in H_2SO_4 solutions at 30–60 °C was studied using weight loss and gasometric techniques. The extracts were found to inhibit the corrosion of mild steel in H_2SO_4 solutions and the inhibition efficiencies of the extracts follow the trend: RT > LV > BK. The inhibition efficiency increased with the extracts concentration but decreased with temperature rise. Physical adsorption of the phytochemical components of the plant on the metal surface is proposed as the mechanism of inhibition. The adsorption characteristics of the inhibitor were approximated by the thermodynamic-kinetic model of El-Awady et al.

1. Introduction

Mineral acids of various concentrations are extensively employed in various industrial processes including chemical cleaning, acid pickling and acid descaling as well as in oil well acidification which result in corrosion. Due to the aggressiveness of these acids many organic compounds have been studied and employed as corrosion inhibitors. It is interesting to note that in the field of corrosion inhibition we are going back to the past as a result of the fact that increasing awareness of health and ecological risks is drawing attention to finding more suitable non-toxic inhibitors, which are found mostly among the class of natural products. The first patent in corrosion inhibition was to Baldwin, British Patent 2327, which specified the use of a natural product, molasses and vegetable oils for pickling sheet steel in acids (Putilova et al., 1960). US Patent 640491 in 1900 to Robinson and Sutherland used starch, a biodegradable material. Present trends in research on environmental friendly corrosion inhibitors are concentrating on natural products origin due principally to their low cost and eco-friendliness. Among these natural products are plants

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extracts. They constitute several organic compounds which have corrosion inhibiting abilities. The yield of these compounds as well as the corrosion inhibition abilities vary widely depending on the part of the plant (Khuzhaeu and Aripova, 2000; Okafor and Ebenso, 2007; Okafor et al., 2008) and its geographical location (Ogan, 1971). The use of natural products as corrosion inhibitors have been widely reported by several authors. The extracts from the leaves, seeds, heartwood, bark, roots and fruits of plants have been reported to inhibit metallic corrosion in acidic media (Ebenso and Ekpe, 1996; Ebenso et al., 2004a,b; Gunasekaran and Chauhan, 2004; Okafor et al., 2005, 2006, 2008, 2009, 2010; El-Etre et al., 2005; Oguzie, 2006; Oguzie et al., 2006; Abdel-Gaber et al., 2006; Umoren et al., 2006; Okafor and Ebenso, 2007; Abiola et al., 2009; Abiola and Otaigbe, 2009; Abiola and James, 2010). The use of extracts from plants as corrosion inhibitors has been reviewed extensively in our previous work (Okafor et al., 2008).

Nauclea latifolia commonly known as Pin Cushion Tree is a straggling shrub or small spreading tree that belongs to the family *Rubiaceae* and to the class *Magnoliopsida* (Dicotyledons). It is a widely distributed savanna plant native to Africa and Asia. It is found in the forest and fringe tropical forest. It bears an interesting flower, a large red ball with long projecting stamens. The fruit is red, edible, but not appealing. The mode of propagation is by seed. In many African communities, the plant enjoys huge popularity on account of its diverse potential for treating various ailments. For instance, numerous applications of this plant have been reported in traditional medicinal practices of the East and West African sub-regions of continental Africa (Dalziel, 1957), where various extracts of the plant is used for the therapeutic management of malaria (Gamaniel et al., 1997); hypertension (Akubue and Mittal, 1982); prolonged menstrual flow (Elujoba, 1995); cough, gonorrhoea, stomach disorders, diarrhea, dysentery, ulcers and liver ailments (Lamidi et al., 1995; Traore-Keita et al., 2000). Phytochemical investigation of the plant revealed the presence of naturally synthesized biological compounds including, monoterpene, triterpene, indole alkaloid, saponins and traces of inorganic compounds (Brown et al., 1979; Hussain and Deeni, 1991; Abreu and Pereira, 1998, 2001). However, to the best of our knowledge, the plant has not been studied for corrosion inhibition abilities. This study was, therefore, carried out to investigate the probable corrosion inhibition abilities of the ethanol extracts of the leaves (LV), barks (BK) and roots (RT) of *N. latifolia* on mild steel corrosion in H_2SO_4 solutions using gasometric and gravimetric techniques.

2. Experimental

The mild steel sheets used in this present work have the composition presented in Table 1. Before measurements, the mild steel coupons were mechanically polished with series of Emery paper of variable grades starting with the coarsest and proceeding in steps to the finest (600) grade, degreased with absolute ethanol, dipped into acetone and air dried. The hydrogen evolution experiments were conducted on mild steel coupons of dimension $2.0 \times 0.08 \times 5.0$ cm (with a surface area of 21.12 cm^2) and for the weight loss study, mild steel specimens of size $4.0 \times 0.08 \times 5.0$ cm (with a surface area of 41.44 cm^2) were used.

2.1. Preparation of plant extracts

The parts (bark (BK), leaves (LV) and root (RT)) of *N. latifolia* were collected as required from a local bush in Calabar, Nigeria. These were cut into small chips, dried in an N53C – Genlab laboratory oven at 50 °C, and ground into powder form. 80.0 g of the powder was extracted continually with 250 cm^3 of absolute ethanol in a soxhlet extractor for 24 h. After recovering most of the ethanol, the extract was heated on a water bath (at 60 °C) until most of the ethanol evaporated. 4.0 g of the ethanol extract was digested in 1.0 liter of 5.0 M H_2SO_4 and 1.0 M H_2SO_4 solutions for hydrogen evolution and weight loss measurements, respectively. The resultant solution was kept for 24 h, filtered and stored. From the stock solution (4.0 g/l), inhibitor test solutions (concentrations of 0.1, 0.5, 1.0, 2.0 and 4.0 g/l) were prepared.

2.2. Phytochemical screening

Phytochemical screening was carried out on the ethanol extracts from *N. latifolia* following the methods described by Harbone (1973), Sofowora (1980), Trease and Evans (1996). The plant extracts were screened for alkaloids, saponins, tannins, flavonoids, polyphenols, cardiac glycosides, anthraquinins, and phenobutinon.

2.3. Weight loss and gasometric measurements

The weight loss and gasometric measurements were carried out as previously described ((Ekpe et al., 1995; Ita and Offiong, 1997). However, experiments were conducted at 30 °C for weight loss, and at 30, 40, 50 and 60 °C for gasometric measurements.

For the weight loss measurements, the mild steel coupons were each suspended and completely immersed in the test solutions (1.0 M H_2SO_4 with and without different concentrations of the plant extracts) with the help of glass hooks and rods for 5 days at 30 ± 1 °C. However, the coupons were retrieved at 24 h intervals, washed several times in 20% sodium hydroxide solution containing 200 g/l of zinc dust until clean, dipped into acetone, air dried and reweighed (Ekpe et al., 1995; Ita and Offiong, 1997). From the weight loss data, the corrosion rates (R) were calculated from Eq. (1):

$$R(\text{mg cm}^{-2}\,\text{h}^{-1}) = \frac{w}{At} \tag{1}$$

where w is weight loss in mg, A is the specimen surface area (of 41.44 cm^2) and t the immersion period in hours (120 h). From the corrosion rate, the surface coverage (θ) as a result of

Table 1 Chemical composition of the mild steel.

Element	C	Si	Mn	S	P	Ni	Cr	Mo	Cu
Composition	0.19	0.26	0.64	0.05	0.06	0.09	0.08	0.02	0.27

adsorption of the components of the extracts, and inhibition efficiencies of the plant extracts ($\eta\%$) were determined using Eqs. (2) and (3), respectively.

$$\theta = \frac{R_0 - R_i}{R_0} \tag{2}$$

$$\eta = \frac{R_0 - R_i}{R_0} \times 100 \tag{3}$$

where R_0 and R_i are the corrosion rates in the absence and presence of the plant extracts, respectively.

Gasometric technique is based on the principle that corrosion reactions in aqueous media are characterized by the evolution of gas resulting from the cathodic reaction of the corrosion process, which is proportional to the rate of corrosion (Okafor et al., 2005). The rate of evolution of the gas (R_H) is determined from the slope of the graph of volume of gas evolved (V) versus time (t) and the inhibitor surface coverage (θ) and efficiencies ($\eta\%$) determined using Eqs. (4) and (5), respectively.

$$\theta = \frac{R_{H0} - R_{Hi}}{R_{H0}} \tag{4}$$

$$\eta = \frac{R_{H0} - R_{Hi}}{R_{H0}} \times 100 \tag{5}$$

where R_{H0} and R_{Hi} are the rates of hydrogen evolution in the absence and presence of the plant extracts, respectively.

This gasometric technique has been corroborated by other well established corrosion rate determination techniques, including weight loss, thermometric and electrochemical techniques (El-Etre, 2003; Abdallah, 2004; Okafor et al., 2006). The data presented here represents the average of two to three measurements from the weight loss and gasometric techniques.

3. Results and discussion

3.1. Gravimetric results

The material loss expressed as the corrosion rate (mg cm^{-2} h^{-1}) for the mild steel coupons in 1.0 M H_2SO_4 solutions containing different concentrations of *N. latifolia* extracts (NLE) as a function of inhibitor concentration is presented in Fig. 1. It is observed that the corrosion rates decreased with the increase in concentration of NLE for all the plant's part used, indicating that the extent of inhibition is dependent on the amount of extract present. The values of the percentage inhibition efficiency were determined for 120 h immersion period using Eq. (3). The results obtained are shown in Table 2 and indicate that the plant extracts show a significant inhibitive effect on mild steel in H_2SO_4 solutions. From Fig. 2 (variation of inhibition efficiency as a function of extract concentration), it is observed that the inhibition efficiencies increase with increase in NLE concentration. This indicates that the phytochemical components of the extracts are adsorbed onto the mild steel surface resulting in the blocking of the reaction sites, and protection of the mild steel surface from the attack of the corrosion active ions in the acid medium. Comparing the inhibition efficiencies of the different parts of the extracts, it is observed that the effi-

Table 2 Calculated values of the corrosion rate, inhibition efficiency and surface coverage for mild steel coupons in 1.0 M H_2SO_4 solutions containing ethanol extracts from *Nauclea latifolia* (using the weight loss technique).

Plant's part	Extract concentration (g/l)	Corrosion rates (mg cm^{-2}/h^{-1})	Inhibition efficiency (%)
	Blank	1.13	–
BK	0.1	1.10	2.42
	0.5	0.97	13.90
	1.0	0.73	35.20
	2.0	0.47	58.67
	4.0	0.28	75.26
LV	0.1	1.10	2.55
	0.5	0.79	30.10
	1.0	0.33	70.54
	2.0	0.18	83.93
	4.0	0.09	91.58
RT	0.1	0.63	43.88
	0.5	0.27	75.77
	1.0	0.12	89.16
	2.0	0.09	91.71
	4.0	0.06	94.26

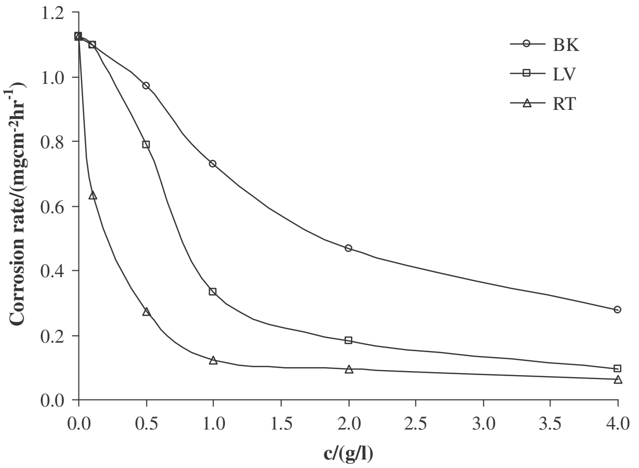

Figure 1 Variation of corrosion rates with extract concentration for mild steel coupons in 1.0 M H_2SO_4 solutions containing the different parts of *Nauclea latifolia* using weight loss technique.

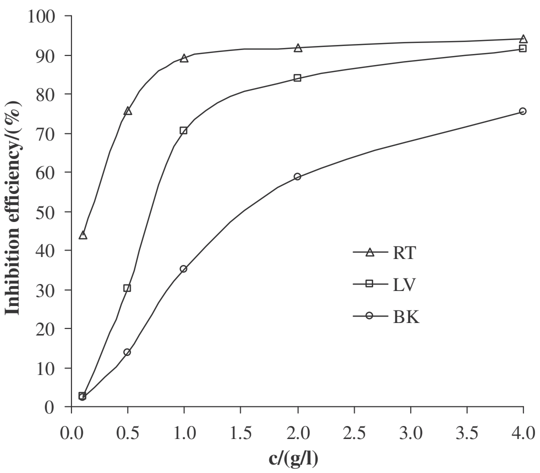

Figure 2 Variation of inhibition efficiency with extracts concentration for mild steel coupons in 1.0 M H_2SO_4 solutions containing the different parts of *Nauclea latifolia* using weight loss technique.

ciencies follow the trend: RT > LV > BK. This shows that the yield of the phytochemicals in the plant extracts responsible for the inhibition of the corrosion reactions depend on the part of the plant. This finding is in line with previous reports (Khuzhaeu and Aripova, 2000; Okafor and Ebenso, 2007; Okafor et al., 2008; Abiola et al., 2009).

To explain the kinetics of the corrosion of mild steel in 1.0 M H_2SO_4 solutions in the absence and presence of NLE, linear plots of the logarithm of the measured weight (in g) of the mild steel coupons after post treatment (W_f) against time (t) (Fig. 3) were obtained which confirm a first order kinetics with respect to the mild steel (Atkins and Paula, 2002; Okafor et al., 2007; Abiola and James, 2010). It could, therefore, be assumed that the inhibition of acid corrosion of mild steel by NLE does not influence the anodic reaction order (Abiola and James, 2010).

3.2. Gasometric results

Hydrogen evolution technique was employed to access the inhibition efficiency of the plant extracts at higher concentration. The weight loss method is most suitable at a low concentration, while the hydrogen evolution method suffices for a high corrodent concentration (Ekpe et al., 1995; Ebenso et al., 1999). The acid corrosion of mild steel is characterized by evolution of hydrogen and the rate of corrosion is proportional to the amount of hydrogen evolved (Okafor et al., 2004, 2008). The volume of hydrogen evolved, V_H, during the corrosion of mild steel in 5.0 M H_2SO_4 solutions in the absence and presence of NLE was assessed and the rates of hydrogen evolution obtained. The rate of hydrogen evolution values are recorded in Table 3 and the variation of rate of hydrogen evolved as a function of *N. latifolia* bark extract concentration is depicted in Fig. 4. It is observed that the presence of the extracts decreases the volume of hydrogen evolved during the corrosion reaction compared to the blank system and that the rate of hydrogen evolution decreased with the increase in NLE concentration and increased with temperature for all systems studied (Fig. 4). Also, the increase in the rate of hydrogen evolution at all the concentrations and temperatures studied followed the trend: BK > LV > RT. This observation also confirms that the yield of the organic compounds in the plant extracts and consequently, the corrosion inhibition ability of the plant extract is dependent on the parts of the plant.

From the rate of hydrogen evolution values, the inhibition efficiencies of the plant extract on the corrosion of mild steel in 5.0 M H_2SO_4 solutions in the absence (blank) and presence of the NLE were determined. The results obtained (Table 3) indicate that the inhibition efficiencies increase with increase in NLE concentration and decrease with increase in temperature. Similar trend was obtained at lower concentration of the acid via the weight loss method. The increase of efficiency with concentration opines that the phytochemicals in the plants are adsorbed on the surface of the metal and the decrease with temperature suggests a physical adsorption mechanism for the corrosion inhibition process (Okafor et al., 2007).

3.3. Activation parameters

The activation parameters for the dissolution of mild steel coupons in 5.0 M H_2SO_4 solutions in the absence and presence of NLE were calculated from the Arrhenius-type plot (Eq. (6)) and the transition state Eq. (7):

$$k = A\exp(-E_a/RT) \tag{6}$$

$$k = RT/Nh\exp(\Delta S^o/R)\exp(-\Delta H^o/RT) \tag{7}$$

where R is the universal gas constant, N is the Avogadro's number, h is the Plank's constant, E_a is the activation energy,

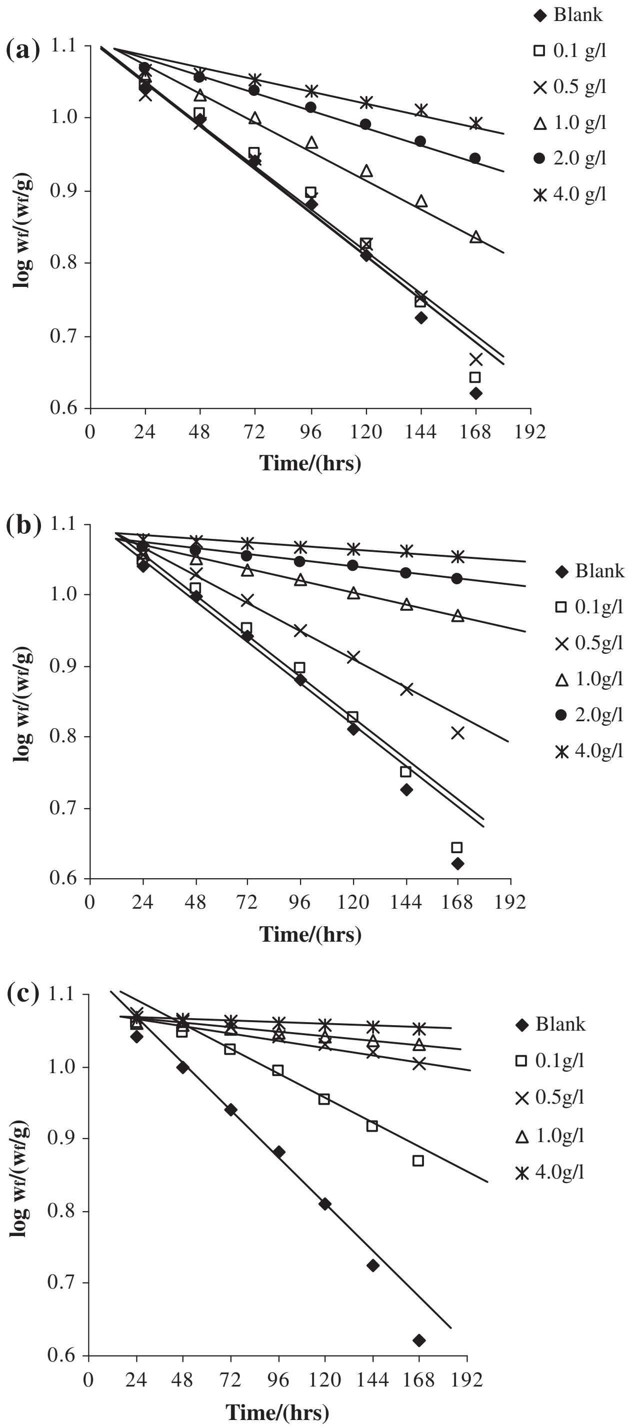

Figure 3 Plot of log W_f against time for mild steel coupons in 1.0 M H_2SO_4 solutions containing: (a) bark (BK), (b) leaves (LV), and (c) roots (RT) extracts from *Nauclea latifolia* using weight loss technique.

Table 3 Calculated values of the rate of hydrogen evolution, inhibition efficiency, activation energy, change in enthalpy and change in entropy for mild steel coupons in 5.0 M H_2SO_4 solutions containing extracts from *N. latifolia* (using hydrogen evolution technique).

Plants part	Extract concentration (g/l)	Rate of hydrogen evolution (cm^3/min)				Inhibition efficiency (%)				E_a (kJ/mol)	ΔH^o (kJ/mol)	ΔS^o (J mol^{-1} K^{-1})
		30 °C	40 °C	50 °C	60 °C	30 °C	40 °C	50 °C	60 °C			
	Blank	0.51	1.34	2.43	4.35	–	–	–	–	58.98	−56.34	−63.98
BK	0.1	0.46	1.22	2.28	4.22	10.71	8.73	5.97	3.01	61.30	−58.66	−57.27
	0.5	0.35	0.97	1.82	3.36	31.12	27.31	25.10	22.86	62.09	−59.45	−56.76
	1.0	0.26	0.71	1.56	2.94	50.32	47.15	35.76	32.53	68.32	−65.68	−39.09
	2.0	0.14	0.42	0.91	1.91	72.89	68.40	62.52	56.15	72.50	−69.87	−30.25
	4.0	0.10	0.31	0.63	1.30	80.25	77.19	73.90	70.08	70.56	−67.92	−30.25
LV	0.1	0.39	1.08	1.97	3.78	23.29	19.27	18.76	13.11	62.15	−59.52	−55.70
	0.5	0.34	0.94	1.77	3.56	33.71	29.67	26.97	18.29	64.53	−61.89	−49.17
	1.0	0.23	0.65	1.27	2.55	56.12	51.67	47.83	41.41	66.31	−64.24	−44.78
	2.0	0.16	0.48	0.98	2.00	68.69	64.23	59.47	53.96	69.72	−67.08	−38.19
	4.0	0.10	0.30	0.62	1.24	79.82	77.22	74.29	71.60	68.60	−65.96	−45.51
RT	0.1	0.32	0.91	1.77	3.51	38.04	31.79	27.08	19.26	66.33	−63.69	−43.72
	0.5	0.26	0.76	1.41	2.86	48.24	43.28	41.98	34.34	65.27	−62.63	−48.73
	1.0	0.20	0.56	1.10	2.36	61.37	57.91	54.61	45.70	68.27	−65.63	−41.43
	2.0	0.13	0.37	0.72	1.53	75.29	72.24	70.37	64.80	68.54	−65.90	−44.16
	4.0	0.10	0.29	0.58	1.22	80.20	78.13	75.97	72.05	68.55	−65.91	−45.98

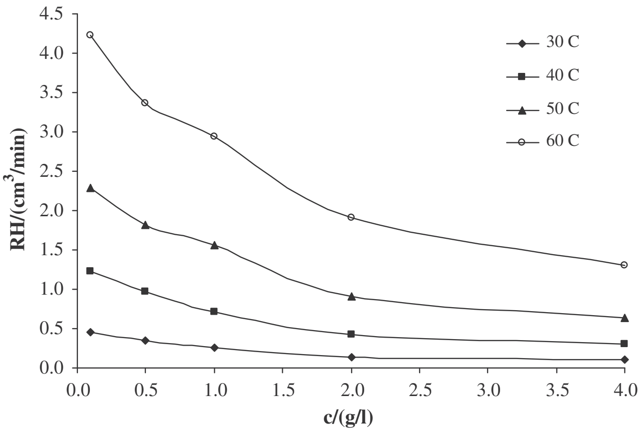

Figure 4 Variation of inhibition corrosion rate with extract concentration for mild steel coupons in 5.0 M H_2SO_4 solutions containing ethanol extracts from bark (BK) of *Nauclea latifolia* using hydrogen evolution technique.

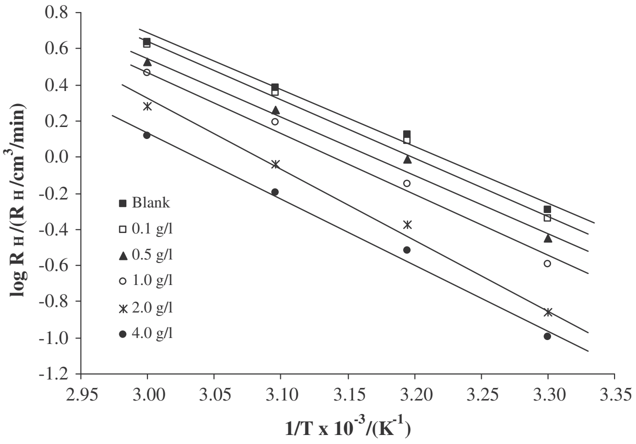

Figure 5 Arrhenius plot for mild steel coupons in 5.0 M H_2SO_4 solutions containing ethanol extracts from the bark of *Nauclea latifolia* using hydrogen evolution technique.

T is the absolute temperature, and ΔH^o and ΔS^o are the standard enthalpy and entropy of activation, respectively. The values of k were taken to be equal to the rate of hydrogen evolution (Putilova et al., 1969; Bockris and Reddy, 1977; El-Awady et al., 1992; Gomma and Wahdan, 1994; Gomma, 1998; Oguzie et al., 2005; Okafor et al., 2007). A plot of log k versus $1/T$, for mild steel in 5.0 M H_2SO_4 containing NLE (Fig. 5 for bark extracts) gave straight lines. The calculated activation energies obtained from the slopes of the plots are listed in Table 3. The results showed that E_a values increased in the presence of the NLE compared to the blank system which is typical of physical adsorption (Putilova et al., 1969; Gomma and Wahdan, 1994; Martinez and Stern, 2002). The average activation energy values of the inhibitor reported: 66.95 kJ/mol (for BK extract), 66.38 kJ/mol (for LV extract) and 67.38 kJ/mol (for RT extract) also confirmed the assertion that the inhibition of steel corrosion is by physical adsorption mechanism which is in agreement with those of Ebenso (2003) and Barrow (1983). According to the authors, the activation energy for physical adsorption mechanism should be less than 80 kJ/mol. The higher E_a values in the presence of inhibitor compared to the blank solution indicates that the inhibitor will be effective at low temperatures, but efficiencies will be diminished at higher temperatures (Umoren et al., 2006).

The enthalpy and the entropy of activation values for the dissolution of mild steel in 5.0 M H_2SO_4 solutions obtained from linear square fit of log (k/T) data versus $1/T$ (Fig. 6 for bark extract) are also presented in Table 3. The higher values for ΔH^o in the presence of the plant extracts are indicative of the higher protection efficiency observed for the system (El-Awady et al., 1992). Generally, negative values of ΔH^o were obtained indicating an exothermic adsorption process. The exothermic adsorption process signifies either physical or

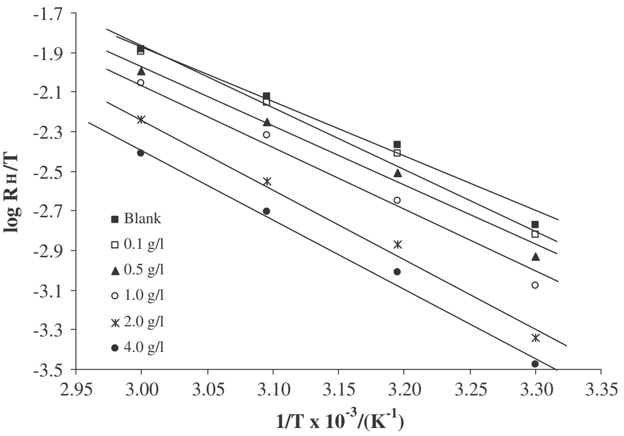

Figure 6 Transition state plot for mild steel coupons in 5.0 M H_2SO_4 solutions containing ethanol extracts from the bark of *Nauclea latifolia* using hydrogen evolution technique.

chemical adsorption while endothermic adsorption process is attributable to chemisorption. In an exothermic process, physical adsorption is distinguished from chemisorption by considering the absolute value of adsorption enthalpy. Typically, enthalpy of physical adsorption process is lower than 80 kJ/mol while the enthalpy of chemisorption process approaches 100 kJ/mol (Martinez and Stern, 2002). The values of the obtained enthalpy, therefore, suggest physical adsorption of the components of the plant extracts on the surface of the metal. The ΔS^o values in the absence and presence of NLE are negative. This implies that, the activation complex in the rate determining step represents association rather than dissociation step, meaning that a decrease in disordering takes place on going from reactants to the activated complex (Abd El Rehim et al., 2001).

3.4. Adsorption isotherm

It is necessary to determine empirically which adsorption isotherm fits best to the surface coverage data in order to use the corrosion rate measurements to calculate the thermodynamic parameters pertaining to inhibitor adsorption. Different adsorption isotherms were found to describe the adsorption of the inhibitors on steel. From the result, it was found that the experimental data fitted the thermodynamic-kinetic model of El-Awady et al. (1992) (Fig. 7). The model may be formulated as Eq. (8):

$$\log\left(\frac{\theta}{1-\theta}\right) = \log K' + y \log c \qquad (8)$$

where c is the concentration of the adsorbate, θ is the coverage degree and $1/y$ is the number of inhibitor molecules occupying one active site. The binding constant K is given by:

$$K = K'^{(1/y)} \qquad (9)$$

The data are given in Table 4. The efficiency of a given inhibitor is a function of both the magnitude of its binding constant K and the number of active sites ($1/y$) it is capable of blocking, with the former being the most important (El-Awady et al., 1992). Large values of K mean better and strong interaction, while small values of K mean that the interaction between the inhibitor molecules and the metal is weaker (Okafor and

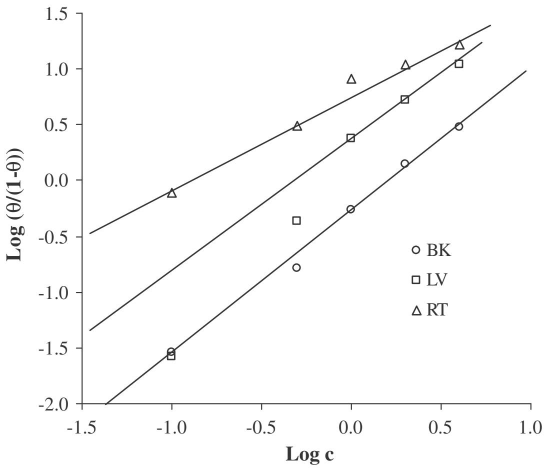

Figure 7 El-Awady et al. thermodynamic-kinetic model for mild steel coupons in 1.0 M H_2SO_4 solutions containing extracts from *Nauclea latifolia* (using weight loss technique).

Table 4 Adsorption parameters for mild steel in H_2SO_4 solutions containing NLE.

Plant's part	Temperature (°C)	Hydrogen evolution technique		Weight loss technique	
		K	$1/y$	K	$1/y$
BK	30	1.08	1.01	0.51	0.60
	40	0.90	1.00		
	50	0.69	0.96		
	60	0.57	0.85		
LV	30	1.39	1.39	1.48	1.26
	40	1.07	1.35		
	50	0.87	1.43		
	60	0.61	1.27		
RT	30	3.01	1.86	6.03	8.18
	40	2.01	1.72		
	50	1.60	1.65		
	60	0.99	1.50		

Table 5 Phytochemical screening of the ethanol extracts from root (RT), leaves (LV) and bark (BK) of *N. latifolia*.

Chemical constituent	Screening		
	Root	Leaves	Bark
Alkaloids	+	+	–
Saponins	–	–	–
Flavonoids	+	+	+
Tannins	–	–	+
Polyphenols	+	+	+
Reducing compounds	–	–	–
Glycosides	+	+	+
Phenobutinones	–	–	–
Anthraquinones	–	–	–

Notes: +, present in the extracts; –, absent in the extracts.

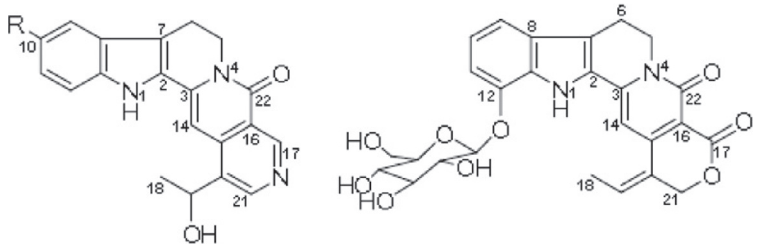

Figure 8 Structure of some indole alkaloids present in *Nauclea latifolia*.

Ebenso, 2007). Hence according to the numerical values of K obtained, the inhibition efficiency of different NLE could be arranged in the order: RT > LV > BK. Inspection of Table 4 shows that K values decrease with increase in temperature. This is interpreted to mean that weaker surface interactions result at higher temperatures. The values of $1/y$ obtained were mostly greater than one. This implies that a given inhibitor molecule will occupy more than one active site on the surface of the metal (El-Awady et al., 1992).

3.5. Inhibition mechanism

The use of corrosion inhibitors increases continually (Antropov et al., 1976). The mechanism of their action can be different, depending on metal, the medium and the structure of the inhibitor. One possible mechanism is the adsorption of the inhibitor, which blocks the metal surface and thus do not permit the corrosion process to take place (Christov and Popova, 2004).

The observed corrosion inhibition of mild steel in H_2SO_4 solutions can be explained by the adsorption of components of NLE on the metal surface (Okafor et al., 2007). Various mechanisms have been proposed for the inhibition or acceleration of metallic corrosion in acid media (Antropov, 1977; Oguzie, 2004; Abdel-Gaber et al., 2006; Okafor et al., 2008). A general mechanism for the inhibition of steel corrosion would be similar to that reported by Abdel-Gaber et al. (2006) and Okafor et al. (2008). According to the mechanism, if a molecule or ion, X^-, is adsorbed on the steel surface, a surface complex forms in the anodic process, and the complex is then desorbed from the surface, Eqs. (10)–(13):

$$\mathrm{Fe} + \mathrm{X}^- \Longleftrightarrow (\mathrm{FeX}^-)_s \quad (10)$$

$$(\mathrm{FeX}^-)_s \Longleftrightarrow (\mathrm{FeX})_s + e \quad (11)$$

$$(\mathrm{FeX})_s \rightarrow \mathrm{FeX}^+ + e \quad (12)$$

$$\mathrm{FeX}^+ \Longleftrightarrow \mathrm{Fe}^{2+} + \mathrm{X}^- \quad (13)$$

where s represents ion or compound at the surface. In general, if the adsorbed molecule/ion on the surface complex is stable, the corrosion of steel is inhibited. Therefore, it can be concluded that the adsorption of the phytochemical components of the plant extract leads to the formation of stable surface complex, which blocks the active sites on the surface of the metal thereby reducing the corrosion rate. Increase in the concentration of the phytochemicals increases the amount of the surface complex resulting in greater inhibition of the corrosion. From the observed results, it can be inferred that the insoluble Fe–NLE complexes dominate the adsorbed intermediate and thus the resultant inhibitive effects. This conclusion is in line with those of Jaen et al. (1999), Oguzie (2004) and Okafor et al. (2008). Studies on the phytochemical constituents of the ethanolic extracts of *N. latifolia* revealed the presence of appreciable quantities of flavonoids, polyphenols and glycosides. Also detected in the plant extracts are alkaloids (in the root and leaves extract) and tannins (in the bark extract) (Table 5). A closer inspection of Table 5 revealed the absence of alkaloids in the bark extracts of the plant, while the extracts from the leaves and roots show the presence of alkaloids which in the present system may be responsible for the observed inhibition efficiency trend (RT > LV > BK). The alkaloids (some of the structures are shown in Fig. 8 (Sun et al., 2008) contain nitrogen, oxygen and aromatic ring in their molecular structures. Organic heterogeneous compounds containing these elements have been reported to be efficient corrosion inhibitors (Ekpe et al., 2001; Ebenso et al., 2004a,b; Khaled and Hackerman, 2003; Okafor et al., 2003, 2004; Ebenso and Oguzie, 2005). Thus, in the system studied, the adsorption of these compounds on the surface of the metal is assumed to be mostly responsible for the inhibition of the corrosion reaction. However, the mutual effects of the phytochemical components of plant may also contribute to its inhibition properties.

4. Conclusions

Ethanol extracts from the root, leaves and bark of *N. latifolia* were found to inhibit the corrosion of mild steel in H_2SO_4 solutions. The inhibition efficiency increases with increase in concentration of the extracts and with decrease in temperature suggesting physical adsorption.

The inhibition is due to the adsorption of phytochemicals in the extracts on the surface of the metal, thereby blocking the active corrosion sites. The presence of alkaloids in the root and leaves extracts is assumed to be responsible for the observed inhibition trend RT > LV > BK.

The experimental data obtained in this study fits the thermodynamic-kinetic model of El-Awady et al. (1992) adsorption isotherm.

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