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Self-Assembled Monolayers of Ponceau 4R as a Green Copper Corrosion Inhibitor in NaCl Solution

N. Khorrammaslack[1], S. M. Seyedahmadian[1], Kh. Farhadi[2*]
[1.] Department of Chemistry, Faculty of Science, Azarbaijan Shahid Madani University, P.O. Box: 53714-161, Tabriz, Iran
[2.] Department of Analytical Chemistry, Faculty of Chemistry, Urmia University, P.O. Box: 165- 5715944931, Urmia, Iran,

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ABSTRACT

The inhibitory behavior of Ponceau 4 R (an important industrial food dye) on the corrosion of copper surface in 3.5% NaCl solution was studied using potentiodynamic polarization, electrochemical impedance spectroscopy (EIS) and Fourier transform infrared (FT-IR) spectroscopy. Polarization curves indicated that the self-assembled monolayer of Ponceau 4 R acts as a mixed inhibitor. The adsorption of inhibitors was well fitted to the Langmuir isotherm and the thermodynamic parameters (K_{ads}, ΔG^0) were also calculated and discussed. The inhibition efficiency of ponceau 4 R film reached 99.5% under optimized conditions and the standard Gibbs energy of 31.1 kJ/mol indicated that the adsorption mechanism of the self-assembled monolayer of Ponceau 4 R on copper was a mixed mode of physical and chemical adsorption. The obtained results revealed that other food dyes containing functional groups such as hydroxyl, sulfonyl, aromatic rings and especially azo groups can act as green inhibitor for corrosion of copper in neutral sodium chloride solutions. Prog. Color Colorants Coat. 13 (2020), 199-212© Institute for Color Science and Technology.

1. Introduction

Metal corrosion is a natural phenomenon that can damage or alter the nature of a metal or alloy in different environments, especially in aqueous media, through an irreversible process. To date, several methods have been introduced to prevent or destroy metal surfaces that utilize corrosion inhibitors as one of the most effective corrosion protection methods are often preferred. In this strategy, the self-assembled and compact thin films of adsorbents with various chemical compositions on metal surfaces have been used for corrosion inhibition of metals [1, 2].

Because of widespread applications of copper and its alloys in different industries, many attempts have been achieved to reduce the corrosion of copper metallic materials [3-6]. Although copper has been known as relative inert metal, it can be corroded in aerated acidic media as well as in the presence of complexing agents such as chloride and sulfide ions [7-9]. Since most of the copper metallic products are used in neutral media containing aggressive chloride ions, extensive researches have been done on copper corrosion protection in aqueous NaCl solutions [10]. Table 1 lists the name and inhibition efficiency of some environment-friendly compounds (along with the proposed inhibitor in this work) used for corrosion protection of copper in NaCl solution. Based on the literature, most of the inhibitors containing aromatic rings, hetero-atoms such as sulfur, nitrogen, phosphorus and oxygen have been developed to reduce the corrosion rate of copper. Therefore, Schiff bases, amino acids, azole derivatives, ionic liquids, oils,

*Corresponding author: khalil.farhadi@yahoo.com
kh.farhadi@urmia.ac.ir

pharmaceutical drugs, natural products (such as chitosan biopolymer, olive mill wastewater, etc.) as well as organic thiol group compounds are known to be desirable copper corrosion inhibitors [11-18]. The excellent performance of these groups of inhibitors arises from their adsorption tendency to copper surface and blocking the active sites through forming a self-assembled thin compact film [19-23]. It should be noted that in situ synthesis (chemical or electrochemically) of heterogeneous polymeric composites or nanocomposites on the metal surface has been considered as an alternative procedure for corrosion control [9, 24].

Ponceau 4R (trisodium (8*Z*)-7-oxo-8-[(4-sulfonatonaphthalen-1-yl) hydrazinylidene] naphthalene-1,3-disulfonate ($C_{20}H_{11}N_2Na_3O_{10}S_3$) (Figure 1), as a member of the azo dye group, is a non-toxic food color that has high resistance to light and heat [25]. It is completely soluble in water as disodium salt (80 mg/mL= 0.13 M) and is used to regulate strawberry red in various foods [25]. The joint FAO/WHO committee on food additives (JECFA) and European Food Safety Authority (EFSA) has declared that Ponceau 4 R and its metabolites are not carcinogenic, genotoxic, neurotoxic or caused reproductive or development toxicity [26].

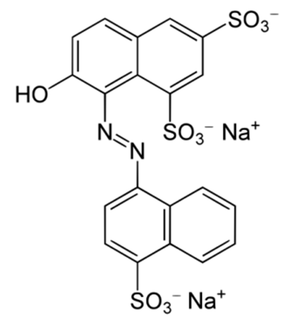


Figure 1: The Chemical structure of ponceau 4 R.

Table 1: The efficiency and concentration of some copper corrosion inhibitors in NaCl solution.

Inhibitor type	Inhibitor	Concentration	Efficiency (%)	Reference
Schiff base	1-Butyl-3-methylimidazolium bromide (BMIMBr) 4-(4-Aminostyryl)-N,N-dimethylaniline (AND)	0.15 mM	84.7	[11]
Amino acid	4-Aminothiophenol	1 mM	84.8	[12]
Azole	Polypyrrole-oxalic acid benzotriazole (PPy-Ox-BTA)	-	<80	[13]
Ionic liquid	1-Butyl-3-methylimidazolium chloride (BMIMCl)	50 mM	96	[14]
Biodiesel	Palm-oil modified hydroxyethyl imidazoline	50 ppm	90	[15]
Biopolymer	Chitosan	1000 ppm	86	[16]
Thiol group compounds	Thiosemicarbazide (inh 1), phenyl isothiocyanate (inh 2) and 1-phenyl- 2,5-dithio hydrazodicarbonamide	100 ppm	60-80	[17]
Pharmaceutical drugs	5-Chloro-1-[1-[3-(2-oxo-2,3-dihydro-1H-benzimidazol-1-yl) propyl]-4-piperidinyl]-1,3-dihydro-2H-benzimidazol-2-one (Domperidone)	20 ppm	93.6	[18]
Food dye	Ponceau 4 R	1 mM	99.5	This work

In current work, considering the presence of various active groups such as hydroxyl, sulfonyl, aromatic rings and especially azo group in the structure of Ponceau 4 R as well as the inherent tendency of copper to adsorb azo dyes [27], self-assembled monolayers (SAMs) of ponceau 4 R was applied for the protection of copper surface in harsh chloride media through the formation of a compact protecting layer. Potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) were applied to analyze the inhibitory behavior of self-assembled monolayers on the copper surface in a 3.5% NaCl solution. The adsorption behavior of Ponceau 4R on copper surface was also fitted to Langmuir adsorption isotherm.

2. Experimental

2.1. Chemicals and solutions

Sodium chloride, Ponceau 4 R and other chemical materials used in this study were purchased from Sigma-Aldrich (St. Louis, MO, USA). For the corrosion environment, accurately weighed NaCl (3.5% w/v) was dissolved in deionized water. To investigate the effect of inhibitor concentration, Ponceau 4 R solutions (1, 0.5, 0.1 and 0.05 mM) were prepared freshly by diluting series of stock solutions with DI water. Sodium chloride solution (3.5% W/V) without inhibitor was used as blank solution and copper electrodes were immersed into these solutions immediately after preparation.

2.2. Apparatus and electrochemical measurements

Electrochemical experiments, including Tafel polarization and EIS measurements, were conducted on an Auto lab PGSTAT30 Potentiostat-Galvanostat (Eco Chemie, Utrecht, Netherlands). The Zview 2 and Sigmaplot software’s were used to fit the EIS and Tafel polarization plots. A conventional three - electrode cell was applied for electrochemical analysis. Copper rod with 0.4 cm in diameter (exposed surface area of 0.1256 cm^2), Ag/AgCl (3 M) (Azar Electrode Instruments, Urmia, Iran) and stainless steel electrodes were used as working, reference and counter electrodes, respectively. EIS and Tafel polarization measurements were made after the immersion of the working electrode at 300 ± 1 K under open circuit potential conditions. The potential was swept from E_{ocp} –1 V to E_{ocp} +1 V at the scan rate of 1 mVs^{-1}. The EIS measurements were performed at frequencies within the range of 0.01-10 kHz with the sinusoidal amplitude potential perturbation of 1 mV.

2.3. Preparation of copper surface

Surface of the copper was first polished with different grades of emery paper (150, 600, 1000, 1500 and 2000, respectively) followed by washing with DI water. Then, to ensure the removal of all greasy impurities and particles, the samples were exposed to ultrasonic waves in an acetone bath for 5 minutes and then rinsed with DI water.

3. Results and Discussion

3.1. Electrochemical polarization studies

Figure 2 (a and b) shows potentiodynamic polarization curves of copper (at two potential swept ranges) immersed in 3.5% NaCl solution containing different concentrations of Ponceau 4 R for 2 h. The mechanism of anodic dissolution of copper is described by the following equations [28, 29]:

$$Cu + Cl^{-} \rightarrow CuCl + e^{-} \quad (1)$$

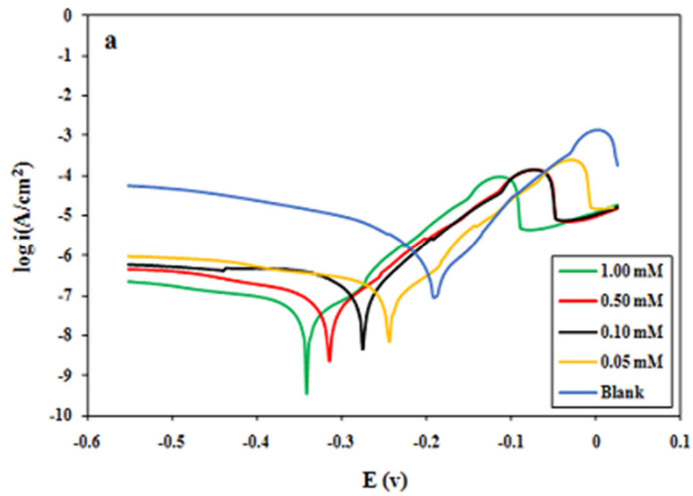
$$CuCl + Cl^{-} \rightarrow CuCl_2^{-}{}_{ads} \quad (2)$$

$$CuCl_2^{-}{}_{ads} \rightarrow Cu^{2+} + 2Cl^{-} + e^{-} \quad (3)$$

Accordingly, both electro-dissolution of copper and diffusion of soluble $CuCl_2^{-}{}_{ads}$ to the bulk solution control the anodic dissolution of copper [30]. Also, the considered cathodic process in the aerated solutions, reduction of oxygen, is as follow:

$$O_2 + 4e + 2H_2O \rightarrow 4OH^{-} \quad (4)$$

Based on the obtained results (Figure 2), the formation of Ponceau 4 R film leads to negative shifts in the corrosion potential in comparison with the bare electrode. In addition, corrosion rate decreased significantly with decreasing the anodic and cathodic currents. Therefore, it can be claimed that the formation of Ponceau 4 R film efficiently inhibited the anodic and cathodic reactions. The corrosion inhibition process may be due to the adsorbed inhibitor molecules on the copper surface and the reduced dissolution of copper.



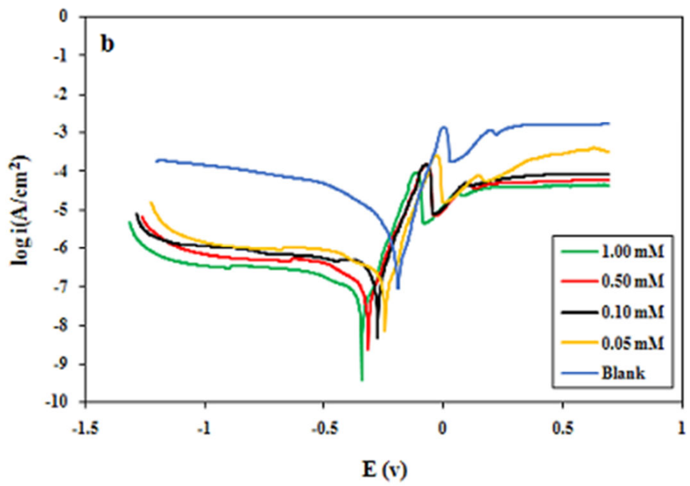


Figure 2: Potentiodynamic polarization curves of copper in 3.5% NaCl solution without and with Ponceau 4 R film coated from solutions with different concentrations of Ponceau 4 R after 2 h immersion swept (a) from E_{ocp} –0.3 V to E_{ocp} +0.3 V and (b) from -1 V to E_{ocp} +1 V at a scan rate of 1 mV s^{-1}.

The values of E_{corr}, I_{corr}, Tafel slopes, β_a, β_c, polarization resistance (R_p), corrosion rate (CR) and inhibition efficiency (η) after 2 h of immersion are summarized in Table 2. The corrosion rate (CR) was calculated according to equation 5 [31]:

$$\text{CR (mm/year)} = 3.268 \times 10^3\ I_{corr}\ E_W/\rho \tag{5}$$

where I_{corr} is the corrosion current density (Acm^{-2}), E_W is the copper molar mass (63.35 g mol^{-1}) and ρ is the copper density (8.94 g cm^{-3}). Polarization resistance and inhibition efficiency were calculated using equations 6 and 7:

$$R_p = \frac{\beta_a \cdot \beta_c}{2.3\ i_{corr}\ (\beta_a + \beta_c)} \tag{6}$$

$$\eta\ (\%) = \frac{i_{corr,0} - i_{corr,i}}{i_{corr,0}} \tag{7}$$

where $i_{corr,0}$ and $i_{corr,i}$ are the corrosion current densities for copper electrode in 3.5 % NaCl inhibitor-free and coated electrode, respectively. It is generally accepted that inhibitors can be classified into two anodic or cathodic types when the change in E_{corr} value is higher than 85 mV (vs. SCE) [32, 33]. As can be seen from the obtained results (Table 2), E_{corr} values were shifted toward more negative values in comparison with bare copper and the displacements are more than 85 mV (vs. SCE) for 1 and 0.5 mM Ponceau 4 R solutions and are less than 85 mV (vs. SCE) for 0.1 and 0.05 mM Ponceau 4R solutions. Therefore, it can be deduced that Ponceau 4R had acted as a mixed-type corrosion inhibitor capable of inhibiting both anodic and cathodic reactions on the copper surface. However, cathodic prevention played a dominant role in this process. It was observed that by increasing the Ponceau 4 R concentration, the values of $i_{corr,i}$ and C_R were decreased. Meanwhile, the Ponceau 4 R self-assembled monolayer (SAM) causes the cathodic Tafel slope was significantly shifted.

On the other hand, the small shift of anodic slope can be considered as another reason for the inhibition of copper dissolution. The data shown in Table 2 illustrates that the inhibition efficiency (η) of copper electrode coated with Ponceau 4 R reaches 99.50% after 2 h immersion in 1mM solution. So, it can be deduced that Ponceau 4 R- SAM on copper surface mainly controls the cathodic reaction of the corrosion process.

Figure 3 shows the potentiodynamic polarization curves of copper in identical solutions after being immersed for 24 h. As can be seen, after this period, the corrosion current was slightly increased and the inhibition efficiency decreased (η=99.18% in 1mM solution), but the corrosion rate in blank solution (inhibitor-free 3.5% NaCl solution) is still significantly low compared to the bare Cu electrode. This fact can probably be justified by the formation of a copper oxide layer on the metal surface that causes a negative change in the copper polarization plot. The values of the E_{corr}, I_{corr}, Tafel slopes βa, βc, polarization resistance (R_p), corrosion rate (CR) and inhibition efficiency (η) after 24 h immersion are shown in Table 3.

Table 2: Corrosion parameters obtained from potentiodynamic polarization curves for copper coated with Ponceau 4 R film from 3.5% NaCl solutions containing different concentrations of Ponceau 4 R after 2 h immersion.

C (mM)	Ecorr (mV/SCE)	I corr (A cm^{-2})	bc (mV dec^{-1})	ba (mV dec^{-1})	CR (mm y^{-1})	Rp(Ω)	(η ± SD)% (n=3)
Blank	-198	8.11×10^{-6}	127	300	3.2×10^{-1}	2.3×10^{4}	-
1	-342	3.65×10^{-8}	67	85	1.21×10^{-3}	4.46×10^{6}	99.5 ± 2.1
0.5	-302	8.92×10^{-8}	144	142	3.08×10^{-3}	9.07×10^{5}	98.9 ± 3.5
0.1	-276	2.98×10^{-7}	108	59	5.20×10^{-3}	4.40×10^{5}	96.3± 3.8
0.05	-246	7.15×10^{-7}	106	178	8.36×10^{-3}	1.48×10^{5}	91.2± 4.8

Table 3: Corrosion parameters obtained from potentiodynamic polarization curves for copper coated with Ponceau 4 R film from 3.5% NaCl solutions containing different concentrations of Ponceau 4 R after 24 h immersion.

C (mM)	Ecorr (mV/SCE)	I corr (A cm^{-2})	bc (mV dec^{-1})	ba (mV dec^{-1})	CR (mm y^{-1})	Rp (Ω)	(η ± SD)% (n=3)
Blank	-228	2.9×10^{-5}	107	91	6.78×10^{-1}	5.79×10^{3}	-
1	-313	6.62×10^{-8}	185	83	1.59×10^{-3}	7.89×10^{5}	99.18 ± 2.4
0.5	-286	1.91×10^{-7}	88	108	6.35×10^{-3}	1.13×10^{5}	97.65 ± 3.6
0.1	-268	5.23×10^{-7}	195	128	1.47×10^{-2}	6.40×10^{4}	93.54 ± 3.8
0.05	-242	7.79×10^{-7}	378	150	1.85×10^{-2}	5.76×10^{4}	90.38 ± 4.3

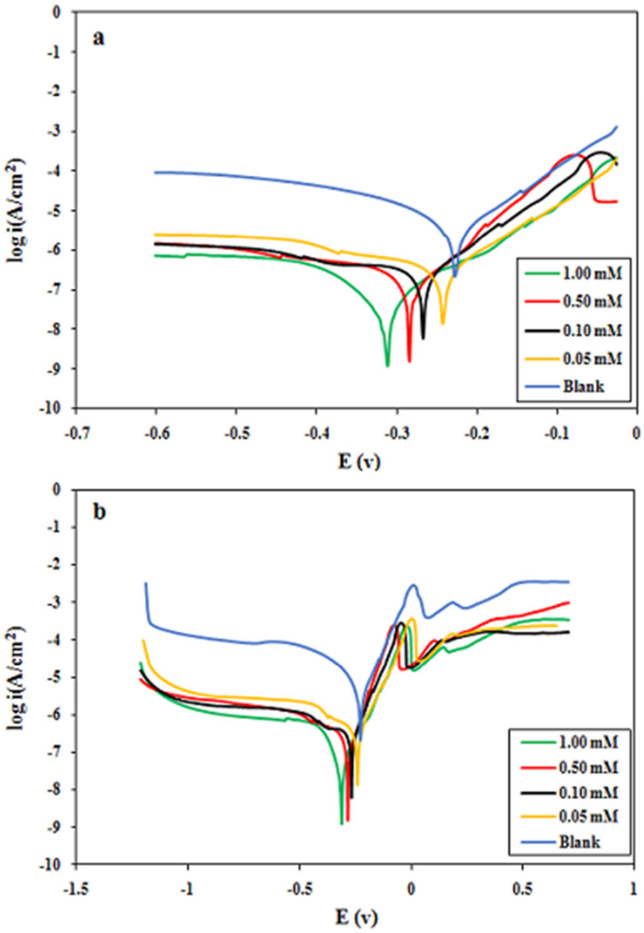


Figure 3: Potentiodynamic polarization curves of copper in 3.5% NaCl solution without and with different concentrations of Ponceau 4 R after 24 h immersion swept (a) from E_{ocp} –0.25 mV to E_{ocp} +0.25 mV and (b) from E_{ocp} –1 mV to E_{ocp} +1 mV at a scan rate of 1 mV s^{-1}.

3.2. Electrochemical impedance spectroscopy measurements

Electrochemical impedance spectroscopy (EIS) is the most cited technique that can be used for investigating the protective features of inhibitors coated on metal surfaces [34, 35]. Therefore, the inhibition effects of Ponceau 4 R films formed on the copper surface at various concentrations were investigated using electrochemical impedance spectroscopy (EIS). Figures 4 and 5 show the Nyquist, Bode, and phase Bode plots of copper electrodes immersed in 3.5% NaCl solution without and with different concentrations of the inhibitor for 2 and 24 h. The Nyquist plot of copper in blank solution consists of two semicircles, one smaller at high frequencies and another at lower frequencies [36]. The semicircle in the low-frequency region was attributed to the transportation of dissolved oxygen to the copper surface [37] and/or the diffusion of chloride–copper complexes ($CuCl_2^-$, $CuCl_4^-$) to bulk solution [38, 39]. For copper electrodes coated with Ponceau 4 R, the large depressed semicircles are extended from high to low frequencies in the Nyquist plots and the diameter of the capacitive loop gradually increases by increasing the inhibitor concentration. These observations indicated the formation of a protective film sufficiently dense to prevent the diffusion of oxygen onto the copper surface. As can be seen in EIS diagrams (Figure 4a), the diameter of the capacitive loop reaches a maximum value when 1mM Ponceau 4 R self-assembly solution was applied. Bode plots (Figure 4b) showed that the impedance values increased significantly with increasing the inhibitor concentration over the whole range of frequency. Based on the phase angle plots (Figure 4c), increasing the concentration of SAM increased the adsorption of

Ponceau 4 R molecules on the copper surface which in turn resulted in higher values of phase angle, proving their superior inhibitory behavior. Actually, the adsorption of inhibitor molecules as monolayers on the surface of copper caused an increase in polarization resistance and reduced the copper corrosion rate [40].

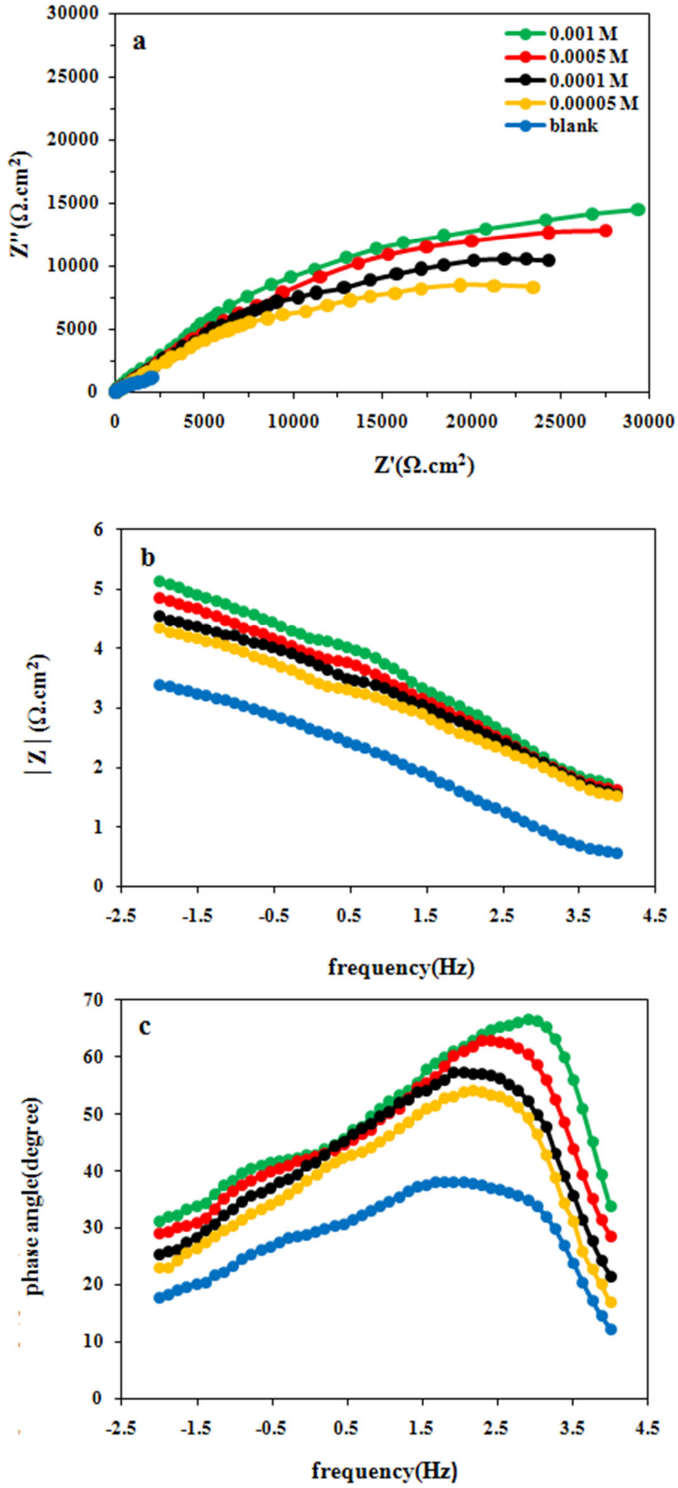


Figure 4: The orthonormal Nyquist (a), Bode (b) and phase Bode (c) plots for copper electrodes immersed in 3.5% NaCl solution without and with different concentrations of Ponceau 4 R inhibitor after 2 h immersion.

Also, Figure 5 shows the Nyquist plot of as-prepared copper electrodes immersed in the selected aggressive solution (3.5% NaCl solution) containing different concentrations of Ponceau 4 R for 24 h. In addition, comparing the two plots (Figures 4 and 5) showed that for the electrodes immersed for more than 24 h, the diameter of the semicircles for all inhibitor concentrations is slightly decreased, while the impedance value is greater than that of the blank solution.

The EIS data were analyzed using an equivalent electrical circuit, given in Figure 6, where R_s is the electrolyte resistance, CPE_c is the constant phase element connected with the coating capacitance, R_{po} is the coating pore resistance, CPE_p is the phase element (indicating all frequency-dependent electrochemical phenomena, double-layer capacitance and diffusion processes) and R_{ct} is the charge transfer resistance related to corrosion processes occur in the pores [41-43].

For a more accurate fit constant phase element, CPE was introduced in the circuit instead of a pure capacitor [44, 45]. Nyquist plots for different inhibitor concentrations were recorded. The EIS data for copper electrode in 3.5% NaCl solution under different conditions (different inhibitor concentrations and immersion times of 2 and 24 h) are presented in Tables 4 and 5. The higher values of R_{ct} and R_{po} and the lower values of CPE_c and CPE_{dl} are indicative of excellent protective performance of SAM coating. The R_{pol} was also calculated by using EIS data as follows (equation 8) [41]:

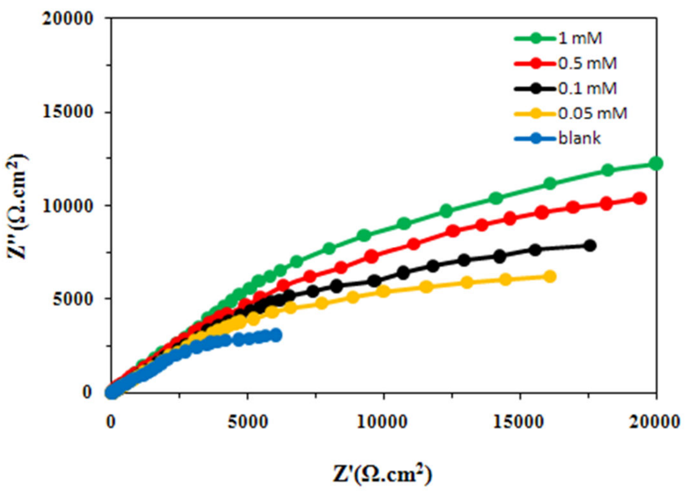


Figure 5: The orthonormal Nyquist plot of copper electrodes immersed in 3.5% NaCl solution without and with different concentrations of Ponceau 4 R inhibitor after 24 h immersion.

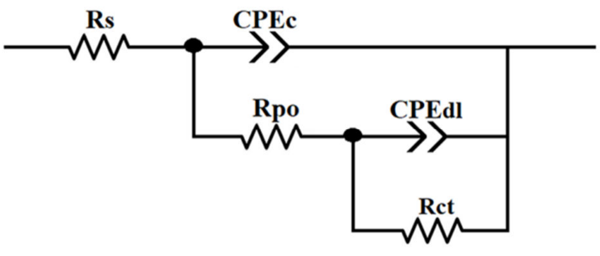


Figure 6: The equivalent circuit used to simulate the experimental data.

$$R_{pol} = R_{po} + R_{ct} \quad (8)$$

The values of R_{pol} obtained after 24 h exposure indicate that the protection efficiency of Ponceau 4 R SAM coating is reduced probably due to the breaking of the thin film.

3.3. Surface morphology and functionality

SEM micrographs of bare copper in the absence and the presence of 1mM Ponceau 4R after 24 h immersion of electrodes in NaCl 3.5% solution are shown in Figure 7. A comparison of the surface images of bare Cu electrode in the absence (Figure 7a) and the presence (Figure 7b) of NaCl without inhibitor indicates that copper seriously corrodes through creation of pits on the rough surface. As can be seen, the obtained holes have been completely blocked with a compact thin film of dye on Ponceau 4 R- SAM copper electrode (Figure 7c).

The formation of Ponceau 4 R SAM on copper surface was also confirmed by FT-IR transmittance spectroscopy using attenuated total reflection (ATR) technique. According to SAM spectrum (data not shown), the broad band around 3438 cm^{-1} and the absorption band at 2930 cm^{-1} was corresponded to the stretching vibration of the hydroxyl group and C-H bonds, respectively. Also, the peaks around 1410-1500 cm^{-1} can be attributed to aromatic rings in Ponceau 4 R structure. On the other hand, the absorption band at 625 cm^{-1} can be assigned to stretching vibrations of S=O bond. These observations demonstrate the presence of Ponceau 4 R at the copper surface electrode after immersion in the dye solution.

3.4. Adsorption isotherm

Adsorption isotherms give valuable information on the interaction between inhibitor molecules and active sites on the surface of copper. The degree of surface coverage (θ) for different inhibitor concentrations in 3.5% NaCl solution was calculated using the results obtained from potentiodynamic polarization (Tables 2 and 3) using the following equation (9):

$$\eta(\%) = 100 \times \theta \quad (9)$$

Table 4: Electrochemical impedance spectroscopy data for copper electrodes immersed in 3.5% NaCl solution without and with different concentrations of Ponceau 4 R inhibitor after 2 h immersion.

C(mM)	Rs ($\Omega.cm^2$)	CPEc-T	CPEc-P	Rpo ($\Omega.cm^2$)	CPEdl-T	CPEdl-P	Rct($\Omega.cm^2$)
Blank	33	5.3×10^{-5}	0.67	416	2.5×10^{-4}	0.81	573
1	81	6.43×10^{-7}	0.97	6134	5.54×10^{-6}	0.81	59650
0.5	75	6.81×10^{-7}	0.94	5576	5.94×10^{-6}	0.79	55430
0.1	69	8.37×10^{-7}	0.89	5024	7.47×10^{-6}	0.75	45780
0.05	58	8.91×10^{-7}	0.86	4121	7.92×10^{-6}	0.71	39650

Table 5: Electrochemical impedance spectroscopy data for copper electrodes immersed in 3.5% NaCl solution without and with different concentrations of Ponceau 4 R inhibitor after 24 h immersion.

C(mM)	Rs ($\Omega.cm^2$)	CPEc-T	CPEc-P	Rpo ($\Omega.cm^2$)	CPEdl-T	CPEdl-P	Rct($\Omega.cm^2$)
Blank	28	$1.32\times10\text{-}^{5}$	0.52	830	5.32×10^{-4}	0.52	9540
1	73	6.68×10^{-7}	0.95	5032	6.11×10^{-6}	0.85	52130
0.5	69	8.45×10^{-7}	0.90	5032	7.91×10^{-6}	0.82	47300
0.1	71	9.42×10^{-7}	0.86	4043	8.54×10^{-6}	0.79	36300
0.05	65	1.49×10^{-6}	0.81	3420	8.74×10^{-6}	0.77	29500

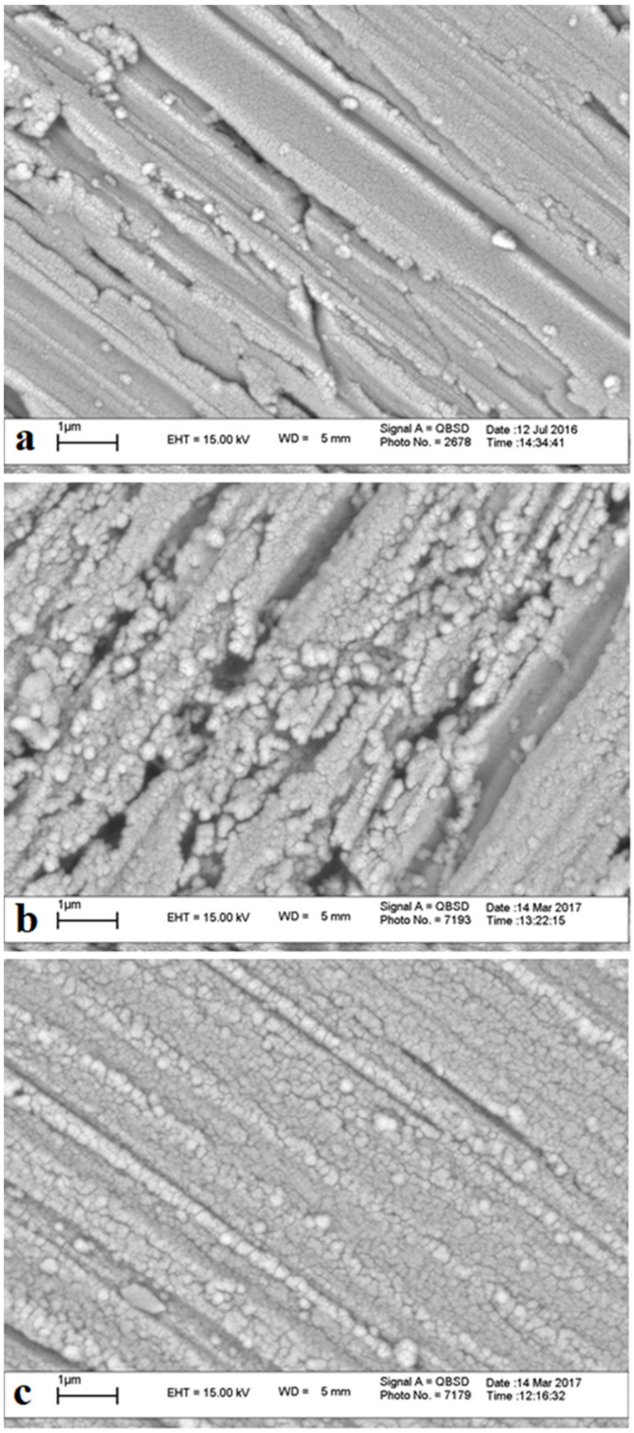


Figure 7: SEM images of (a) bare copper surface (b), copper surface exposed to 3.5% NaCl without inhibitor (as blank solution) after 24 h and (c) copper surface exposed to 3.5% NaCl with Ponceau 4 R film formed in 1mM solution of inhibitor after 24 h at 300 K.

To better understand the nature of the adsorption, it was assumed that the adsorption of Ponceau 4 R on the copper surface followed Langmuir adsorption isotherm equation (10):

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

where C is the inhibitor concentration and K_{ads} is the equilibrium constant. The calculated value for K_{ads} after 2 h immersion in the solution was 2.5×10^5 which proves the high adsorption ability of the proposed compound on the copper surface. The value of correlation coefficient (R^2=0.9995) was employed to find the best fit for the isotherm. The plot of C/θ versus C (Figure 8a) gave a straight line (y =0.9894x + 0.0039) with linear correlation coefficient which proved the assumption that the adsorption of Ponceau 4 R on the copper surface obeys Langmuir adsorption isotherm. K_{ads} is related to the standard free energy of adsorption, ΔG^0_{ads}, by the following equation [42, 46]:

$$\Delta G^0 = -RT\ ln\ K_{ads} \tag{11}$$

where R is the general gas constant (8.314 $Jmol^{-1}K^{-1}$). The temperature was reported as the absolute temperature in Kelvin (300 K). The calculated value of ΔG^0_{ads} was −31.1 kJ mol^{-1}. It is commonly accepted that values of ΔG^0_{ads} around −20 kJ mol^{-1} or less negative values belong to physisorption process; whereas values more negative than −40 kJ mol^{-1} indicate charge sharing or transfer from the inhibitor structure to the metal surface to establish a coordinate bond (chemisorption) [44, 45, 47]. All parameters were obtained after 24 h immersion after which the calculated value of K_{ads} was 1.43×10^6 with correlation coefficient of R^2=0.9999. The plot of C/θ versus C (Figure 8b) gave a straight line (y =0.9909 x + 0.0074) and the calculated value of ΔG^0_{ads} was −29.607 kJ mol^{-1} which indicates that the adsorption of Ponceau 4 R on the copper surface follows a mixed mode of physical and chemical adsorption mechanisms, where the latter was dominant.

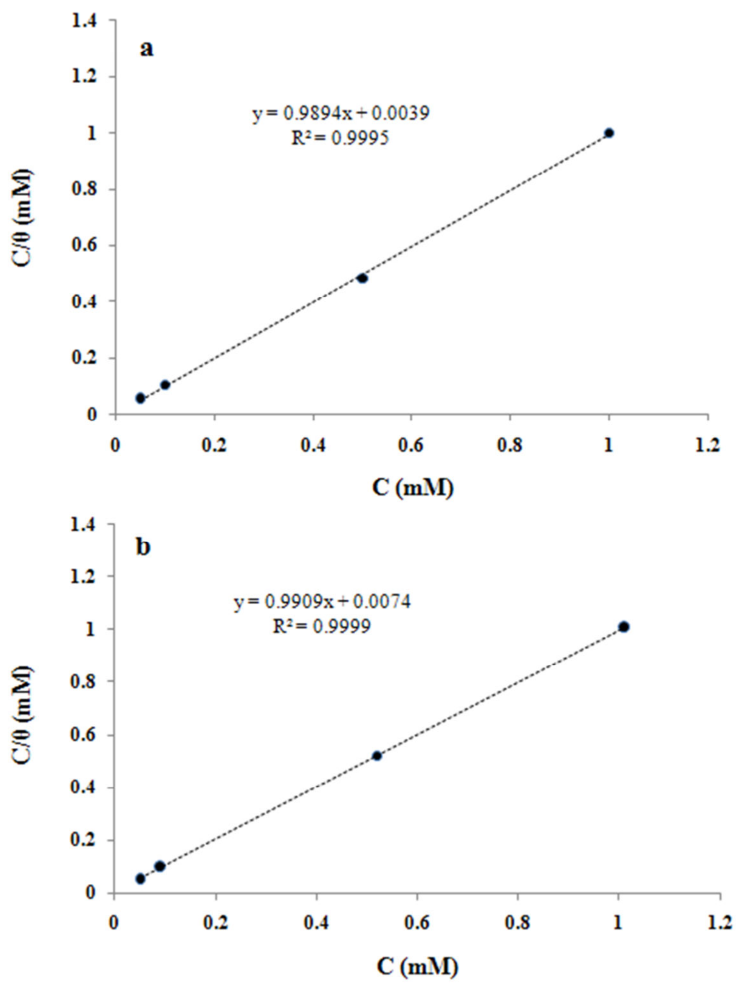


Figure 8: The Langmuir isotherm adsorption plot for Ponceau 4 R film formed on the copper surface in 3.5% NaCl solution containing different concentrations of Ponceau 4 R at 300 K after immersion for (a) 2 h and (b) 24 h.

4. Conclusion

In this work, we investigated the inhibition impact of Ponceau 4R self-assembled monolayer on the corrosion of copper in 3.5% NaCl solution. Electrochemical findings proved that Ponceau 4R film effectively inhibited copper corrosion in the aggressive medium. Under optimized conditions, inhibition efficiencies up to 99% could be obtained. Potentiodynamic polarization investigations demonstrated that Ponceau 4R SAM acts as a mixed-type inhibitor. The adsorption of Ponceau 4R was successfully predicted by Langmuir adsorption isotherm. Furthermore, ΔG^0_{ads} value confirmed that the adsorption mechanism of Ponceau 4R on copper was a combination of both physical and chemical adsorption mechanisms, which based on the obtained results, the latter was dominant. Finally, comparison of inhibition efficiencies and concentrations of the proposed inhibitor and other green inhibitors reported in recent years demonstrated a high copper protection behavior using low concentrations of Ponceau 4R in NaCl solution.

5. References

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