

***Sinapis Alba* Extract as Green Corrosion Inhibitor for Aluminum in Alkaline Media**

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Received: 1 February 2014 / Accepted: 13 March 2014 / Published: 14 April 2014

The inhibition effect of *sinapis alba* (SA) extract on the corrosion of aluminum in 1.0 M sodium hydroxide (NaOH) was investigated using weight-loss measurements, and electrochemical polarization methods; also, surface morphology was analyzed by scanning electron microscopy (SEM) technique. The results show that *sinapis alba* extract is a good inhibitor, and the inhibition efficiency increases with inhibitor (*sinapis alba* extract) concentration, and slightly increases with increasing temperature. The inhibition efficiency reaches a maximum value of 97.98% with the highest extract concentration at 50°C. In the presence of *sinapis alba* extract, the results were indicative of slightly decreased aluminum dissolution with increasing temperature. The adsorption of *sinapis alba* extract on aluminum surface obeys Langmuir adsorption isotherm, with high regression coefficient value. The entropy (ΔS^\ddagger) and enthalpy (ΔH^\ddagger) of activation are calculated and discussed. The thermodynamic adsorption free energy ($\Delta G_{\text{ads}}^\circ$) value and sign were indicative of the physisorption of *sinapis alba* extract molecules on aluminum surface. Electrochemical polarization studies showed that *sinapis alba* extract acts as mixed type inhibitor. The results reveal that *sinapis alba* extract provided a very good protection to aluminum against corrosion in alkaline media. SEM results confirmed the existence of an absorbed protective film on the aluminum surface.

Keywords: *sinapis alba*; aluminum; corrosion inhibitor; adsorption; alkaline inhibition; weight loss

1. INTRODUCTION

Inhibition of metals corrosion by organic compounds is a result of adsorption of organic molecules or ions at the metal surface forming a protective layer. This layer reduces the corrosion of the metal surface. The extent of adsorption depends on the nature of the metal, the metal surface

condition, and the type of corrosive media [1]. Several previous studies showed that the naturally occurring substances of plant origin are successfully used as inhibitors of corrosion [2-6]. The presence of hetero atoms in the structure of inhibitor molecules such as O, N, S, P; enhance the adsorption process and inhibition efficiency [7-9]. Corrosion of aluminum and its alloys has been a subject of numerous studies due to their importance in the recent civilization. Accordingly, numerous studies concerning the inhibition of aluminum corrosion using organic substances have been conducted [10-13]. The exploration of natural products of plant origin as inexpensive, eco-friendly corrosion inhibitors is an essential field of study. The extracts from their leaves, barks, seeds, and roots comprise of mixture of organic compounds and some have been reported to function as effective inhibitors of metal corrosion [14-16]. The corrosion inhibition efficiency of *sinapis alba* extract is normally ascribed to the presence of complex organic species such as benzyl isothiocyanate as major constituents, besides, benzyl nitrile, 2-phenyl isothiocyanate, 1-butenyl isothiocyanate, 1-butenyl isothiocyanate, dimethyl trisulfide, dimethyl tetrasulfide, and hydroxyl phenyl choline [17].

In the present work, weight loss method and electrochemical polarization methods were used to investigate the inhibition of aluminum corrosion by *sinapis alba* extract in 1M NaOH solution. Weight loss measurement was used to study effect of inhibitor concentration and temperature on the inhibitor efficiency of *sinapis alba* extract on the corrosion aluminum. The surface morphology was analyzed by scanning electron microscopy (SEM) technique.

2. EXPERIMENTAL

2.1 Material preparation

Pure aluminum (purity 99.999%) was supplied in the form of foil of thickness 0.5 mm (Aldrich). The experiments were carried out using rectangular aluminum foil specimens (dimensions: length = 3 cm, width = 1 cm and thickness = 0.5 mm). The aluminum specimens were treated by a mixture of H₃PO₄ (85 wt% in water) and HNO₃ (15 v%) at 80 °C for 30 s, then immersed in HNO₃ solution (50 v%) at 50 °C for 20 second, rinsed well in deionized water and placed in alkaline solution (40 g NaOH in 1L deionized water). The specimens dried well on air stream and isolated from outside atmosphere for further use in experiments.

2.2 Samples preparation and weight loss measurements

The inhibition efficiency of aluminum in aqueous solution of sodium hydroxide by using *sinapis alba* extract as inhibitor was determined by gravimetric technique. A 50 g of dry *sinapis alba* powder was refluxed in 250 mL of 1 M NaOH solution for 3 h, allowed to stand overnight then filtered using Whatman general-purpose filter paper, diam. 90 mm (Aldrich). The weight loss experiments were carried out using the aluminum foil specimens (total exposed area = 6.4 cm²), weighed and immersed for 2 h in 10 ml of 1 M NaOH solutions containing different concentrations of the *sinapis alba* extract (0, 0.2, 0.4, 0.6, 0.8, and 1.0 v/v). After testing they were rinsed thoroughly with deionized water, dried, and reweighed. The measurements were carried out at 25, 30, 40, and 50 °C using a water

thermostat controlled to ± 0.5 °C and weighed using Electronic Semimicro Balance Sartorius 2024 MP6 with precision of ± 0.01 mg. Triplicate determinations were carried out.

2.3 Potentiostatic polarization measurements

Potentiostatic polarization studies were carried out using EG&G (model 264) potentiostat/galvanostat. The current-potential curves were measured using a conventional three-electrode cell. The working electrode was aluminum (a cylindrical rod embedded in araldite with exposed surface area of 0.6 cm^2); saturated calomel electrode (SCE) was used as a reference and a platinum foil was used as counter electrode. Polarization was carried out in alkaline solution in the absence and presence of various concentrations of the inhibitor (*sinapis alba*). The current-potential curves were recorded automatically. The polarization was scanned from a potential of -1000 mV to 0.0 mV (SCE) with a scan rate of 10 mV s^{-1} .

The electrochemical corrosion current density was evaluated using the well-known Stern-Geary equation (Eq. 1):

$$I_{corr} = \frac{\beta_a \times \beta_c}{2.303(\beta_a + \beta_c)} \times \frac{1}{R_p} \quad (1)$$

where, I_{corr} is the corrosion current density; β_a is the anodic Tafel constant; β_c is the cathodic Tafel constant and R_p is the polarization resistance.

Corrosion current density (I_{corr}) was estimated from intercept of cathodic and anodic Tafel lines and the inhibition efficiency (I%) was calculated by using the following equation (Eq. 2)

$$I\% = \frac{I_{corr}^o - I_{corr}}{I_{corr}^o} \quad (2)$$

where, I_{corr} and I_{corr}^o are the corrosion current density with and without the inhibitor, respectively.

2.4 Scanning electron microscopy (SEM)

The surface morphology of the aluminum specimens was examined after polishing and after exposure to 1 M NaOH in the absence and presence of optimal concentration of the inhibitor, *sinapis alba* (1.0 v/v), using FEI Inspect F50 scanning electronic microscope (Netherlands) equipped with a Field Emission Gun (FEG).

3. RESULTS AND DISCUSSION

3.1 Weight loss measurements

The weight loss recorded to the nearest 0.0001 g . The weight loss of the metal in the corrosive solution is given by Equation 3.

$$\Delta w = w_o - w_i \quad (3)$$

where w_o and w_i are the weights of metal before and after exposure to the corrosive solution, respectively.

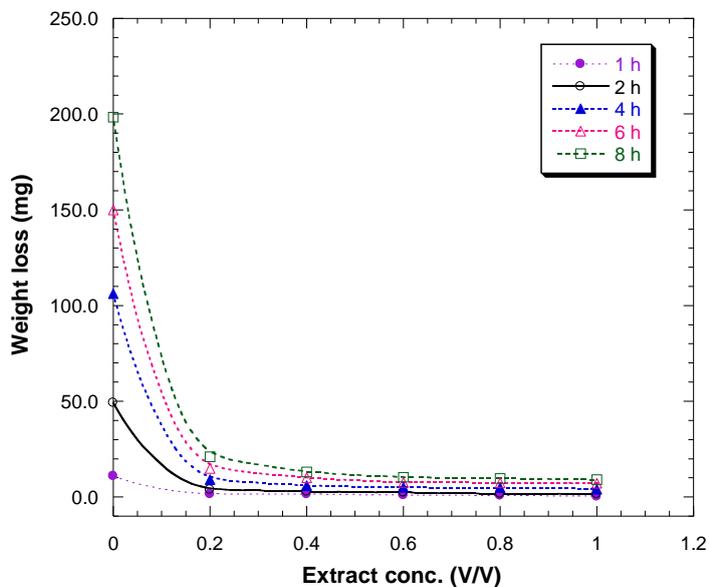


Figure 1. Weight loss variation of aluminum coupon versus *sinapis alba* extract concentration in 1 M NaOH at 25 °C at different immersion period.

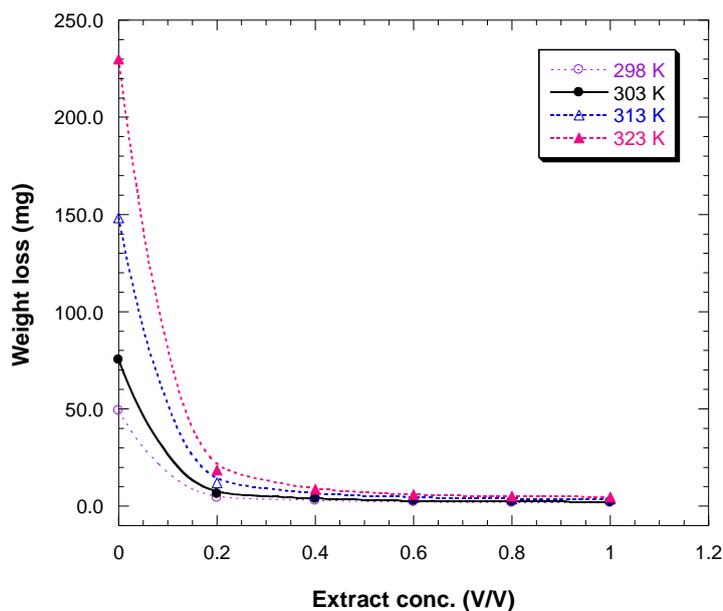


Figure 2. The weight loss curves of aluminum due to corrosion in 1M NaOH in the presence *sinapis alba* extract at various temperatures.

Figure 1 shows the variation of the weight loss (mg) of Al due to corrosion with the immersion time in 1M NaOH solution of various concentrations of *sinapis alba* extract at 25 °C. The rate of reaction of Al in 1M NaOH decreases with time.

Weight loss of aluminum was determined, at various time intervals, in the absence and presence of different concentrations of *sinapis alba* extract. The curves in Figure 1 show that the weight loss values (mg) of Al in 1M NaOH solution containing *sinapis alba* extract decreased as the concentration of the inhibitor increased, i.e. the corrosion inhibition increases with increasing the surfactant concentration. This trend, it may result from the fact that adsorption amount and the coverage of surfactants on the Al surface increases with the increase of the concentration, thus the Al surface is efficiently separated from the medium [18].

The weight loss curves of the Al with the addition of the inhibitor in different concentration at various temperatures in 1M NaOH are shown in Figure 2. The effect of temperature on the corrosion of Al in 1M NaOH over the temperature range of (25–50 °C) in the absence and presence of different concentrations of the *sinapis alba* extract has been studied. The weight loss is found to increase with increasing temperature.

The percentage inhibition efficiency (%I) and the degree of surface coverage (θ) of the investigated *sinapis alba* extract were computed from the following equations (Eq. 4 and 5):

$$\%I = (w_o - w_i) / w_o \times 100\% \quad (4)$$

$$\theta = (w_o - w_i) / w_o \quad (5)$$

where w_o and w_i are weight losses of metal in the absence and presence of inhibitor, respectively.

Table 1. Inhibition efficiency of *sinapis alba* extract on aluminum in 1M NaOH for 120 min immersion period at different temperatures.

Extract conc. (v/v)	%I (25 °C)	%I (30 °C)	%I (40 °C)	%I (50 °C)
0.2	91.26	91.50	91.84	92.01
0.4	94.09	94.95	95.68	96.23
0.6	95.62	96.28	96.92	97.43
0.8	96.24	96.89	97.47	97.79
1.0	96.44	97.11	97.61	97.98

Table 1 shows the percentage inhibition efficiency of the inhibitors at various concentrations in 1M NaOH for 120 min immersion period at different temperatures (25-50°C). The results showed that inhibition efficiency increased as the concentration of inhibitor increases from 0.2 to 1.0 (v/v) (Figure 3). A maximum inhibition efficiency of 97.98% was observed at 50 °C for 1.0 v/v of extract, which is probably due to an increase in the metal surface area covered by the exudates. From Table 1, it is seen that inhibition efficiency of *sinapis alba* extract increases with increase in temperature.

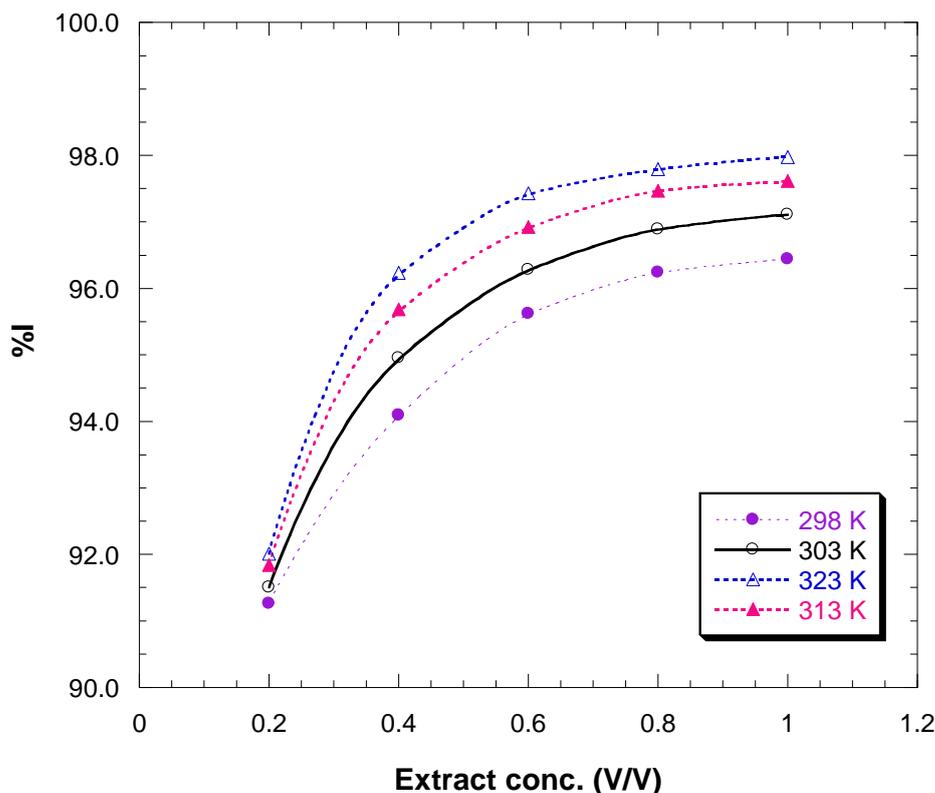


Figure 3. Inhibition efficiency of *sinapis alba* extract on aluminum in 1M NaOH for 120 min immersion period at different temperatures.

The inhibition effect of the *sinapis alba* extract could be attributed to the presence of some organic matrix contains S and N atoms with excessive π electrons in the extract. A previous study by Al-Qudah *et al.* has shown that the *sinapis alba* extract contains a mixture of compounds having sulfur and nitrogen atoms which can act as a centers for adsorption on the aluminum surface [17]. Therefore, we can conclude that the inhibition action of SA extract mainly due to the adsorption of its organic component molecules on the metal surface. This adsorption process creates a barrier between the metal and the corrosive medium leading to inhibition of corrosion. Consequently, as the concentration of the SA extract increases, the metal surface will be highly covered with the adsorbed molecules and the inhibition efficiency increased.

3.2 Potentiostatic polarization measurements

The polarized anodic and cathodic potentials were reported in the absence and presence of various concentration of SA (inhibitor) in a current density range of 0.25-4.8 $\mu\text{A cm}^{-2}$ for NaOH. Figure 4 show the cathodic and anodic polarization curves of aluminum in the absence and presence of various concentrations of inhibitor in 1.0 M of sodium hydroxide.

Table 2. Electrochemical corrosion parameters of aluminum in the absence and presence of various concentrations of inhibitor (SA) in 1.0 M NaOH

[Inhibitor] (v/v)	E_{corr} (mV/SCE)	I_{corr} (mA cm ⁻²)	β_a (mV/decade)	β_c (mV/decade)	$I\%$
Blank	-531.5	5.215	212.05	150.15	-
0.20	-528.2	0.391	145.70	110.50	92.50
0.40	-522.8	0.164	132.73	100.90	96.86
0.60	-518.2	0.128	131.19	91.56	97.54
0.80	-514.6	0.104	128.05	81.90	98.00
1.00	-510.5	0.083	127.15	72.95	98.41

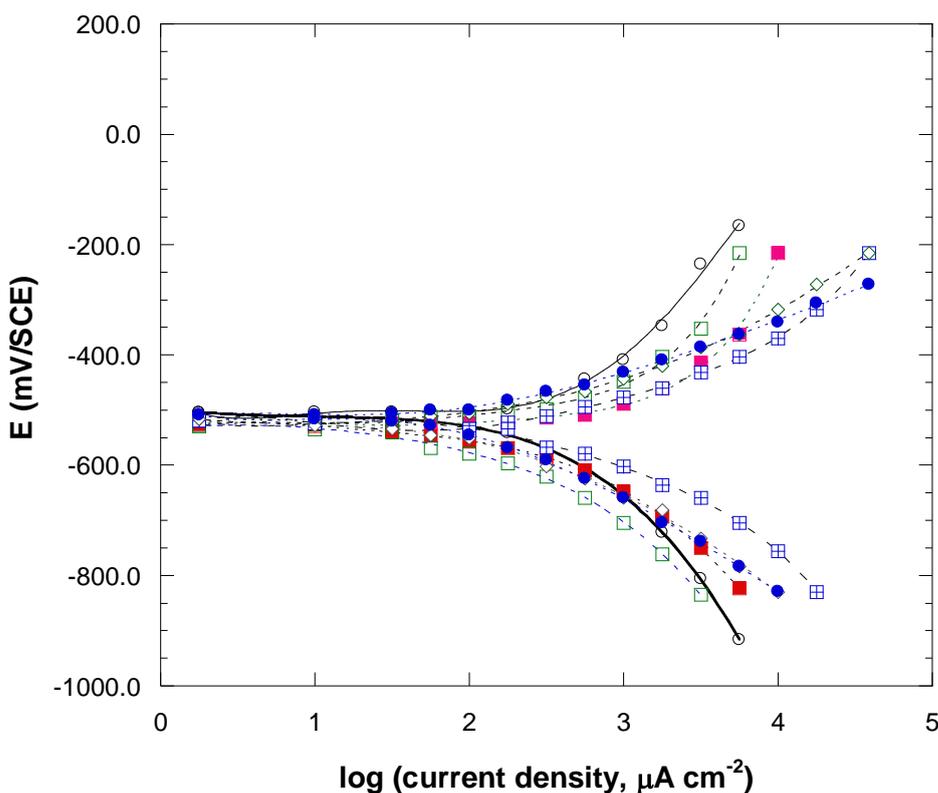


Figure 4. Polarization anodic and cathodic curves of aluminum in the absence and presence of various concentrations of SA in 1.0 M NaOH. [SA] (V/V) = 1.0 (●), 0.8 (◇), 0.6 (□), 0.4 (○), 0.2 (■), blank (⊠).

The electrochemical corrosion parameters including corrosion potential (E_{corr}), corrosion current density (I_{corr}), anodic Tafel constant (β_a), cathodic Tafel constant (β_c) and inhibition efficiency ($I\%$) were calculated from the polarization curves of aluminum in the absence and presence of various concentrations of inhibitor in 1.0 M of NaOH and summarized in Tables 2. The electrochemical corrosion parameters summarized in Table 2 shows that the corrosion current density is markedly reduced as the concentration of inhibitor increases, which indicates that the SA has a pronounced

corrosion inhibition effect of aluminum in basic media. From the shape of the polarization curves (Fig. 4) it is obvious that both anodic and cathodic reactions are inhibited. It is evident from the data shown in Table 2 that as the concentration of the inhibitor increases, the corrosion potential (E_{corr}) is not changing significantly and lower corrosion current density (I_{corr}) values are obtained. Moreover, the values of both anodic (β_a) and cathodic (β_c) Tafel constants are strongly changed in the presences of the inhibitor (SA). This confirms the mixed mode (anodic and cathodic) inhibition action of the *sinapis alba*. The data summarized in Table 2 shows that the anodic Tafel constant (β_a) is greater than the cathodic (β_c) Tafel constant at all inhibitors' concentrations suggesting that the inhibitors' effect on the anodic polarization is more pronounced than that on cathodic polarization. Furthermore, inspection of Table 2 reveals that the inhibition efficiency (I%) increases with increasing the concentration of inhibitor. The obtained values of inhibition efficiency (I%) from polarization study were in good agreement with those obtained from the weight loss study with small variation. The results of both weight loss and polarization methods revealed that the *sinapis alba* provide a very good protection to aluminum against corrosion in basic medium. This can be attributed to the relative stability of the *sinapis alba* film that formed on the surface of aluminum.

3.3 Scanning electron microscope (SEM)

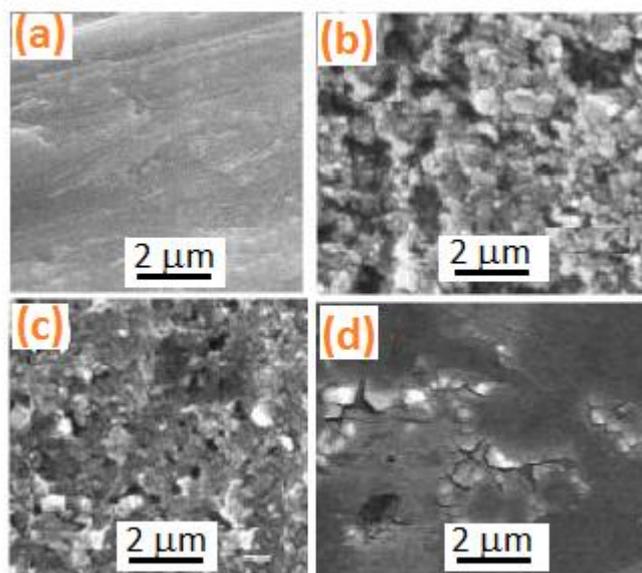


Figure 5. Scanning electron micrograph of plain polished aluminum (a) aluminum in 1.0 M NaOH at 25°C, for 35 days (b) aluminum in 1.0 M NaOH in the presence of 0.2 v/v SA at 25 °C for 35 days (c), and aluminum in 1.0 M NaOH in the presence of 1.0 v/v SA at 25 °C for 35 days (d).

The surface morphology of treated aluminum assessed by scanning electron microscope is shown in Fig. 5. Scanning electron micrograph of mechanically polished aluminum shows parallel grooves with relatively light areas, which were identified as clean surface (Fig. 5a). Fig. 5b shows the surface morphology of aluminum exposed to 1.0 M sodium hydroxide in the absence of inhibitor (SA).

Fig. 5b shows a uniform severe corrosion in the absence of inhibitor, and the forming of adherent amorphous corrosion products. The appearance of such corroded areas may be attributed to the dissolution of alumina layer due to the aggressive attack of OH^- anions and the increased alkalinity of the solution in the vicinity of the surface.

However, the SEM obtained for aluminum in presence of inhibitor showed that the metal surface is partially covered with inhibitor giving it a reasonable degree of protection and it is obvious that the surface is covered with inhibitor in presence of sodium hydroxide (Fig. 5c and d). The formation of an adsorbed protective film of the inhibitor molecules on the aluminum surface is also confirmed by scanning electron micrographs in Fig. 5c and d, which proves that the *sinapis alba* acts as good inhibitor at 1.0 M basic solution.

In presence of SA, there is an improvement in the surface morphology due to the obvious decrease in the corroded areas caused by the SA layer covering the active sites. This improvement in the surface morphology enhances with SA concentration (Fig.5c and d). Therefore, it can be concluded that on the aluminum surface, after a full immersion test of 35 days in 1.0 M NaOH solutions containing various concentrations of SA, a protective film of the inhibitor is developed, and the protectiveness of such film depends on SA concentration. Even though the corrosion is highly inhibited with increasing the concentration of inhibitor (SA), but it seems that the adsorbed layer of SA is not well-protective, may be due to the formation of porous or cracked film of SA. This means that the SA film is not protective enough to completely prevent the corrosion.

3.4 Kinetic and thermodynamic study

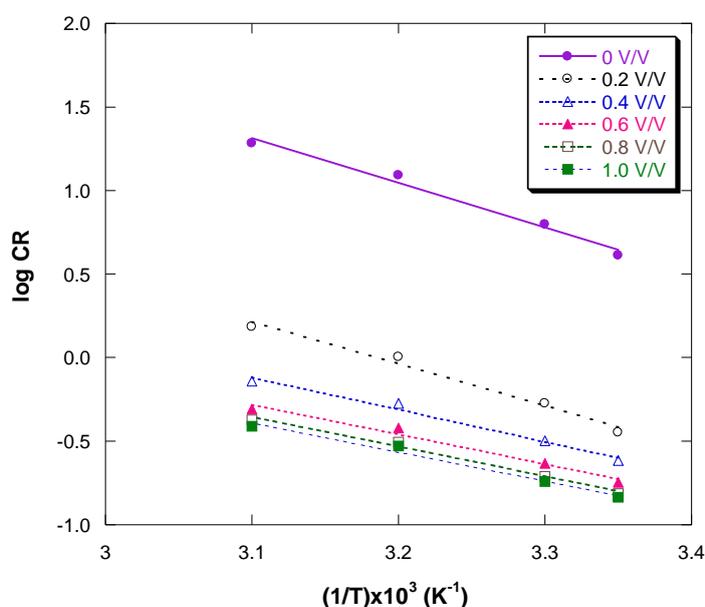


Figure 6. Arrhenius plot for aluminum dissolution in 1M NaOH in the absence and presence of *sinapis alba* extract.

The corrosion rate of Al is determined by using the relation (Eq. 6):

$$CR = \Delta w / A.t \tag{6}$$

where Δw is the mass loss, A the area and t the immersion period. The plot of logarithm of the corrosion rate versus the reciprocal of absolute temperature gives straight lines according to Arrhenius equation (Eq. 7), Figure 6:

$$CR = Ae^{(-E_a / RT)} \tag{7}$$

where CR is the corrosion rate, A is the constant frequency factor and E_a is the apparent activation energy. The values of E_a were calculated and summarized in Table 3.

Table 3. Activation parameters of the dissolution of Al in 1 M NaOH in the absence and presence of *sinapis alba* extract.

[Extract] (v/v)	R ²	E _a (kJ mol ⁻¹)	R ²	ΔH [#] (kJ mol ⁻¹)	ΔS [#] (J mol ⁻¹ K ⁻¹)
0	0.984	51.2	0.981	48.5	-70.1
0.2	0.984	48.2	0.982	45.5	-100.3
0.4	0.993	36.8	0.992	34.1	-142.0
0.6	0.989	34.0	0.973	31.3	-153.9
0.8	0.983	33.8	0.987	31.2	-155.2
1.0	0.986	33.1	0.985	30.5	-158.5

It is clear that, the activation energy decreases with increasing the concentration of *sinapis alba* extract. The activation energy, E_a , of the dissolution of plain aluminum in 1 M NaOH found to be higher than that in the presence of the inhibitor (Table 3). This indicates that inhibition of corrosion of aluminum by SA occurred by both the passivation mechanism and by barrier protection. Furthermore, this implies that the plant extract functioned via mixed inhibition mechanisms at high temperature, and can be attributed to chemisorptions at high temperature [19]. This confirms the mixed mode (anodic and cathodic) inhibition action of the *sinapis alba*, which is in good agreement with those obtained from polarization study in section 3.2.

An alternative formulation of the Arrhenius equation is the transition state equation (Eq. 8) [20]:

$$CR = (K_B T / h) e^{(\Delta S^\# / R)} e^{(-\Delta H^\# / RT)} \tag{8}$$

where h is Planck's constant, K_B Boltzmann constant, $\Delta S^\#$ is the entropy of activation and $\Delta H^\#$ is the enthalpy of activation.

Figure 7 shows a plot of $\log (CR/T)$ against $(1/T)$. Straight lines are obtained from which the values of $\Delta H^\#$ and $\Delta S^\#$ are calculated and presented in Table 3. It's well-known that the absolute values of enthalpy of activation less than 42.0 kJ mol⁻¹ indicates a physical adsorption and as it approaches 100 kJ mol⁻¹ indicates a chemical adsorption [19]. In this study, the reported values of $\Delta H^\#$ indicate a physical adsorption. The values of $\Delta S^\#$ in the presence and absence of the inhibitors are

negative. This implies that the formation of the activation complex, which is the rate determining step, representing association rather than dissociation. Therefore, a decrease in disorder takes place on going from reactant to the activated complex [21].

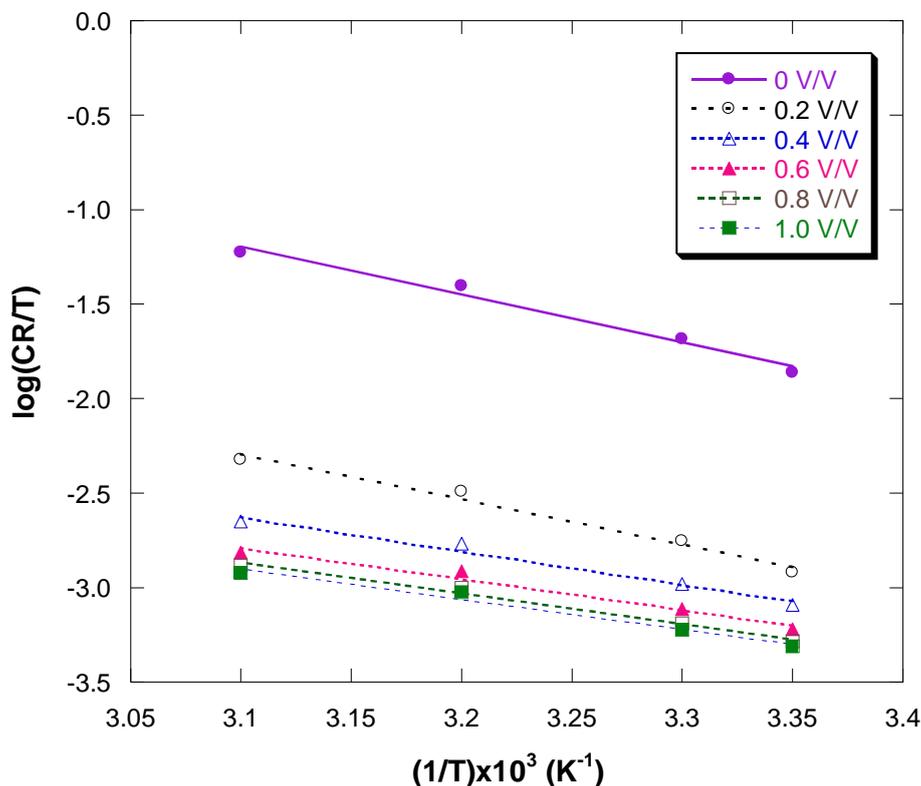


Figure 7. Log (CR./T) vs. 1000×1/T for Al coupon in 1 M NaOH in the absence and presence of *sinapis alba* extract.

The kinetics of the corrosion of aluminum in alkaline solution (1M NaOH), in the absence and presence of the tested inhibitor (SA) was studied at 25 °C by fitting the corrosion data into different rate laws. Figure 8 shows the dependence of log [w_i - Δw_t] as a function of time. The corrosion data fit the rate law for first-order reaction as expressed in Equation 9:

$$\log(w_i - \Delta w_t) = \frac{-kt}{2.303} + \log w_i \tag{9}$$

where w_i is the initial weight of aluminum specimen, Δw_t is the weight loss of aluminum specimen at time t, [w_i - Δw_t] is the residual weight of aluminum coupon at time t and k is the first-order rate constant. Figure 8 show linear plots with correlation coefficients close to 1 which confirm first-order kinetics for the corrosion of aluminum in 1 M NaOH solution in the presence and absence of *sinapis alba* extract. The linearity of the curves in the absence and presence of the *sinapis alba* extract implies that the presence of inhibitor does not change the kinetics of the corrosion reaction though it significantly reduces its rate (in the absence of SA k = 0.335 h⁻¹, in presence of 1.0 v/v SA k = 2.13x10⁻³ h⁻¹). This observation is in agreement with the report on acid corrosion of aluminum in the presence of other extracts [22,23].

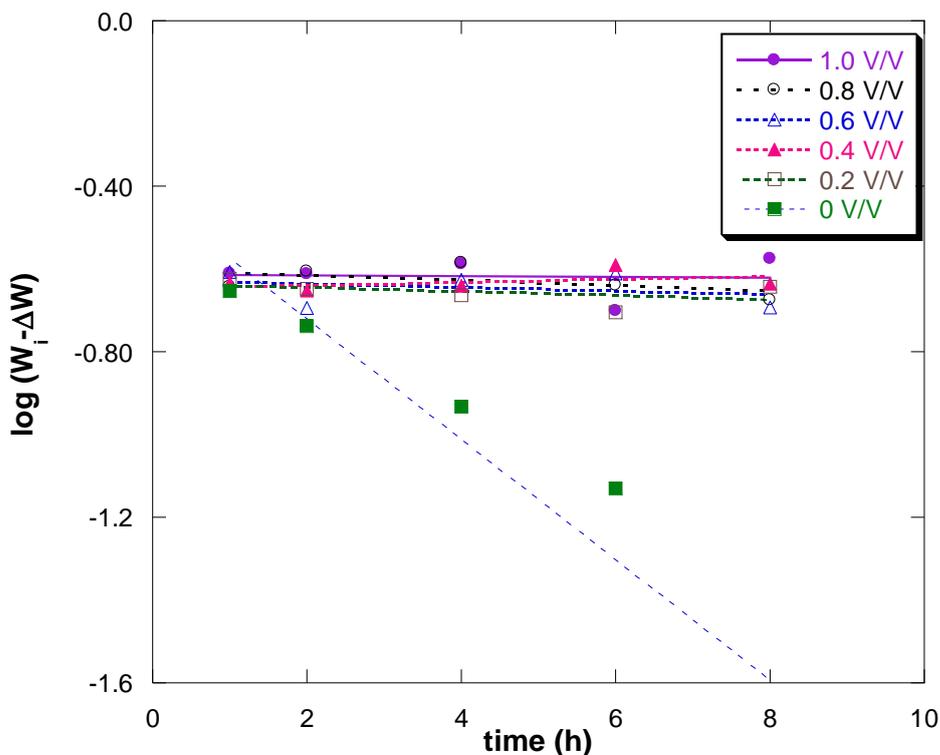


Figure 8. Plot of Log[wi-Δw] versus time for Al in 1M NaOH solution with and without *sinapis alba* extract at 25 °C.

3.5 Adsorption isotherms

The values of the amount of inhibitor adsorbed from the solution, Q_{ads} , on aluminum specimen in the presence of inhibitor are estimated by the following equation (Eq. 10):

$$Q_{ads} = 2.303R \left[\log \left(\frac{\theta_2}{1-\theta_2} \right) - \log \left(\frac{\theta_1}{1-\theta_1} \right) \right] \left(\frac{T_1 T_2}{T_2 - T_1} \right) \quad (10)$$

where R is the gas constant, θ_1 and θ_2 are the degree of surface coverage at temperatures T_1 (313K) and T_2 (323K) respectively.

The calculated values of Q_{ads} are found to be ranged from 1.0 to 7.6 kJ mol^{-1} . The positive sign of Q_{ads} indicates an increase in efficiency at high temperature [24].

The experimental data for the tested inhibitor (SA) in alkaline solution have been applied to different adsorption isotherms. The best correlation among the experimental results from the adsorption of *sinapis alba* extract on aluminum surface fitted Langmuir adsorption isotherm equation. The adsorption of *sinapis alba* extract molecules obeys the Langmuir adsorption isotherm which is expressed by Eq. 11 [25, 26]:

$$\log \left(\frac{C}{\theta} \right) = -\log K_{ads} + \log C \quad (11)$$

where C is the inhibitor concentration and K_{ads} is the equilibrium constant for the adsorption/desorption process of the inhibitor molecules on the metal surface.

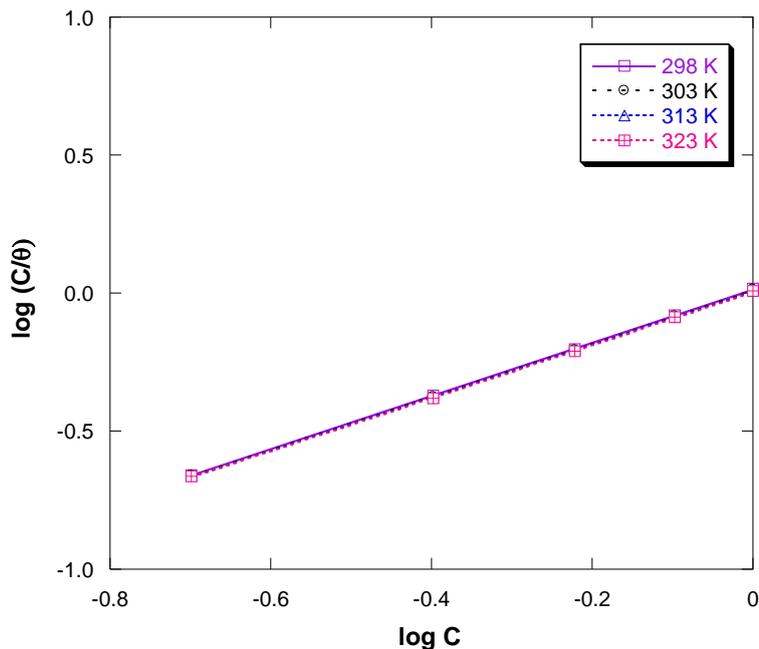


Figure 9. Langmuir adsorption model on aluminum surface of *sinapis alba* extract in 1 M NaOH solution for 2 hour at different temperatures.

Figure 9 shows a typical Langmuir adsorption isotherm of SA in alkaline solution. The equilibrium constants, K_{ads} , for the adsorption of *sinapis alba* extract on aluminum in 1M NaOH at different temperatures estimated from the regression equation of the linear plot of Fig. 9 and were summarized in Table 4.

Table 4. Langmuir adsorption parameters for the adsorption of *sinapis alba* extract on aluminum in 1M NaOH for 120 min immersion period at different temperatures.

Isotherm	Temperature (K)	K_{ads}	R^2	ΔG°_{ads} (kJ mol ⁻¹)
Langmuir	298	0.9694	0.9999	-10.0
	303	0.9770	0.9999	-10.2
	313	0.9831	0.9999	-10.5
	323	0.9874	0.9999	-10.8

The equilibrium constant, K_{ads} , of adsorption is related to the standard free energy of adsorption, ΔG°_{ads} , by Eq. 11 [26, 27]. Thus, by using the estimated values of K_{ads} from the Langmuir adsorption isotherm, the free energy of adsorption have been calculated using Eq. 12 and listed in Table 4. Table shows that all values of ΔG°_{ads} at different temperature are negative and less than - 40 kJmol⁻¹, which is the reported value for physical adsorption [27]. Therefore, the reported values of ΔG°_{ads} imply that the adsorption of *sinapis alba* extract on aluminum surface is spontaneous and confirms physical adsorption mechanism [27].

$$\Delta G^{\circ}_{ads} = -2.303RT \log(55.5K_{ads}) \quad (12)$$

Furthermore, it has been noticed that the value of K_{ads} increases with increasing temperature, indicating that adsorption of inhibitor molecules on the aluminum surface was favorable at higher temperatures. Such results imply activation that the interactions between the adsorbed molecules and the metal surface become stronger as temperature increased up to 50°C, in this study. This result explains the increase in the inhibition efficiency with increasing temperature. Moreover, the low values reported for the free energy change, ΔG°_{ads} , confirm the physisorption mechanism of the tested inhibitor (SA) on the aluminum surface.

4. CONCLUSIONS

The following main conclusions can be drawn from the present study:

1. The results of weight loss, and polarization methods proposed the potential applicability of *Sinapis alba* extract as a green corrosion inhibitor for aluminum in alkaline media.
2. Polarization measurements showed that the inhibitor (SA) is a mixed type inhibitor (anodic and cathodic).
3. The SEM results showed that the metal surface is partially covered with the inhibitor giving it a reasonable degree of protection.
4. The inhibition efficiency increased with increasing the concentration of *sinapis alba* extract to attain a value of 97.98% (1.0 v/v) at 50 °C.
5. The inhibition efficiency increased with increasing temperature.
6. The activation energy, E_a , of the dissolution of plain aluminum in 1 M NaOH found to be higher than that in the presence of the inhibitor. This indicates that inhibition of corrosion of aluminum by SA occurred by both the passivation mechanism and by barrier protection.
7. The sign of the free energy of adsorption indicates that the process is spontaneous.

ACKNOWLEDGEMENTS

The authors would like to thank the Yarmouk University - faculty of graduate studies and scientific research for providing financial support. N.A.F. Al-Rawashdeh acknowledges the financial support of the UAEU (Project No.: 31S014).

References

1. R.M. Saleh. and A.M Shams Eldin, *Corros. Sci.* 12(9) (1972) 689-697.
2. G. Gunsekaran and L.R. Chauhan, *Electrochim. Acta* 49(25) (2004) 4387-4395.
3. M.L. Doche, J.J. Rameau, R. Durand, F. Novel-cattin, *Corros. Sci.* 41(2007) 805-826
4. a) M. A. Abu-Dalo, A. A.Othman and N. A.F. Al-Rawashdeh, *Int. J. Electrochem. Sci.* 7 (2012) 9303-9324; b) Muna A. Abu-Daloo, Nathir A.F. Al-Rawashdeh and Ayman Ababneh, *Desalination* 313 (2013) 105-114.
5. O.K. Abiola and J.O.E. Otaigbe, *Corros. Sci.* 50 (2008) 242-247.
6. A.R. Yazdjad. T. Shahrabi and M.G. Hosseini, *Mater. Chem. Phys.* 109 (2008) 199-205.
7. P.C. Okafor, U.J. Ekpe, E.E. Ebenso, S.A. Umoren and K.E. Leizou *Bull. Electrochem.* 21(8) (2005) 347-352.

8. M.M. Al-Abdallah, A.K. Maayta, M.A. Al-Qudah and N.A.F. Al-Rawashdeh, *The Open Corros. J.* 2 (2009) 71-76.
9. N.C. Subramanyam, B.S. Sheshadri and S.M. Mayanna *Corros. Sci.* 34(4) (1993) 563-571.
10. A.K. Maayta and N. A. F. Al-Rawashdeh, *J. Jordanian Chem.* 5(2) (2010) 175-189.
11. A. Ruosan and N. A. F. Al-Rawashdeh, *Corros. Eng. Sci. Tech.*, 41(3) (2006) 235-239.
12. Nathir Al-Rawashdeh and A.K. Maayta, *Anti-Corros. Method. Mater.*, 52(3) (2005) 160-166.
13. A.K. Maayta and Nathir Al-Rawashdeh, *Corros. Sci.*, 46(5) (2004) 1129-1140.
14. E.E. Oguzi, *Mater. Chem. Phys.*, 99(2-3) (2006) 441-446.
15. E.E. Oguzi, *Port Electrochim Acta*, 26(3) (2008) 303-314.
16. R.P. Bothi, R.A. Abdul, O. Hasnah and A. Khalijah, *Acta. Phys. Chim. Sin.* 26(8) (2010) 2171-2176.
17. M. A. Al-Qudah, H. I Al-Jaber, R. Muhaidat, E. I. Hussein, A. Al Abdel Hamid , M. L. Al-Smadi, I. F. Abaza, F. U. Afifi and S. T. Abu-Orabi. *Research J. Pharmace. Biological Chemical Sci.*, 2(4) (2011) 1136-1144
18. S.A. Umoren, I.B. Obot, E.E. Ebenso, P.C. Okafor, O. Ogbobe and E.E. Oguzie, *Anti-Corros. Methods and Mater.* 53(5) (2006) 277-282.
19. A. Popova, E. Sokolova, S. Raicheva and M. Christov, *Corros. Sci.* 45 (2003) 33-58.
20. M. I. Awad, *J. Appl. Electrochem.* 36 (2006) 1163-1168.
21. L. Valek and S. Martinez, *Mater. Lett.*, 61 (2007)148-151.
22. O.K. Abiola, N.C. Oforika, E.E. Ebenso and N.M. Nwinuka, *Anti- Corros. Method. Mater.* 54 (2007) 219-224.
23. O.K. Abiola, A.O.C. Aliyu, A.A. Phillips and A.O. Ogunsipe, *J. Mater. Environ. Sci.* 4 (3) (2013) 370-373.
24. J. Peterson, *Aust. J. Exp. Biol. Med. Sci.* 41 (1963) 903-906.
25. K.C. Emeregul and A.A. Aksut, *Corros. Sci.* 42 (2000) 2051-2067.
26. M.L. Doche, J.J. Rameau, R. Durand and F. Novel-Cattin, *Corros. Sci.* 41 (2007) 805-826.
27. M. Wink, C. Meibner and L. Witte, *Phytochemistry* 38 (1995) 139-153.
28. E. Kamis and N. Alandis, *Corros.* 46 (1990) 476-484.
29. S.S. Abd El-Rehim, M.A.M. Ibrahim and K.F. Khaled, *J. App. Electrochem.* 29(5) (1999) 593-599.
30. E. McCafferty, in *Corrosion Control by Coating*; H. Leidheiser Jr. (Ed.), Science press, Princeton, (1979) 279.