Synergistic Effect of Isopropylamine with Cl- and SO_4^{2-} on Inhibition of Mild Steel Corrosion in Phosphoric Acid

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ABSTRACT: Synergistic effect of Isopropylamine with Cl- and SO_4^{2-} on the inhibition of corrosion of mild steel in phosphoric acid medium has been investigated by using mass loss, potentiostatic polarization and A.C. impedance techniques at 302K. Isopropylamine showed very good inhibition efficiency. It has been found that the inhibition efficiency of the Isopropylamine increased with increase in inhibitor concentration and decreased with increase in acid concentrations. The maximum inhibition efficiency of Isopropylamine in 1N and 5N H_3PO_4 at 2.5% of Isopropylamine were found to be 96.92% and 90.39% respectively. The corrosion rate of mild steel in phosphoric acid has been reduced in the presence of chloride and sulphate ions. Under the synergistic effect, in the presence of 500 ppm of chloride with Isopropylamine inhibition efficiency was 98.24% in 1N and 92.03% in 5N phosphoric acid, and in the presence of 500 ppm of sulphate with Isopropylamine, the inhibition efficiency was found to be 97.50% in 1N and 91.42% in 5N phosphoric acid. The adsorption of these compounds on the mild steel surface has been found to obey Temkin's adsorption isotherm.

Keywords: Mild steel, phosphoric acid, corrosion, inhibition.

Introduction

Phosphoric acid is a major chemical product, which has many important uses, especially in the production of fertilizers. Most of the acid is produced from phosphate rock by wet process. Generally nickel-base alloys and stainless steel are frequently used in many parts of the wet process and a considerable quantity of data has been published about the resistance of these materials to corrosion by phosphoric acid solution [1-5]. Most of the previous studies were focused on the inhibition of stainless steel or chromium-nickel steel in HCl or H_2SO_4 solutions using organic compounds containing nitrogen, sulfur and oxygen atoms as corrosion inhibitors [6]. Organic inhibitors are widely used in various industries. Mild steel is extensively used in industries especially for structural applications. But its susceptibility to rusting in humid air and its very high dissolution rate in acidic medium are the major obstacles in its use on a large scale. Hence, the study of corrosion inhibition of mild steel in

aqueous aggressive media is very important. Different nitrogen containing organic compounds have been studied as corrosion inhibitors for mild steel [7, 8]. Aliphatic, heterocyclic and aromatic amines have been extensively investigated as corrosion inhibitors [9]. According to Hackerman *et al.* [10-11] the inhibitive properties of a series of secondary aliphatic and cyclic amines in acid media are controlled by the percentage of π orbital of free electrons on the nitrogen atom of these compounds. The aim of the present investigation is to examine the synergistic effect on inhibitive action of Isopropylamine (IPA) with Cl- and SO_4^{2-} towards the corrosion of mild steel in 1N and 5N phosphoric acid by mass loss, potentiostatic polarization and A.C. impedance methods at 302K.

Experimental

Materials and Solutions

Mild steel specimens were cut into the size of 5cm x 1cm from the mild steel sheets having the following

percentage composition: Fe=99.686, Ni=0.013, Mo=0.015, Cr=0.043, S=0.014, P=0.009, Si=0.007, Mn=0.196, C=0.017. All the test solutions (1N and 5N H3PO4, 0.5% to 2.5% IPA, and 100 ppm to 500 ppm of chloride and sulphate) were prepared using AR grade chemicals with double distilled water.

Gravimetric Measurements

Gravimetric measurements (mass loss measurements) were performed as per ASTM method described previously [12-13]. The surfaces of the specimens were polished with emery papers ranging from 110 to 410 grades and degreased with tirchloroethylene. Specimens were dried and stored in vacuum desiccator containing silica gel. These specimens were initially weighed in an electronic balance. After that the specimens were suspended in the test solutions (with and without inhibitor). The specimens were removed after a definite exposure period, washed with distilled water to remove any corrosion products and finally washed with acetone. After that they were dried in an oven and re-weighed. These experiments were carried out at room temperature (302K).

Electrochemical Measurements

For potentiostatic measurements, mild steel electrode of 1 cm x 1cm dimensions with stem was cut. The stem and the face of the electrode were masked with araldite, so as to expose an area of 1 cm^2. The electrodes are polished using 1/0, 2/0, and 3/0 and 4/0 emery papers and degreased with trichloroethylene. Potentiostatic polarization measurements were carried out in three-electrode cell using BAS-100A model instrument. The potential of the test electrode was measured with respect to SCE and platinum was used as auxillary electrode and the experiments were carried out at 302K. In the Impedance measurements, a well polished mild steel electrode was introduced into test solution and allowed to attain a steady potential value A.C. signal of amplitude 10mV was impressed to the system with frequency ranging from 10 MHz to 10 KHz using Solartron Electrochemical measurement unit (1280B).

Results and Discussion

Mass Loss Measurements

Table 1 shows the values of the corrosion rate obtained, the inhibition efficiency (IE%) obtained and the surface coverage (θ) at different concentrations of the inhibitor (IPA, Chloride, Sulphate, IPA + Chloride and IPA +

Sulphate) in 1N and 5N phosphoric acid for an immersion period of 5 hours. From the mass loss values, the inhibition efficiency (IE%) and surface coverage (θ) were calculated using the following equation [14-15].

$$IE\% = \frac{Wu - Wi}{Wu} \times 100 \qquad ...(1)$$

$$\theta = \frac{Wu - Wi}{Wu} \qquad ...(2)$$

Where

Wu is the corrosion rate of uninhibited system.

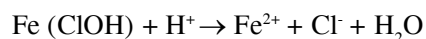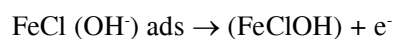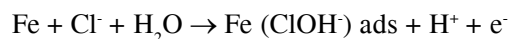Wi is the corrosion rate of inhibited system.

From the Table 1, it clearly indicates that the addition of inhibitor (IPA) to the acid has reduced the corrosion rate. The inhibition efficiency increased with increase in concentration of inhibitor (IPA) and decreased with increase in acid concentration from 1N to 5N. The values of corrosion rate and inhibition efficiencies of the inhibitor (IPA) were found to depend on the molecular structure of inhibitor (IPA). It is also observed that the addition of chloride and sulphate to the acid has reduced the corrosion rate [16-17]. The inhibition efficiency for chloride and sulphate increased with the increase in concentration of chloride and sulphate and decreased with increase in acid concentration from 1N to 5N. From the inhibition efficiency values chloride ions has found to be more efficient than sulphate ions [18].

Stabilization of adsorbed pollutant ions (chloride and sulfate) on the metal surface gives the inhibition efficiency. Pollutants are good legends (chloride and sulphate) because they exhibit low electronegativity (less than 3.5) [19-20]. The inhibiting effect of pollutants (chloride and sulfate) can be explained as due to adsorption of pollutants according to the mechanism given below.

The corrosion of steel in acidic solution is the sum of the following reactions.

Anodic: $Fe \rightarrow Fe^{2+} + 2e^-$

Cathodic: $H^+ + e^- \rightarrow \frac{1}{2} H_2$
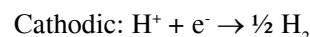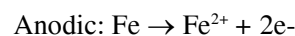
However, each of the reactions proceeds with many consecutive steps depending on the pH and the type of anion present in the solution. According to Bockris [21], theory indicates the participation of (OH^-) ions directly. Anodic dissolution of iron in acidic solution could be written as

Fe + Cl$^-$ + H$_2$O → Fe (ClOH$^-$) ads + H$^+$ + e$^-$

FeCl (OH$^-$) ads → (FeClOH) + e$^-$

Fe (ClOH) + H$^+$ → Fe^{2+} + Cl$^-$ + H$_2$O

Adsorption of pollutant ions (chloride and sulphate) on the electrode surface affects the kinetic dissolution of mild steel [22-24]. It [25] suggested that the pollutant ions (chloride and sulfate) interaction with the metal surface possibly through chemisorption's. Anion adsorption is found to be chloride and sulfate. Moreover the lower corrosion rate for mild steel in phosphoric acid containing pollutants (chloride and sulfate) might be due to the formation of Fe(OH$^-$)ads species where as in phosphoric acid free from pollutants, only hydroxide ions are involved and so the formation of [Fe(OH)]$_{ads}$ [25].

The maximum inhibition efficiency of IPA was 96.92% in 1N phosphoric acid and 90.39% in 5N phosphoric acid at 2.5%. The inhibition efficiency of chloride (500 ppm) and sulphate (500 ppm) were 49.89% and 42.76% in 1N and 43.11% and 40.97% in 5N phosphoric acid, respectively.

But in the presence of 500 ppm of chloride with IPA (2.5%) inhibition efficiency was 98.24% in 1N and 92.03% in 5N and in the presence of 500ppm of sulphate with IPA (2.5%) inhibition efficiency was 97.50% in 1N and 91.42% in 5N.

Synergism Considerations

The synergism parameter S was calculated using the relationship given by the following equation [26]

$$S = \frac{R_1 + R_2}{R\exp} \qquad ...(3)$$

Where R_1, R_2 are the calculated rate of inhibition of surfactant 1 and 2 respectively, Rexp is the experimental rate of inhibition of their mixture.

The calculated 'S' values are given in Table 2. It can be seen that the values of S are greater than unity, which clearly shows that the corrosion inhibition brought about by IPA and combination of Cl$^-$ and SO$_4^{2-}$ is synergistic in nature. The increase in inhibition efficiency (and surface coverage values) found to be in the order Cl$^-$ >SO$_4^{2-}$ is also displayed in the synergistic considerations, which clearly indicates that the radii and the electronegativity of Cl$^-$ and SO$_4^{2-}$ play a significant role in the adsorption process. It can also be concluded that the Cl$^-$ and SO$_4^{2-}$ is adsorbed and facilitates the adsorption of organic cations thus producing an inhibition synergism [26] and Values of the parameter which are more than unity indicate the fact that the enhanced inhibition efficiency in the presence of Cl$^-$ and SO$_4^{2-}$ ions are only due to synergism and there is a definite contribution from the inhibitor molecules, which are adsorbed by coulombic interaction on the metal surface, where Cl$^-$ and SO$_4^{2-}$ are already adsorbed and thus reduces the corrosion rate [27].

Adsorption Isotherm

The electrochemical process on the metal surface is likely to be closely related to the adsorption of the inhibitor [28] and the adsorption is known to depend on the chemical structure of the inhibitor [8, 29-30]. The adsorption of the inhibitor molecules from aqueous solution can be regarded as quasisubstitution process [8] between the organic compound in the aqueous phase, org$_{(aq)}$ and water molecules at the electrode surface, H$_2$O$_{(s)}$.

$$Org_{(aq)} + x\ H2O_{(s)} = Org_{(s)} + x\ H_2O_{(aq)} \qquad ...(4)$$
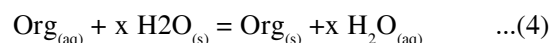
Where x the size ratio, is the number of water molecules displaced by one molecule of organic inhibitor.

Adsorption isotherms are very important in determining the mechanism of organo-electrochemical reactions. The most frequently used isotherms are those of Langmuir, Frumkin, Parsons, Temkin, Flory-huggins and Bockris-Sinkles. All these isotherms are of the general form:

$$f(\theta, x)\exp(-2a\ \theta) = KC \qquad ...(5)$$

Where f (θ, x) is the configurationally factor that depends essentially on the physical model and assumptions underlying the derivation of the isotherm [8].

The mechanism of inhibition of corrosion is generally believed to be due to the formation and maintenance of a protective film on the metal surface. The plot of surface coverage (θ) obtained by mass loss method versus log concentration for different concentrations of the compound show a straight line indicating that the adsorption of the compounds from acids on mild steel surface follows Temkin's adsorption isotherm. This also pointed to corrosion inhibition by these compounds being a result of their adsorption on the metal surface. Figures

Table 1
**Calculated Values of Corrosion Rate, Inhibition Efficiency (IE%) and Surface Coverage (?) for IPA, Cl- ,
SO$_4$$^{2-}$ and IPA Containing Cl- and SO$_4$$^{2-}$ in 1N and 5N H3PO4.**

Conc. of (IPA) with Cl- and SO$_4$$^{2-}$	1N			5N		
	Corrosion rate (mmpy)	Surface coverage (θ)	Inhibition efficiency (IE%)	Corrosion rate (mmpy)	Surface coverage (θ)	Inhibition efficiency (IE%)
Blank	6.80	-	-	26.22	-	-
(%) 0.5 IPA	2.39	0.6490	64.90	11.75	0.5520	55.20
(%) 1.0 IPA	1.72	0.7480	74.80	10.11	0.6143	61.43
(%) 1.5 IPA	1.10	0.8388	83.88	6.58	0.7490	74.90
(%) 2.0 IPA	0.92	0.8648	86.48	3.62	0.8620	86.20
(%) 2.5 IPA	0.21	0.9692	96.92	2.52	0.9039	90.39
Blank	6.80	-	-	26.22	-	-
100 ppm Cl-	5.13	0.2444	24.44	20.19	0.2297	22.97
200 ppm Cl-	4.66	0.3140	31.40	18.59	0.2911	29.11
300 ppm Cl-	4.45	0.3450	34.50	17.83	0.3198	31.98
400 ppm Cl-	4.09	0.3989	39.89	16.34	0.3767	37.67
500 ppm Cl-	3.41	0.4989	49.89	14.92	0.4311	43.11
Blank	6.80	-	-	26.22	-	-
100 ppm SO$_4$$^{2-}$	5.23	0.2310	23.10	20.72	0.2097	20.97
200 ppm SO$_4$$^{2-}$	4.76	0.3000	30.00	19.14	0.2699	26.99
300 ppm SO$_4$$^{2-}$	4.59	0.3248	32.48	18.35	0.3001	30.01
400 ppm SO$_4$$^{2-}$	4.28	0.3699	36.99	16.75	0.3610	36.10
500 ppm SO$_4$$^{2-}$	3.90	0.4276	42.76	15.47	0.4097	40.97
Blank	6.80	-	-	26.22	-	-
500 ppm Cl-	3.41	0.4989	49.89	14.92	0.4311	43.11
0.5 IPA+500 ppm Cl-	2.28	0.6647	66.47	10.88	0.5850	58.50
1.0 IPA+500 ppm Cl-	1.46	0.7853	78.53	9.03	0.6556	65.56
1.5 IPA+500 ppm Cl-	0.71	0.8956	89.56	5.83	0.7777	77.77
2.0 IPA+500 ppm Cl-	0.37	0.9456	94.56	3.21	0.8778	87.78
2.5 IPA+500 ppm Cl-	0.12	0.9824	98.24	2.09	0.9203	92.03
Blank	6.80	-	-	26.22	-	-
500 ppm SO$_4$$^{2-}$	3.90	0.4276	42.76	15.47	0.4097	40.97
0.5 IPA+500 ppm SO$_4$$^{2-}$	2.35	0.6544	65.44	11.36	0.5667	56.67
1.0 IPA+500 ppm SO$_4$$^{2-}$	1.59	0.7662	76.62	9.64	0.6323	63.23
1.5 IPA+500 ppm SO$_4$$^{2-}$	0.87	0.8721	87.21	6.24	0.7551	75.51
2.0 IPA+500 ppm SO$_4$$^{2-}$	0.51	0.9250	92.50	3.35	0.8722	87.22
2.5 IPA+500 ppm SO$_4$$^{2-}$	0.17	0.9750	97.50	2.25	0.9142	91.42

1, 2, 3 and 4 show the Temkin's adsorption isotherm for IPA, Cl- & SO$_4$$^{2-}$, IPA + chloride and IPA + sulphate in 1N H$_3$PO$_4$.

Electrochemical Studies

The corrosion of mild steel in 1N and 5N phosphoric acid and its inhibition by the addition of inhibitor was studied by potentiostatic polarization measurements.

Potentiostatic Polarization Studies

Table 2
Calculated Values of Synergism Parameter 'S'

Inhibitor	S	
	$1N\ H_3PO_4$	$5N\ H_3PO_4$
(%) 0.5 IPA+500 ppm Cl⁻	1.7269	1.6805
(%) 1.0 IPA+500 ppm Cl⁻	1.5878	1.5946
(%) 1.5 IPA+500 ppm Cl⁻	1.4936	1.5174
(%) 2.0 IPA+500 ppm Cl⁻	1.4421	1.4731
(%) 2.5 IPA+500 ppm Cl⁻	1.4944	1.4506
0.5% IPA+500 ppm SO₄²⁻	1.6452	1.6970
1.0% IPA+500 ppm SO₄²⁻	1.5343	1.6195
1.5% IPA+500 ppm SO₄²⁻	1.4521	1.5345
2.0% IPA+500 ppm SO₄²⁻	1.3972	1.4580
2.5 % IPA+500 ppm SO₄²⁻	1.4326	1.4369

The various corrosion kinetic parameters such as corrosion current density (I_{corr}), corrosion potential (E_{corr}), anodic and cathodic Tafel slopes (ba and bc) were derived from potentiostatic polarization studies on mild steel in 1N and 5N phosphoric acid in the presence and absence of different concentration of inhibitor and the polarization curves are depicted in Figures-5-9.

E_{corr} values are shifted slightly in presence of inhibitor suggesting that the inhibitor inhibit the corrosion of mild steel in 1N and 5N phosphoric acid solution by controlling both anodic and cathodic reactions by blocking the active sites of the mild steel surface. The polarization behaviour of mild steel functioning as cathode as well as anode in the test solutions is shown in Figures 5-9 for 1N H_3PO_4 at 302K for IPA. Similar curves were also obtained for 5N phosphoric acid and the electrochemical data obtained from the studies are shown in Table 3 and 4. It is evident that IPA brings about considerable polarization of the cathode as well as anode. It was, therefore, inferred that the inhibitive action is of mixed type. The cathodic and anodic Tafel slopes increased with increasing inhibitor concentrations and the increase was predominant in the case of the former indicating that the cathodic inhibition was dominating through the inhibitive active is of mixed nature. The non-constancy of Tafel slopes for different inhibitor concentration reveals that the inhibitor act through their interference in the mechanism of the corrosion processes at the cathode as well as the anode.

The corrosion parameters deduced from Tafel polarization such as corrosion current density i_{corr}, corrosion potential E_{corr}, Tafel constant ba and -bc and inhibition efficiency are given in Tables 3 and 4. The i_{corr} values were decreased with the increasing concentration of inhibitor. The inhibition efficiencies were determined from the values of corrosion current density and the inhibition efficiency values were found to show good agreement, with those obtained from mass loss measurements.

Linear Polarization Method

The polarization resistance values (Rp) calculated as the slope of the current curve near the corrosion potential by the linear polarization method are tabulated in the Tables 3 and 4. The results show that the addition of inhibitor (IPA) increases the Rp value than blank.

A.C.-Impedance Measurements

A.C. impedance measurements were carried out at room temperature for corrosion of mild steel in 1N and 5N H_3PO_4 after immersion for about 10 minutes. The Nyquist plots for mild steel in uninhibited acid and for the various concentrations inhibitor are shown in Figures 10 - 12 for 1N H3PO4 for IPA, Cl- and SO₄²⁻ (Similar plots were obtained for 5N H_3PO_4 and IPA-Cl- & IPA-SO₄²⁻). The impedance parameters and the IE% are given in the Table 5.

The charge transfer resistance (R_{ct}) value for mild steel in uninhibited H_3PO_4 significantly changes after the addition of inhibitor. The Rct values increased with increase in inhibitor concentrations. The fact is advocated by the increase in inhibitor efficiency. The semicircular nature of Nyquist plots obtained for all experiments indicates that the corrosion of mild steel is controlled by charge transfer process [31]. The double layer capacitance (C_{dl}) decreased with increasing inhibitors concentration. The decrease in Cdl values in presence of inhibitors indicates the fact that these additives inhibit corrosion by adsorption on the metal surface [31].

The inhibition efficiencies obtained from A.C. impedance measurements are not in very good agreement with these obtained from mass loss studies. Some differences are always noticed when corrosion rates and inhibition efficiencies determined by conventional mass loss method are compared with those obtained from electrochemical techniques.
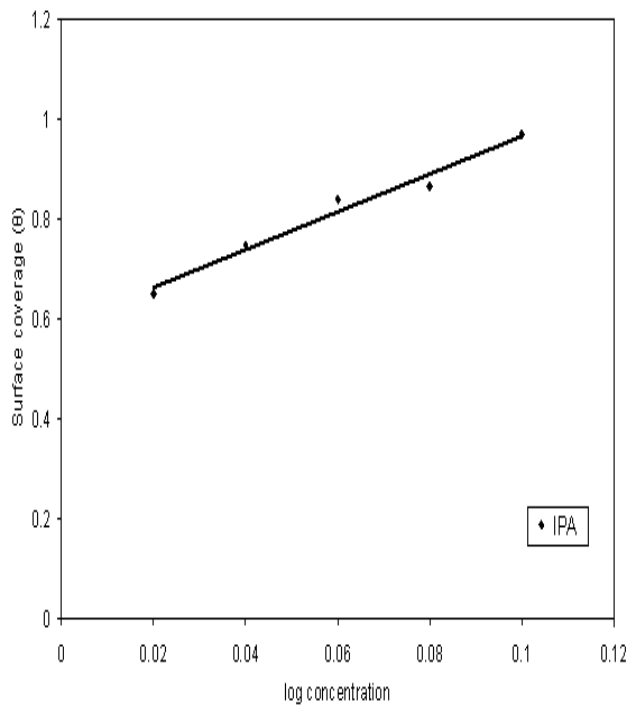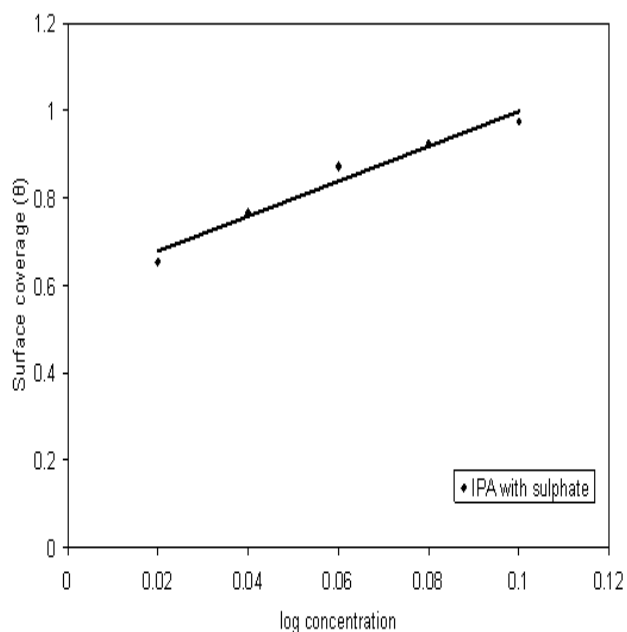
Figure 1: Temkin's adsorption isotherm plot for corrosion in
1 N H_3PO_4 with IPA
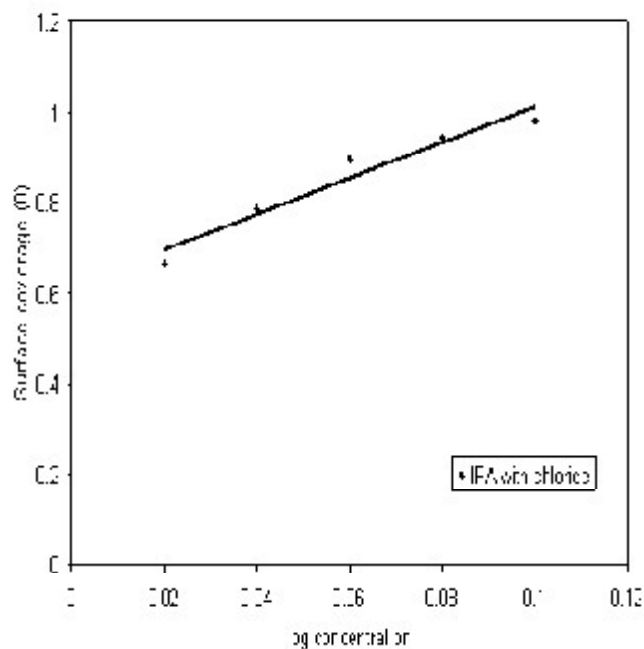
Figure 3: Temkin's adsorption isotherm plot for corrosion in
1 N H_3PO_4 with IPA + chloride.
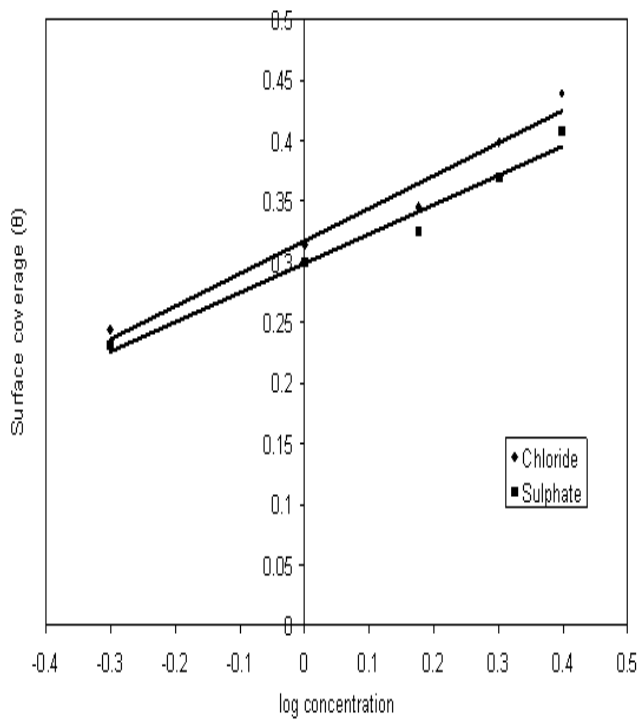
Figure 2: Temkin's adsorption isotherm plot for corrosion in
1 N H_3PO_4 with Cl^- and SO_4^{-2}

Figure 4: Temkin's adsorption isotherm plot for corrosion in
1 N H_3PO_4 with IPA + sulphate

Table 3
Electrochemical Polarization Parameters for Corrosion of Mild Steel in 1N Phosphoric acid with IPA, Cl- , SO42- and IPA containing Cl- and SO42

Conc. of inhibitor	E_{corr} Vs SCE (mV)	I_{corr} µA/cm²	Tafel constants (mV / decade)		IE%	LPR Rp (ohm cm²)
			ba	- bc		
Blank	-543	210	50	130	-	74.67
(%) 0.5 IPA	-588	73	45	126	65.24	197.23
(%) 1.0 IPA	-577	53	44	121	74.76	264.35
(%) 1.5 IPA	-573	33	46	117	84.29	434.46
(%) 2.0 IPA	-570	25	45	114	88.10	560.39
(%) 2.5 IPA	-567	9	42	105	95.71	1444.39
Blank	-543	210	50	130	-	74.67
100 ppm Cl⁻	-540	180	50	125	14.29	83.20
200 ppm Cl⁻	-537	150	40	110	28.57	84.15
300 ppm Cl⁻	-533	137	35	105	34.76	86.15
400 ppm Cl⁻	-542	130	45	95	38.09	91.18
500 ppm Cl⁻	-538	120	35	90	42.86	101.99
Blank	-543	210	50	130	-	74.67
100 ppm SO₄²⁻	-562	185	50	127	11.90	80.66
200 ppm SO₄²⁻	-555	154	45	117	26.66	83.45
300 ppm SO₄²⁻	-550	144	40	110	31.43	85.66
400 ppm SO₄²⁻	-548	136	40	100	35.23	90.55
500 ppm SO₄²⁻	-545	127	37	95	39.52	97.22
Blank	-543	210	50	130	-	74.67
500 ppm Cl	-538	120	35	90	42.86	101.99
0.5 IPA+500 ppm Cl⁻	-585	66	45	124	68.71	217.22
1.0 IPA+500 ppm Cl⁻	-574	47	45	123	77.60	304.38
1.5 IPA+500 ppm Cl⁻	-572	29	43	120	86.19	473.99
2.0 IPA+500 ppm Cl⁻	-568	19	42	118	90.95	707.89
2.5 IPA+500 ppm Cl⁻	-565	6	40	117	97.14	2157.25
Blank	-543	210	50	130	-	74.67
500 ppm SO₄²⁻	-545	127	37	95	29.52	97.67
0.5 IPA+500 ppm SO₄²⁻	-586	69	48	126	67.14	218.74
1.0 IPA+500 ppm SO₄²⁻	-577	52	46	124	75.24	316.72
1.5 IPA+500 ppm SO₄²⁻	-570	31	45	127	85.24	465.41
2.0 IPA+500 ppm SO₄²⁻	-568	23	45	122	89.05	620.63
2.5 IPA+500 ppm SO₄²⁻	-567	8	43	120	96.19	1718.22

Table 4
Electrochemical polarization parameters for corrosion of mild steel in 5N Phosphoric acid with
IPA, Cl- , SO42- and IPA containing Cl- and SO42

Conc. of inhibitor	E_{corr} Vs SCE (mV)	I_{corr} $\mu A/cm^2$	Tafel constants (mV / decade)		IE%	LPR Rp (ohm cm²)
			ba	- bc		
Blank	-510	700	50	150	-	23.26
(%) 0.5 IPA	-580	301	50	145	57.00	53.63
(%) 1.0 IPA	-570	276	48	140	60.57	56.24
(%) 1.5 IPA	-567	177	44	138	74.71	81.85
(%) 2.0 IPA	-560	90	43	135	87.14	157.34
(%) 2.5 IPA	-555	63	40	133	91.00	211.95
Blank	-510	700	50	150	-	23.26
100 ppm Cl⁻	-505	625	50	145	10.71	23.84
200 ppm Cl⁻	-505	570	35	150	18.57	24.95
300 ppm Cl⁻	-498	510	35	140	25.71	25.83
400 ppm Cl⁻	-497	480	30	130	31.43	26.38
500 ppm Cl⁻	-503	450	35	125	35.71	27.55
Blank	-510	700	50	150	-	23.26
100 ppm SO_4^{2-}	-556	627	55	147	10.42	23.45
200 ppm SO_4^{2-}	-551	586	39	142	16.28	24.52
300 ppm SO_4^{2-}	-547	544	37	140	22.28	25.54
400 ppm SO_4^{2-}	-544	496	35	135	29.14	25.99
500 ppm SO_4^{2-}	-541	475	36	132	32.14	26.69
Blank	-510	700	50	150	-	23.26
500 ppm Cl⁻	-503	450	35	125	35.71	54.54
0.5 IPA+500 ppm Cl⁻	-581	278	47	147	60.29	55.63
1.0 IPA+500 ppm Cl⁻	-572	268	46	142	61.71	56.29
1.5 IPA+500 ppm Cl⁻	-570	161	44	141	77.00	90.44
2.0 IPA+500 ppm Cl⁻	-568	76	43	140	89.14	187.95
2.5 IPA+500 ppm Cl⁻	-550	48	41	138	93.14	285.94
Blank	-510	700	50	150	-	23.26
500 ppm SO_4^{2-}	-541	475	36	132	32.14	33.63
0.5 IPA+500 ppm SO_4^{2-}	-582	268	48	147	59.14	54.93
1.0 IPA+500 ppm SO_4^{2-}	-574	275	47	144	60.71	55.95
1.5 IPA+500 ppm SO_4^{2-}	-571	172	45	142	75.43	86.27
2.0 IPA+500 ppm SO_4^{2-}	-568	81	45	141	88.43	182.87
2.5 IPA+500 ppm SO_4^{2-}	-554	55	42	140	92.14	255.06

The difference observed can be attributed due to the fact mass loss methods give average corrosion rates where as electrochemical methods give instantaneous corrosion rates [32], mass loss measurements are experiments of long duration which helps in the formulation of inherent and continuous film on the metal surface. This leads to the complete shielding of the metal surface from the corrosive experiments. But electrochemical studies are experiments of short duration and the time will not be enough for the formation of the thick continuous film. This leads to slight difference in the inhibition efficiency [33].
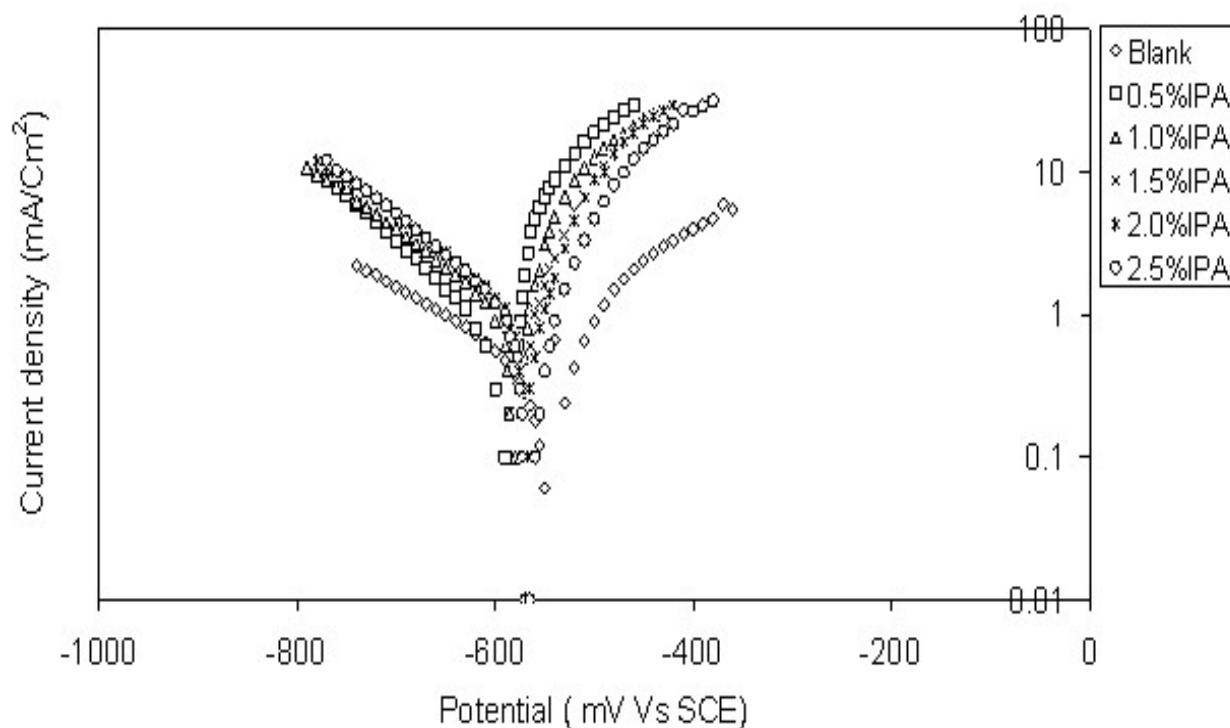
Figure 5: Typical potentiodynamic curves for mild steel in 1 N H$_3$PO$_4$ with IPA
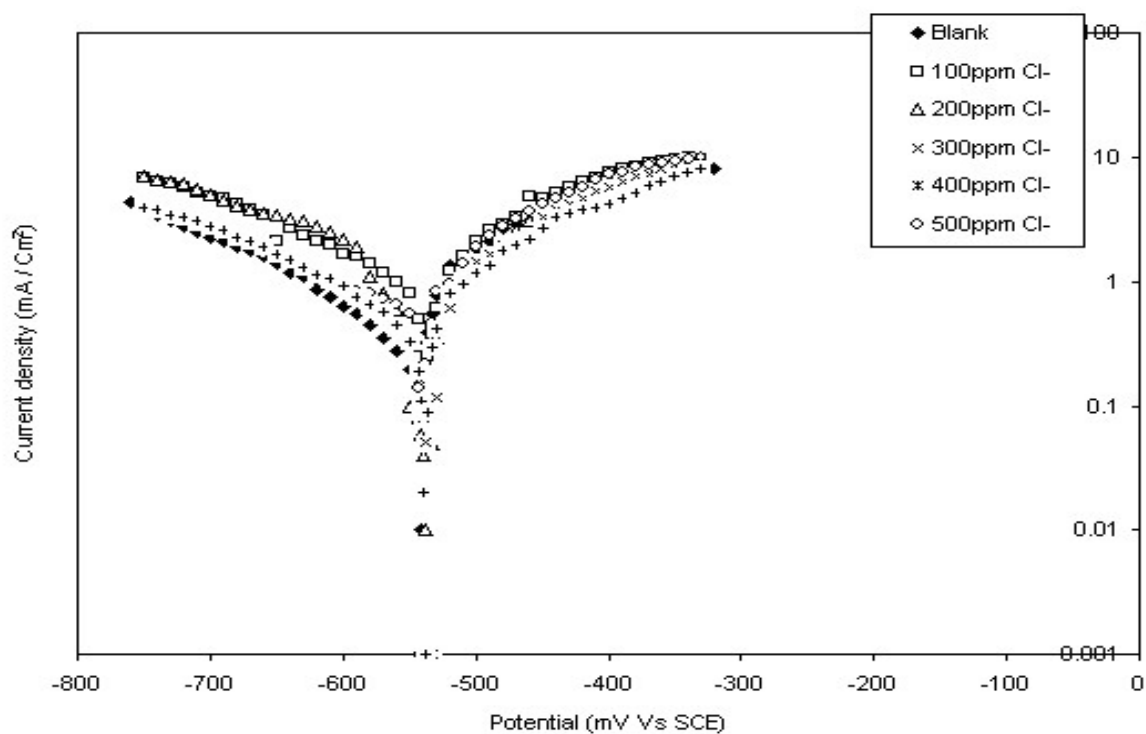

Figure 6: Typical potentiostatic curves for mild steel in 1 N H$_3$PO$_4$ with chloride
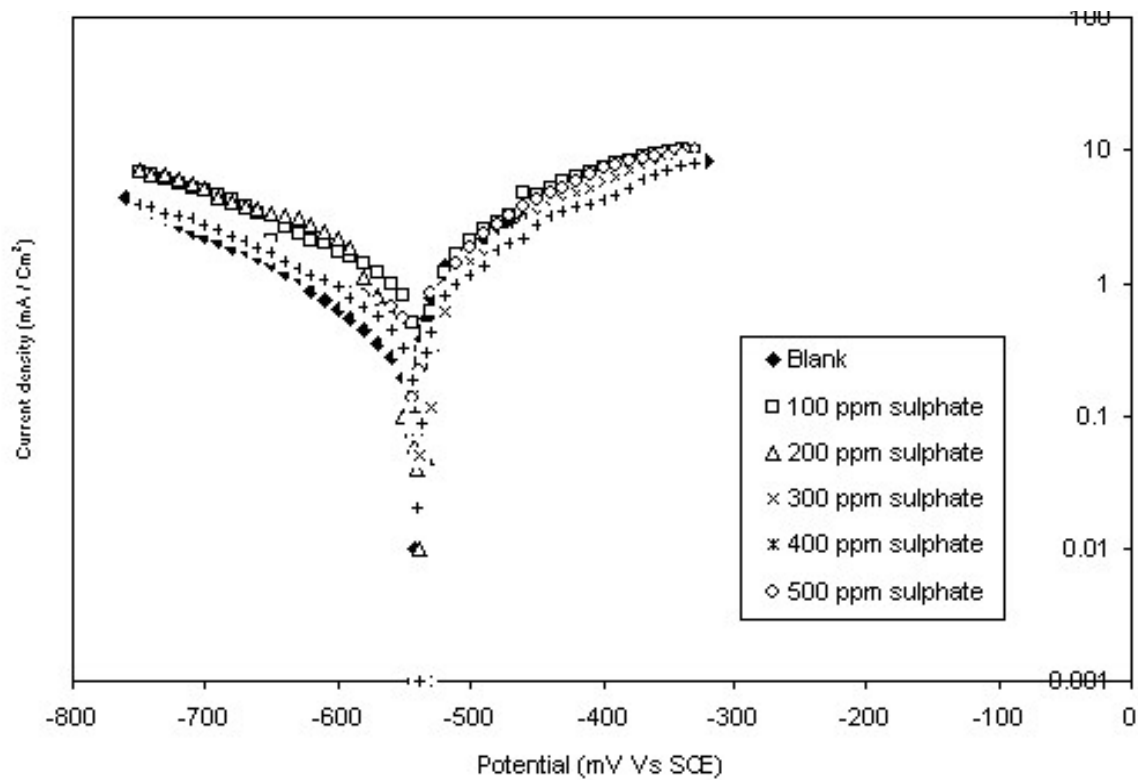
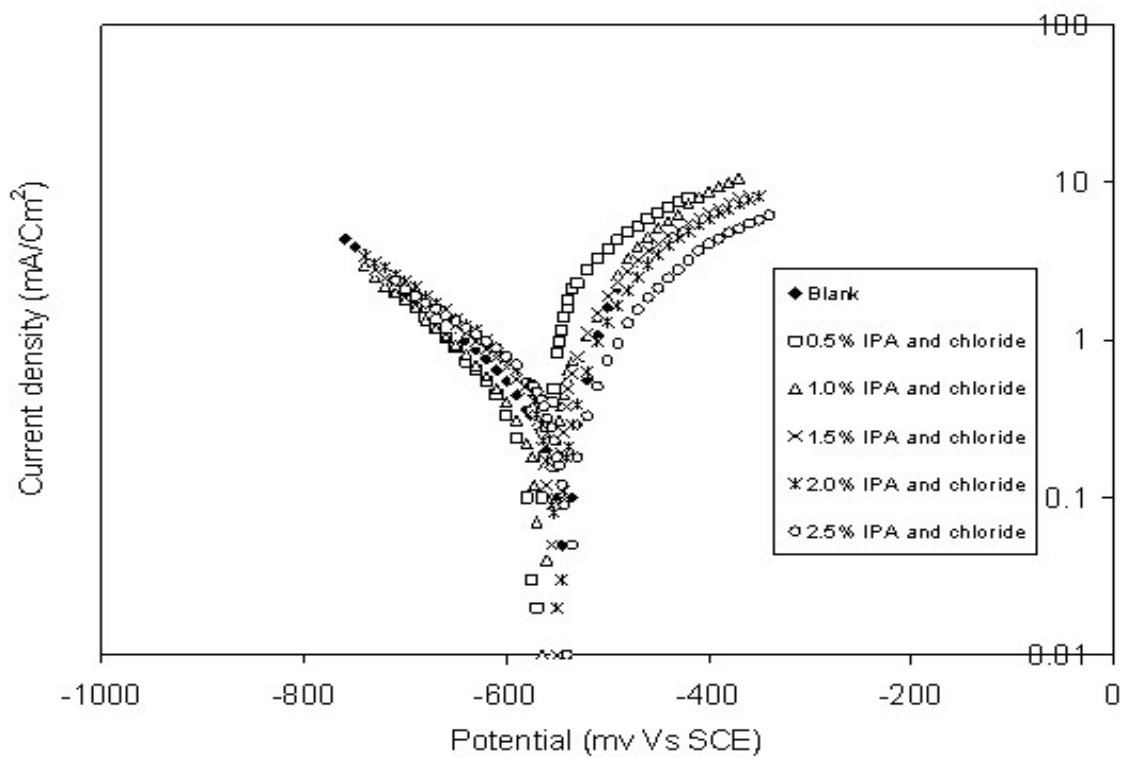**Figure 7:** Typical potentiostatic curves for mild steel in 1 N H_3PO_4 with sulphate

Figure 8: Typical potentiodynamic curves for mild steel in 1 N H_3PO_4 with IPA and chloride
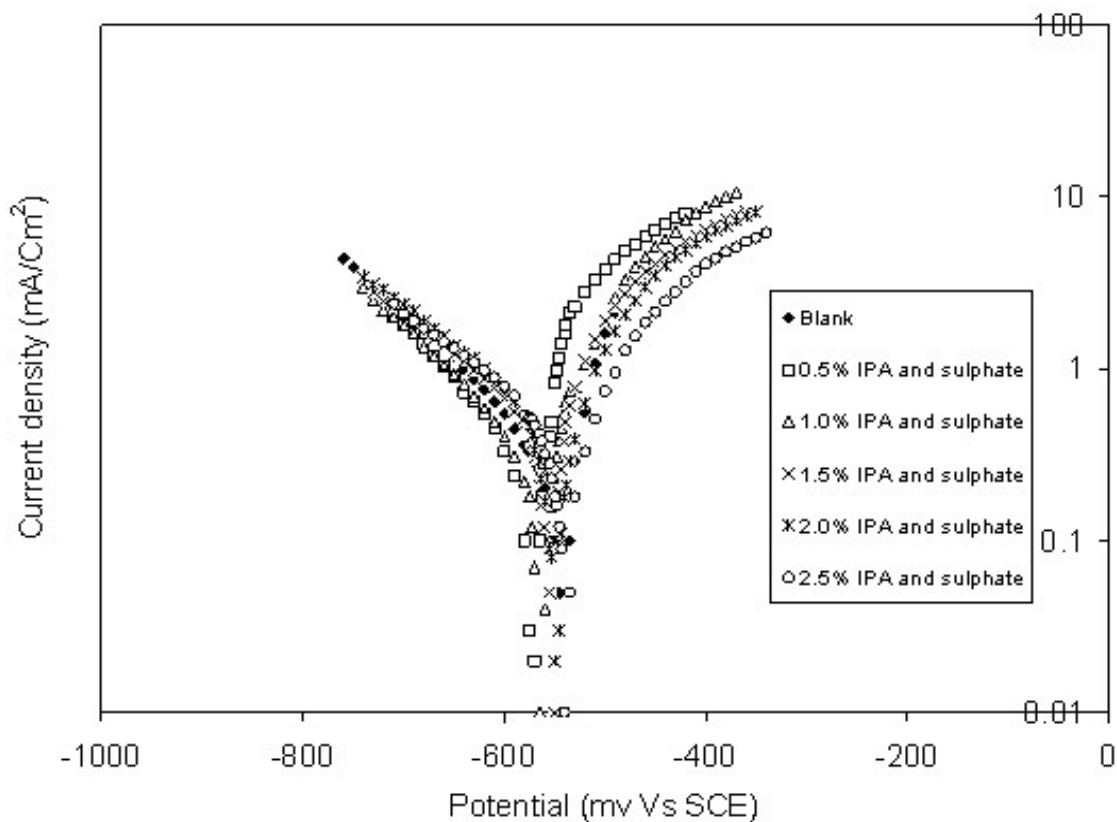
Figure 9: Typical potentiodynamic curves for mild steel in 1 N H_3PO_4 with IPA and sulphate
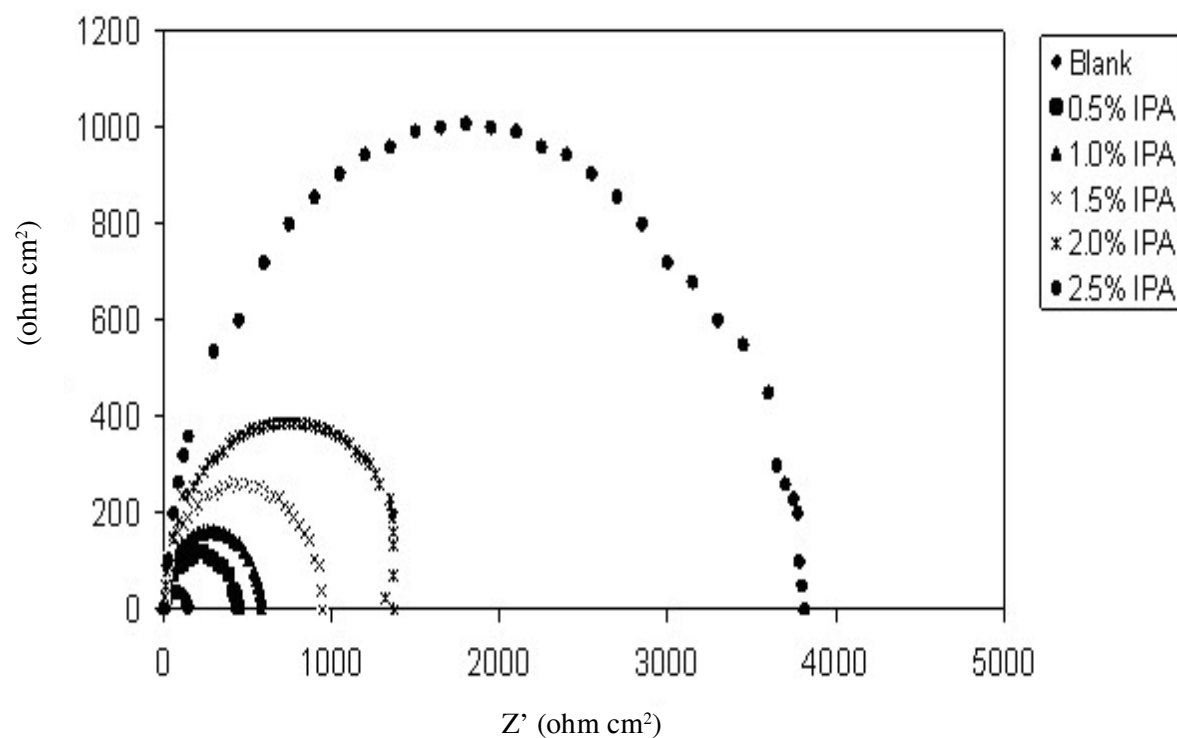

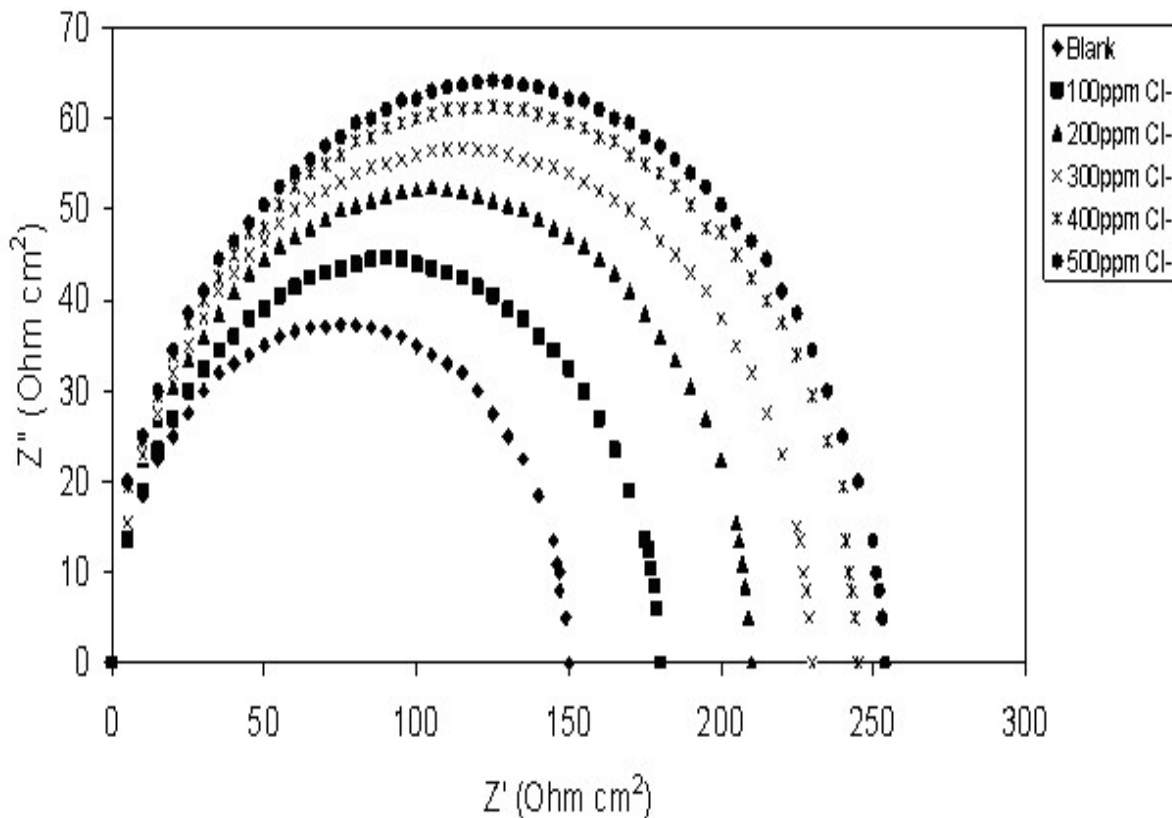**Figure 10:** Nyquist plot of mild steel in 1N H_3PO_4 with IPA

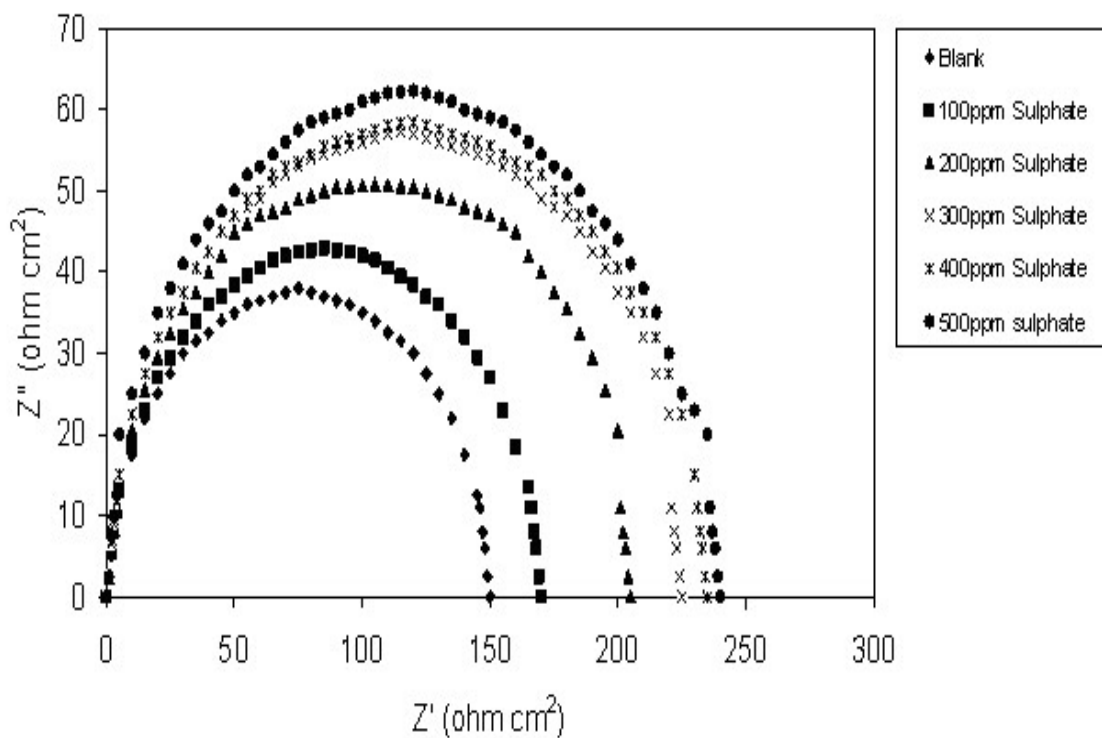**Figure 11:** Nyquist plot of mild steel in 1N H$_3$PO$_4$ with chloride

Figure 12: Nyquist plot of mild steel in 1N H$_3$PO$_4$ with sulphate

Table 5
A.C. Impedance Parameters for Corrosion of Mild Steel in 1N and 5N Phosphoric acid with
IPA, Cl-, SO_4^{2-} and IPA Containing Cl- and SO_4^{2-}

Conc. of pollutants	1N			5N		
	Rct (ohm cm²)	C_{dl} (μF/cm²)	Inhibition efficiency (IE%)	Rct (ohm cm²)	C_{dl} (μF/cm²)	Inhibition efficiency (IE%)
Blank	150.60	5.74	-	100.12	13.20	-
0.5 IPA	445.12	2.53	66.16	238.12	8.67	57.95
1.0 IPA	614.20	1.98	75.48	264.20	8.37	62.10
1.5 IPA	1112.66	1.24	86.46	404.67	5.71	75.26
2.0 IPA	1410.20	1.02	89.32	860.71	2.82	88.37
2.5 IPA	3820.67	0.40	96.05	146.20	1.73	93.14
Blank	150.60	5.74	-	100.12	13.20	-
100 ppm Cl⁻	180.00	5.07	16.30	112.20	12.33	10.77
200 ppm Cl⁻	210.85	4.54	28.57	123.53	11.99	18.95
300 ppm Cl⁻	230.68	4.24	34.71	136.87	11.49	26.85
400 ppm Cl⁻	245.74	4.08	38.72	149.32	11.15	32.95
500 ppm Cl⁻	255.43	3.97	41.04	158.64	10.49	36.89
Blank	150.60	5.74	-	100.12	13.20	-
100 ppm SO_4^{2-}	172.41	5.18	12.65	111.02	12.32	9.81
200 ppm SO_4^{2-}	205.52	4.55	26.72	120.49	11.92	16.91
300 ppm SO_4^{2-}	223.89	4.31	32.27	131.60	11.27	23.92
400 ppm SO_4^{2-}	234.55	4.19	35.79	142.96	11.20	29.97
500 ppm SO_4^{2-}	245.95	4.06	38.77	149.15	11.15	32.87
Blank	150.60	5.74	-	100.12	13.20	-
500 ppm Cl⁻	255.43	3.97	41.04	158.64	10.97	36.89
0.5 IPA+500 ppm Cl⁻	490.12	2.35	69.27	258.10	8.26	61.21
1.0 IPA+500 ppm Cl⁻	686.17	1.79	78.05	265.12	8.38	62.22
1.5 IPA+500 ppm Cl⁻	1311.20	1.08	88.51	460.98	5.22	78.28
2.0 IPA+500 ppm Cl⁻	1909.28	0.76	92.11	1120.87	2.18	91.11
2.5 IPA+500 ppm Cl⁻	7390.10	0.21	97.96	1674.22	1.56	94.02
Blank	150.60	5.74	-	100.12	13.20	-
500 ppm SO_4^{2-}	245.95	4.06	38.77	149.15	11.15	32.87
0.5 IPA+500 ppm SO_4^{2-}	475.12	2.42	68.30	252.11	8.37	60.29
1.0 IPA+500 ppm SO_4^{2-}	655.76	1.85	77.03	257.28	8.34	61.09
1.5 IPA+500 ppm SO_4^{2-}	1080.77	1.29	86.07	420.27	5.48	76.18
2.0 IPA+500 ppm SO_4^{2-}	1520.27	0.95	90.09	921.22	2.64	89.13
2.5 IPA+500 ppm SO_4^{2-}	5130.20	0.30	97.06	1432.10	1.77	93.01

Conclusion

1. Isopropylamine (IPA) acted as efficient corrosion inhibitor in 1N and 5N phosphoric acid.

2. The maximum inhibition efficiency of Isopropylamine was found to be 96.92% in 1N phosphoric acid and 90.39% in 5N phosphoric acid at 2.5%.

3. The corrosion rate of mild steel in phosphoric acid was high in the absence of pollutants (chloride and sulphate). The pollutants chloride and sulphate ions

reduced corrosion rate of mild steel in phosphoric acid

4. Under the synergistic effect in the presence of 500 ppm of chloride with IPA inhibition efficiencies were found to be 98.24% in 1N and 92.03% in 5N, and in the presence of 500 ppm of sulphate with IPA, the inhibition efficiencies were found to be 97.50% in 1N and 91.42% in 5N

5. The inhibition efficiency decreased with increasing concentration of phosphoric acid.

6. The inhibition efficiency value obtained from mass loss studies and polarization measurements showed fairly good agreement.

7. Isopropylamine inhibits corrosion by an adsorption mechanism and the adsorption of these compounds from acid solution follows Temkin's adsorption isotherms at all concentrations.

8. The corrosion inhibition appears to be of mixed type.

Acknowledgement

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