MINAR International Journal of Applied Sciences and Technology

Article type : Research Article

Date Received : 02/04/2021
Date Accepted : 25/04/2021
Date published : 01/06/2021
: www.minarjournal.com

http://dx.doi.org/10.47832/2717-8234.2-3.1

PREDICTING THE ROLE OF LOW AND HIGH SALT CONCENTRATION ON CORROSION OF CARBON STEEL C45

Asmaa Y. AL-BAITAI[1] & Madeeha H.MAHMOOD[2]

Abstract

The corrosion behavior of carbon steel C45 has been investigated in the absence and presence of different content of NaCl at four different temperatures 293, 303, 313, and 323 K by using potentiodynamic polarization technique. The results shown that the corrosion of carbon steel in the absence of NaCl is lower than in the presence of NaCl, and increased the concentration of NaCl lead to increase the corrosion rate at all the experimental temperatures and the maximum corrosion rate was observed in 14% NaCl. The corrosion rate was decreased after reaching the maximum value and increase the solution concentration of NaCl at 20% and 26% at all the four temperatures and that could be attributed to the high resistance of the solution when the concentration be higher. All the thermodynamic functions and activation energy are calculated and the results of Gibbs Free energy and enthalpy shown that the corrosion of carbon steel C45 in the absence or presence of NaCl at each same temperature is nonspontaneous and endothermic. The obtained results were in a good agreement with previous work based on the using of the weight loss method by another research work).
Keywords: Corrosion, Carbon steel, NaCl, Corrosion Rate, Thermodynamic Functions.

[1] Al-Nahrain University, Iraq, ayi@sc.nahrainuniv.edu.iq, https://orcid.org/0000-0001-9140-5975
[2] Al-Nahrain University, Iraq

1. Introduction

Corrosion is defined as a process which involves a degradation of the metal or alloy due to the chemical reaction between these materials and the environment [1-3], and most common corrosion process take place in the water or aqueous system which will lead to form a thin film on the surface of the metal, but still the investigation of the corrosion for non-aqueous system is not known. However, the corrosion process usually occurs in different fields such as, in the oil, gas and chemical industries and due to the cost of corrosion effects on several domestic applications in public sectors, for instance, wasted of valuable resources as a result of the harmful of the surface such as the steel or the iron. In addition, the corrosion also effect the safety and health of the everyday life and environment, which is contributing to the failures of bridges, aircraft, automobiles, gas pipelines etc. In the develop countries the cost of the corrosion per year is about 3-4% GDP [4], while the cost of the corrosion annually for the gas, oil and in the chemical industries only about170 billion USD [5], all these reasons made the corrosion as one of the most challenging tasks for many scientific research, therefore, it was necessary to find some ways to protection from the effects of the corrosion which caused a harmful for the surface of the equipment, and there are different methods and/or techniques have been applied for the corrosion protection such as, using the cathodic protection [6], inhibitors [7-10] ,or using the principle of the coating method via using the nanoparticle or organic coating [11-13], and also have been employed the principle of the corrosion resistant for alloys.

One of the most common model which has been interested for many scientific research is investigate the corrosion behavior and the protection processes of the carbon steel [14-20]. The carbon steel is a type of material which used widely for different purpose such as, in the engineering applications used as a preferred construction materials and its considered the most economical option than any other alloys, which are known as corrosion resistance alloys [21]. Carbon steel is also used for other different applications such as, the industrial pipes, bridge construction, kitchen appliances, also in the petroleum industry field [14, 22-24], and the production of the steel around the Worldwide is approximate 85%. Per year. In General, the carbon steel alloys in compare with other alloys are considered the more susceptible to corrosion under the conditions that used in the industry fields, but one of the major problems related to its use is it low corrosion resistance in this environment.

The basic content of typical carbon steel is less than 1.5 carbon content also there is presence of Mn, Si, P and S. According to this variation of the percentage of carbon content lead to divide the carbon steels into three different forms, namely low carbon steels (<0.25% C), medium carbon steels (0.25–0.70% C), and high carbon steels (0.70–1.05% C). In fact, this variation is allowed to achieve different important mechanical properties as the hardness and softness, ductility and strength ,etc. and based on these properties there are additional divided according to the certain grades, for instance, grade 1008 (0.08 wt% C) this one has a good ductility and its use for forming while grade 1018 (0.18 wt% C) is can be used for general application and also useful for welding , but the grade which has the low hardenability is grade 1030 (0.30 wt% C) and the last one is grade 1045 (0.45wt% C) and this be can used in the application of power transmission [14]. Overall, the various application of carbon steel is always related to the environment, for instance water, oil or air, and these different environments will effect on the corrosion of the carbon steel in different ways which is depending on ion concentration , but the corrosion it can be affected by other factors such as the temperature, humidity and the resistance of the solution. There are several studies have been carried out to investigate and understand of the corrosion of carbon steel in NaCl solutions [25], in air atmosphere and in soil as well [26], and all the outcome results shows that the corrosion rate of carbon steel in different solutions of NaCl is significantly increased [27] and in a similar way that the corrosion rate of steel in the soil is shown to be effected by both the resistance and concentrations of available ions. Generally, there are several studies to investigate the corrosion behavior via determine the corrosion rate of carbon steel using variation concentrations of NaCl solution and only few outcome results shown how the corrosion rates affected by the concentrations of NaCl. Therefore, to understand the effect of using low and high NaCl concentration solution needs to be clearly confirmed, for reliability reasons, for construction materials and enrichment of the welding field reference. The objective of this work is investigate the effect of low and high salt concentration of NaCl on the corrosion rate of carbon steel C45 using the potentiodynamic polarization technique.

2. Experimental

2.1 Specimens Preparation

In this study the specimens or rods of carbon steel C45 were purchased from a store of metal samples located in Baghdad Iraq. However, the specimens of carbon steel C45 were prepared by cut into cylindrical samples within dimensions of (25 mm diameter and 3 mm height) and the chemical composition of carbon steel C45 is listed in Table 1.

Table -1: The chemical composition of Carbon steel C45.

Element	C	Si	Mn	S	P	Cu	Ni	Cr	Fe
%	0.42	0.30	1.40	0.05	0.05	0.50	0.20	0.20	96.88

However, before used the carbon steel specimen was need to polished it, and that by using several grades of emery papers (from 80 to 3000) grade, and to improve the surface of the specimen as mirror-like surface it was necessary to polish it again by using the micro cloth. After that, all the samples were cleaned, washed with distilled water and absolute ethanol, and to prevent them from oxidation have been stored in vacuum desiccators before plummeting to corrosion solution, then carbon steel specimen was covered with adhesive tape except for a known distance which is 1cm2.

2.2 Corrosive Environment

For the corrosive media, was used six different concentration of NaCl solutions (0%, 3%, 8%, 14%, 20%, and 26% NaCl), and all these concentrations were applied to investigate the effect of NaCl on the corrosion rate of Carbon steel C45 at four different temperatures (293, 303, 313, and 323 K) via employed the phenomena of potentiostatic polarization technique.

2.3 Polarization Measurements

For electrochemical measurements were carried out using a three-electrode setup by using the carbon steel specimen as a working electrode, while the saturated calomel electrode and platinum electrodes were used as reference and auxiliary electrodes, respectively. First, the open circuit potential was measured then the carbon steel model was polarized in the simulate NaCl solution. After that, Tafel plots were recorded for corrosion rate measurement by scanning the potentials ±200mv around the OCP with a rate of 2mv/sec. The same procedure repeated at four temperatures; 293, 303, 313, and 323 K and different concentrations.

3. Results and discussion

3.1 Electrochemical Measurements.

In this study, the potentiostatic anodic and cathodic polarization method (Tafel extrapolation technique) was used to study the corrosion behavior of carbon steel C45 in absence and presences of different concentrations of NaCl (0%, 3%, 8%, 14%, 20%, and 26% NaCl) with range of temperatures (293-323K). Fig. 1 (a-f) illustrates the polarization curves for the model under investigate in absence and presence of different concentrations of NaCl at different temperatures. However, from Tafel plots there are three different parameters are used to understanding the corrosion process of the system under investigation and these parameters are including the corrosion current density which is donated by (icorr), corrosion potential (Ecorr), and both the anodic and cathodic Tafel slopes which are donated by (βa) and (βc), respectively, have been recorded in Table 2, and the calculation of these parameters are used to determine the polarization resistance (Rp) as in the following equation[28]:-

$$R_p = \frac{\beta_a \beta_c}{2.303\,(i_{corr})(\beta_a+\beta_c)} \qquad (1)$$

It can be seen from Table 2, that the corrosion rate of C45 in the distilled water(blank solution) is lower than in the presence of NaCl, also its found that the increasing of the NaCl content (3%,8%,and 14%) leads to raise the values of corrosion current densities i_{corr} and corrosion rate CR for each solution at the same temperature and this was in good agreement with a previous work [29, 30], but at high salt concentration (20% and 26% NaCl) both the i_{corr} and CR are decreased, and the 26% NaCl has the least values of CR. Generally, the corrosion process is mainly depend on the concentration of the corroding media (NaCl solutions) and the amount of the oxygen dissolved in the media, but this reduction in the corrosion rate could be attributed to due to the high resistance of the solution at higher concentrations. However, The higher salt concentration mean the more film will build up by the corrosion products, which play as a physical barrier against the diffusion of the oxygen and adsorption to the metal surface all these lead to the decrease the value of corrosion rate also at higher salt concentration that mean the solubility of the electrolyte will be decrease and became more saturated than with the corrosion product will build up the film on some surface site and which will reduce the corrosion rate also the mobility of the ions at high concentration may be less, see Fig. 1e and 1f.

On the other hand, rising the reaction temperature lead to rise the icorr at constant solution concentration while the values of both βc and βa are changed with increasing the temperature from (293-323K) and this could be because the changing of the anodic and cathodic reaction. Also it was observed that the higher the temperature is to be the higher the corrosion rate and this could be attributed to reaction kinetics themselves and the higher diffusion rate of many corrosive agents and reaction products at increased temperatures [31], however, our results give a good agreement with previous work to investigated the effect of low and high NaCl on the corrosion of low carbon steel using the weight loss method [32].

Table -2: Electrochemical corrosion parameters obtained from potentiodynamic polarization curves for C45 in different solutions of NaCl over temperatures range (293-323) K.

NaCl	T(K)	Ecorr (mV)	icorr (A*10-6 /cm2)	Bc (mV/ Dec)	βa (mV/ Dec)	CR	PR
0	293	-246.8	12.68	-96.3	124.2	3.170	0.147
	303	-280.0	25.81	-105.8	162.7	6.450	0.3
	313	-273.7	52.39	-136.9	240.6	13.100	0.608
	323	-279.7	66.34	-127.1	255.6	16.600	0.77
3	293	-309.9	26.56	-124.1	209.1	6.640	0.308
	303	-417.6	74.75	-107.3	121.0	18.7	0.868
	313	-413.9	130.93	-107.2	132.4	32.7	1.520
	323	-413.9	191.37	-121.2	153.5	47.8	2.220
8	293	-452.8	66.09	-103.8	134.2	16.5	0.767
	303	-452.1	99.89	-101.1	123.2	25	1.160
	313	-443.8	156.10	-114.5	133.9	39	1.810
	323	-448.2	197.39	-126.1	124.2	49.3	2.290
14	293	-468.8	76.29	-133.1	125.3	19.1	0.886
	303	-488.0	112.19	-167.5	105.3	2.800	1.300
	313	-475.6	166.24	-151.3	105.7	41.6	1.930
	323	-477.5	233.51	-167.0	139.9	58.4	2.710
20	293	-505.4	59.09	-103.6	116.5	14.8	0.686
	303	-527.6	86.86	-118.1	142.5	21.7	1.010
	313	529.9-	125.97	137.3-	159.5	31.5	1.460
	323	487.6-	207.26	180.0-	130.3	51.8	2.410
26	293	-518.1	50.92	-114.3	103.4	12.7	0.591
	303	550.9-	61.69	83.3-	138.9	15.4	0.716
	313	660.5-	122.69	89.4-	144.1	30.700	1.42
	323	599.9-	142.92	123.5-	170.4	35.700	1.66

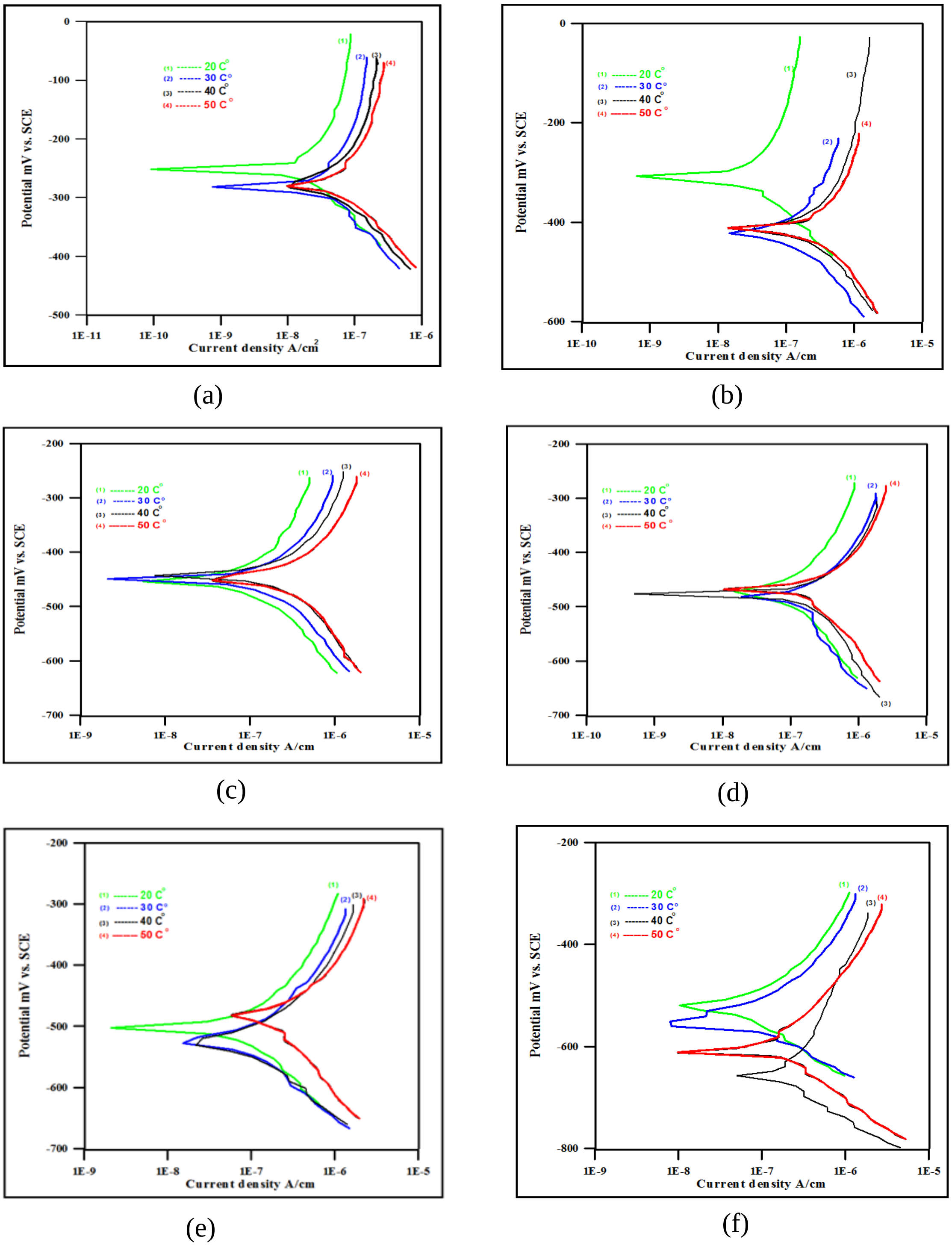

Fig. 1(a-f):The polarization curves of Carbon steel C45 in different content (0%, 3%,8%,14%,20% and 26%) of NaCl over temperatures range (293-323) K.

3.2 Kinetics of corrosion.

The experimental data that obtained from Tafel extrapolation method were used to calculate the activation energy (Ea), based on the rate of corrosion of C45 in a given environment is directly proportional with the its corrosion current density icorr as shown in equation (2) [33]:

$$C_R = 0.13\left(\frac{e}{\rho}\right) i_c \qquad (2)$$

And for the system obeying Arrhenius equation, it's reasonable to re-write the equation (2) as shown below:

$$\log i_{corr} = \log A - \frac{E_a}{2.303\, RT} \qquad (3)$$

where A is the Arrhenius constant, Ea is the activation energy, R is the gas constant, and T is the solution temperature. When equation (3) is applicable to rate of corrosion of C45 in a given medium at a number of temperatures, a linear relationship should exist between the value of logicorr and the reciprocal of temperature (1/T) as shown in Fig. 2.

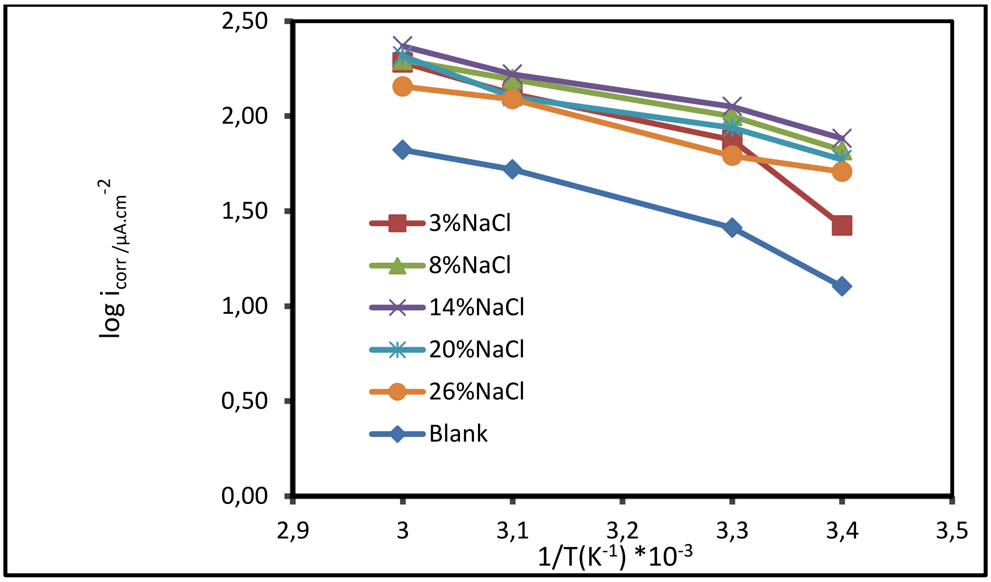

Fig. 2:Arrhenius plot relating of log icorr against 1/T for the corrosion of C45 in various concentration of NaCl solutions over temperatures range (293-323) K.

3.3 Thermodynamics of corrosion.

The change in the Gibbs free energy (ΔG) for the corrosion of a metal or alloy in an environment at a given temperature could be related to the corrosion potential Ec of the metal or alloy by the well-known relation [3] as shown in equation (4):

$$\Delta G = -nFE_{corr} \qquad (4)$$

where n is the number of electrons, F is Faraday's constant.

Values of (ΔG) have been determined for the corrosion of C45 in absence and presence of different concentrations of NaCl solutions at four experimental temperatures over range (293-323K).

The change of the entropy (ΔS) for the corrosion process has been calculated from the value of (ΔG) at different temperatures using the following relation :

$$-\frac{d(\Delta G)}{dT} = \Delta S \qquad (5)$$

While The enthalpy (ΔH) values are calculated depends on the values Gibbs free energy (ΔG) and (ΔS) as shown in equation (6) [3], and all the calculated parameters are displayed in Table 3.

$$\Delta G = \Delta H - T\Delta S \qquad (6)$$

Table -3:The kinetic and thermodynamic quantities (Ea,ΔG, ΔH ,and ΔS) for the carbon steel in the absence and presence of different NaCl concentration over temperatures range (293-323) K.

Concentration of NaCl	T(K)	Ea (kJ/mole)	ΔH(kJ/mol)	ΔS(kJ/mol.K)	ΔG(kJ/mol)
0%	293	23.244	14.773	-0.166	0.0634
	303				0.0650
	313				0.0667
	323				0.0683
3%	293	37.501	35.611	-0.970	0.3198
	303				0.3295
	313				0.3392
	323				0.3489
8%	293	21.910	20.020	-1.0169	0.31797
	303				0.3284
	313				0.3383
	323				0.3484
14%	293	21.866	19.985	-1.0160	0.31767
	303				0.32783
	313				0.3379
20%	323				0.3481
	293	23.960	22.072	-1.0112	0.31835
	303				0.3284
	313				0.3385
	323				0.3486
26%	293	22.877	20.9871	-1.0165	0.3188
	303				0.3289
	313				0.3391
	323				0.3493

The observed results in Table 3, indicate that the calculated Gibbs free energy ΔG values are positive for both case with or without the NaCl and this indicate that the reaction is nonspontaneous. As well as, the positive values of enthalpy (ΔH) indicate that the reaction is endothermic. Also the results shown that all calculated entropy ΔS were negative, and that indicated the activated complex in rate determining step represents an association rather than a dissociation step which means a decreasing in disordering take place on going from reactant to the activated complex [2]. As well as, the results in Table 3 indicates that the maximum value of Ea was (37.501kJ.mole-1; 3% NaCl), while the calculated Ea for the blank was 23.224 kJ.mole-1 .

4. Conclusion

At each same temperature, NaCl different concentrations have a critical effect on the corrosion rate of C45, and have been found that the increasing the content of NaCl lead to increase the corrosion rate, but at certain concentration (20% and 26% NaCl) the corrosion rate break down. Also the test temperatures are affected the corrosion of C45 in NaCl clearly, at each same concentration of NaCl, the corrosion of the system under investigated is increased whereas the temperature increased. Also, It has been observed there is a linear relationship between the plot of log icorr which are derived from the extrapolation of cathodic and anodic of polarization curves at absence and presence of different concentrations of NaCl against 1/T, which indicate that all these parameters are under activation control.

Acknowledgment

This work have been carried in the Al-Nahrain university / college of science / Chemistry department.

5. References

A. Pradityana, Sulistijono, A. Shahab, L. Noerochim, D. Susanti, Inhibition of Corrosion of Carbon Steel in 3.5% NaCl Solution by Myrmecodia Pendans Extract, International Journal of Corrosion, (2016),2016 , 6058286.

H. Tamura, The role of rusts in corrosion and corrosion protection of iron and steel, Corrosion Science, (2008),50 , 1872-1883.

N. Birbilis, B. Hinton, 19 - Corrosion and corrosion protection of aluminium, in: R. Lumley, (Ed.), Fundamentals of Aluminium Metallurgy, Woodhead Publishing, p. 574-604(2011).

F.U. Renner, A. Stierle, H. Dosch, D.M. Kolb, T.L. Lee, J. Zegenhagen, Initial corrosion observed on the atomic scale, Nature, (2006),439 , 707-710.

F.M. Song, D.W. Kirk, J.W. Graydon, D.E. Cormack, Predicting Carbon Dioxide Corrosion of Bare Steel under an Aqueous Boundary Layer, CORROSION, (2004),60 , 736-748.

A. FATEHI, A. ESLAMI, M.A. GOLOZAR, A. KAVIAN, S.D. TAVOOSI, K. REISI, EFFECT OF CATHODIC PROTECTION ON CORROSION OF X-52 PIPELINE STEEL UNDER DISBONDED COATING, SCIENCE AND ENGINEERING CORROSION, (2016), 6 , 55-67.

H.H. Zhang, Y. Chen, Z. Zhang, Comparative studies of two benzaldehyde thiosemicarbazone derivatives as corrosion inhibitors for mild steel in 1.0 M HCl, Results in Physics, (2018),11 , 554-563.

Y. Chen, Y.Y. Jiang, H. Chen, Z. Zhang, J.Q. Zhang, C.N. Cao, Corrosion Inhibition of Mild Steel in Acidic Medium by Linseed Oil-Based Imidazoline, Journal of the American Oil Chemists' Society, (2013),90, 1387-1395.

N.A. Odewunmi, S.A. Umoren, Z.M. Gasem, S.A. Ganiyu, Q. Muhammad, l-Citrulline: An active corrosion inhibitor component of watermelon rind extract for mild steel in HCl medium, Journal of the Taiwan Institute of Chemical Engineers, (2015),51 , 177-185.

A. Zeino, I. Abdulazeez, M. Khaled, M.W. Jawich, I.B. Obot, Mechanistic study of polyaspartic acid (PASP) as eco-friendly corrosion inhibitor on mild steel in 3% NaCl aerated solution, Journal of Molecular Liquids, (2018), 250 , 50-62.

A. Mahmoodi, M. Ebrahimi, Role of a hybrid dye-clay nano-pigment (DCNP) on corrosion resistance of epoxy coatings, Progress in Organic Coatings, (2018),114 , 223-232.

A. Yabuki, S. Tanabe, I.W. Fathona, Self-healing polymer coating with the microfibers of superabsorbent polymers provides corrosion inhibition in carbon steel, Surface and Coatings Technology, (2018),341 , 71-77.

S.B. Lyon, R. Bingham, D.J. Mills, Advances in corrosion protection by organic coatings: What we know and what we would like to know, Progress in Organic Coatings, (2017),102 , 2-7.

D. Dwivedi, K. Lepková, T. Becker, Carbon steel corrosion: a review of key surface properties and characterization methods, RSC Advances, (2017),7 , 4580-4610.

I. Santana, A. Pepe, E. Jimenez-Pique, S. Pellice, I. Milošev, S. Ceré, Corrosion protection of carbon steel by silica-based hybrid coatings containing cerium salts: Effect of silica nanoparticle content, Surface and Coatings Technology, (2015),265 , 106-116.

Y. Ye, Z. Liu, W. Liu, D. Zhang, H. Zhao, L. Wang, X. Li, Superhydrophobic oligoaniline-containing electroactive silica coating as pre-process coating for corrosion protection of carbon steel, Chemical Engineering Journal, (2018),348 , 940-951.

O. Sotelo-Mazon, S. Valdez, J. Porcayo-Calderon, M. Casales-Diaz, J. Henao, G. Salinas-Solano, J.L. Valenzuela-Lagarda, L. Martinez-Gomez, Corrosion protection of 1018 carbon steel using an avocado oil-based inhibitor, Green Chemistry Letters and Reviews, (2019),12 , 255-270.

R.G.M.d.A. Macedo, N.d.N. Marques, J. Tonholo, R.d.C. Balaban, Water-soluble carboxymethylchitosan used as corrosion inhibitor for carbon steel in saline medium, Carbohydrate Polymers, (2019),205 , 371-376.

[N. El Hamdani, R. Fdil, M. Tourabi, C. Jama, F. Bentiss, Alkaloids extract of Retama monosperma (L.) Boiss. seeds used as novel eco-friendly inhibitor for carbon steel corrosion in 1M HCl solution: Electrochemical and surface studies, Applied Surface Science, (2015),357 , 1294-1305.

Y. Liu, Z. Song, W. Wang, L. Jiang, Y. Zhang, M. Guo, F. Song, N. Xu, Effect of ginger extract as green inhibitor on chloride-induced corrosion of carbon steel in simulated concrete pore solutions, Journal of Cleaner Production, (2019),214 , 298-307.

Q. Wang, B. Tan, H. Bao, Y. Xie, Y. Mou, P. Li, D. Chen, Y. Shi, X. Li, W. Yang, Evaluation of Ficus tikoua leaves extract as an eco-friendly corrosion inhibitor for carbon steel in HCl media, Bioelectrochemistry, (2019),128 , 49-55.

S. Ghareba, S. Omanovic, Interaction of 12-aminododecanoic acid with a carbon steel surface: Towards the development of ‘green’ corrosion inhibitors, Corrosion Science, (2010), 52 , 2104-2113.

A.S. El-Tabei, M.A. Hegazy, A.H. Bedair, M.A. Sadeq, Synthesis and Inhibition Effect of a Novel Tri-cationic Surfactant on Carbon Steel Corrosion in 0.5 M H2SO4 Solution, Journal of Surfactants and Detergents, (2014),17, 341-352.

M.A. Hegazy, A.Y. El-Etre, M. El-Shafaie, K.M. Berry, Novel cationic surfactants for corrosion inhibition of carbon steel pipelines in oil and gas wells applications, Journal of Molecular Liquids, (2016),214 , 347-356.

H.B.E.T. Mï¿½ller, H. Froneman, The corrosion behaviour of a low carbon steel in natural and synthetic seawaters, Journal of the Southern African Institute of Mining and Metallurgy, (2006), 106 , 585-592.

N.S. Palsson, K. Wongpinkaew, P. Khamsuk, S. Sorachot, W. Pongsaksawad, Outdoor atmospheric corrosion of carbon steel and weathering steel exposed to the tropical-coastal climate of Thailand, Materials and Corrosion., 71 , 1019-1034(2020).

B.O. Hasan, Effect of Salt Content on The Corrosion Rate of Steel Pipe in Turbulently Flowing Solutions, Nahrain University, College of Engineering Journal (NUCEJ)., 13 , 66-73(2010).

R.A. Buchanan, E.E. Stansbury, 4 - Electrochemical Corrosion, in: M. Kutz, (Ed.), Handbook of Environmental Degradation of Materials (Second Edition), William Andrew Publishing, Oxford, (2012), p. 87-125.

M. May, Corrosion behavior of mild steel immersed in different concentrations of NaCl solutions, Journal of Sebha University.,15 , 1-12(2016).

L. Li, Q.Q. , Wei Bai, Y.C. , S.Z. , G.G. , Z.D. , Effect of NaCl on the Corrosion of Cold Rolled Steel in Peracetic Acid Solution, International Journal of ELECTROCHEMICAL SCIENCE AND ENGINEERING CORROSION, (2012),7 , 3773-3786.

W. Dreyer, C. Guhlke, M. Landstorfer, A mixture theory of electrolytes containing solvation effects, Electrochemistry Communications, (2014), 43 , 75-78.

N. Ali, T.E. Putra, Husaini, V.Z. Iskandar, S. Thalib, Corrosion Rate of Low Carbon Steel for Construction Materials in Various NaCl Concentrations, IOP Conference Series: Materials Science and Engineering, (2019),536 , 012015.

X. Li, S. Deng, G. Mu, H. Fu, F. Yang, Inhibition effect of nonionic surfactant on the corrosion of cold rolled steel in hydrochloric acid, Corrosion Science, (2008)50 , 420-430.