Corrosion Rate Model for Mild Steel in Hydrochloric Acid

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Abstract
This paper presents a corrosion rate model for mild steel in hydrochloric acid. A non-linear corrosion rate equation was developed, validated and used to relate the acid point, pH of hydrochloric acid as corrosive medium for mild steel to other variables like corrosion rate and substrate immersion period. The inhibitor used is Sinclair synthetic paint - an organic inhibitor. The effect of variables on corrosion rate has been investigated using non-linear regression analysis. The derived model is an exponential decay function of two input factors. The coefficient of correlation between the calculated and experimental data indicates good performance of the derived model.

Keywords: *Mild steel, Corrosion rate, Corrosion, Model, Hydrochloric acid*

Introduction

The most common material for many industrial applications is mild steel, because of its low cost and excellent mechanical properties (Andrea, 2014). But it suffers severe corrosion attack in service particularly in acid media. This causes severe consequences resulting in great economic loss, loss of materials and often times, loss of lives.

Prediction of corrosion rates is difficult owing to the complexity of the underlying physicochemical phenomena (Anees, and Ali, 2014). Hence many researchers (Gan, and Mark, 2010; Kexi et al, 2012; Rosa et al, 2013) have concentrated on the corrosion inhibition mechanism, adsorption isotherms, activation parameters, quantum chemistry, etc. But due to the high cost and long duration of corrosion experiments, and with the knowledge of the effect of various factors, such as temperature, concentration, etc., on the reaction rate, most researchers are now considering interpretation of predictive empirical laws in terms of reaction mechanism (Teknos, 2012).

The various models that have been applied to corrosion rate include the artificial neural network, analysis of variance, the Monto Carlo model, numerical methods (Nwigbo, 2016; Nwoye et al, 2013; Khadom et al, 2010; Durowaye et al, 2014) etc. However, general corrosion has been assumed to vary linearly with time. The uncertainties in predicting residual strength of corroded structures are mainly dependent on the variability in remaining plate thickness (Anees, 2013). These linear models (Kexi et al, 2012; Talo et al, 2013) of corrosion growth were adopted for linear studies of structural reliability considering corrosion wastage.

Hence linear and bilinear models for corrosion wastage were considered appropriate for design purposes (Teknos, 2012; Abida, and Harikrishna, 2014). But most experimental data such as those obtained from corrosion studies do not normally obey linear laws. To effectively model corrosion behavior of structures, most researchers (Ramana, 2010; Andrea, 2014) utilize non-linear regression analysis, power laws, and even polynomials of higher degrees.

In this work however, non-linear regression analysis is applied to experimental corrosion rate data to derive an exponential corrosion rate model. The derived model is expected to predict directly the corrosion rate of mild steel in HCl at various exposure time and acid point. The validity of the model is evaluated by various statistical and computational techniques.

Materials and methods

The materials used for this work are mild steel (C -35), hydrochloric acid and Sinclair synthetic paint - an organic coating. Details of the experimental procedure and associated process conditions are as stated in a research report (Nwigbo, (2016).

Model formulation

Experimental data obtained from research work (Nwigbo, (2016) were used for this work. The corrosion rate model as a function of acid point, pH, and immersion period t, is given by

$$C_r = (pH, t) \quad (1)$$

The model equation adopted is,

$$C_r = (pH)ue^{bt} \quad [\ C_r > 0\ ] \quad (2)$$

where C_r = corrosion rate (mm/yr), pH = pH of medium (-), t = immersion period (yr), u = random error and b = experimental parameter (material decay rate).

Equation (2) is rewritten as

$$\ln(C_r) = \ln(u) + bt + \ln(pH) \quad (3)$$

Substituting y = $\ln(C_r)$, $a_0 = \ln(u)$, a_1 = b, x_1 = t, a_2 = constant term and $x_2 = \ln(pH)$ in equation (3) yields,

$$y = a_0 + a_1x_1 + a_2x_2 \quad (4)$$

Equation (4) is detailed as follows

$$\sum y = a_0 n + a_1 \sum x_1 + a_2 \sum x_2$$
$$\sum x_1 y = a_0 \sum x_1 + a_1 \sum x_1^2 + a_2 \sum x_1 x_2 \quad (5)$$
$$\sum x_2 y = a_0 \sum x_2 + a_1 \sum x_1 x_2 + a_2 \sum x_2^2$$

Regression and computational analysis of the experimental data (Nwigbo, 2016) shown in Table 1, indicates that,

$a_0 = -13.8214,\ a_1 = -2.8464\ and\ a_2 = -0.1370$

Thus, $\ln(u) = -13.8214;\ u = e^{-13.8214} = 9.94 \text{ x } 10^{-7}$

$$a_1 = b = -2.8464 mm/yr\ \ and\ \ a_2 = -0.1370 = Constant$$

The corrosion rate model thus becomes,

$$C_r = 9.94 \text{ x} 10^{-7}(pH)e^{-2.8464t} \quad [\ C_r > 0\ ] \quad (6)$$

Table 1 Variation of corrosion rate with immersion time and pH of medium as obtained from experiment

	C_r [mm/yr]	t [days]	t [yrs]	pH [-]
0.00000085	3	0.0082	3	
0.00000078	6	0.0164	4	
0.00000069	12	0.0329	5	
0.00000072	15	0.0411	6	

Model validation

The validity of the model is strongly rooted on equation (6) which is the core equation. The data given in Table 1 also agrees with equation (6) following the constants in the equations evaluated from the experimental results. Furthermore, the derived models were validated by comparing the corrosion rates predicted by the respective models and that obtained from the experiment. This was done using various analytical techniques.

Results and Discussions

The derived model is equation (6). It is non-linear and two-factorial in nature because it is dependent on two input factors: acid point pH, and immersion time. This implies that the predicted corrosion rate for mild steel in HCl acid is dependent on these two factors.

Figures 1 – 4 give the graphical variation of corrosion rate with exposure time as obtained from experiment and derived model at the indicated acid point.

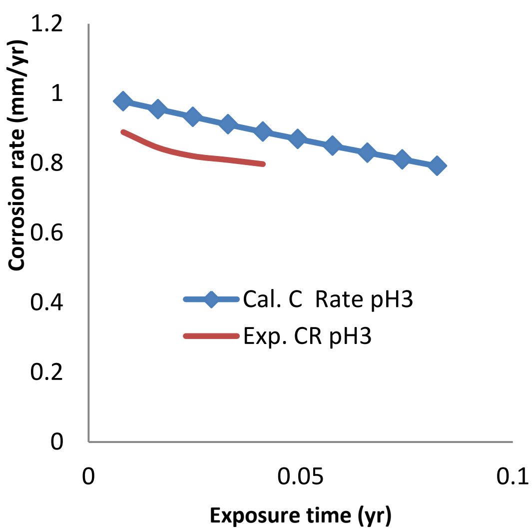

Figure 1 Variation of corrosion rate with exposure time at pH3 as obtained from experiment compared with Model-predicted data

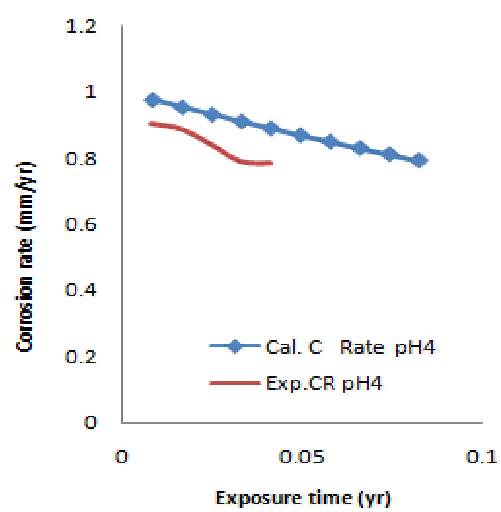

Figure 2 Variation of corrosion rate with exposure time at pH4 as obtained from experiment compared with Model -predicted data

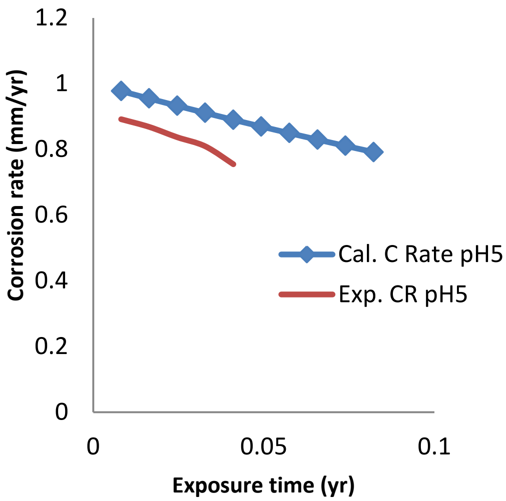

Figure 3 Variation of corrosion rate with exposure time at pH5 as obtained from experiment compared with Model 1-predicted data

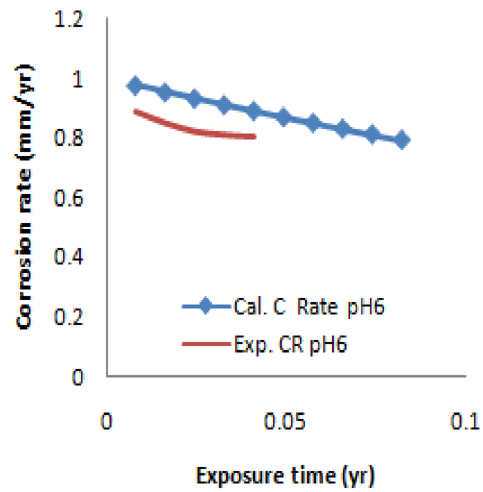

Figure 4 Variation of corrosion rate with exposure time at pH6 as Obtained from experiment compared with Model 1-predicted data

The upper lines in Figures 1 to 4 represent the variation of corrosion rate with exposure time as predicted by the derived model at pH3, pH4, pH5 and pH6 respectively. The predictions were done for a period of 30 days (0.0822yrs). The graph indicates a gradual decrease in corrosion rate with increasing exposure time. The linearity of the graph is due the introduction of random error factor during formulation of the model. The lower curve show the variation of corrosion rate with exposure time as obtained from experiment at pH3, pH4, pH5 and pH6 respectively for 15 days (0.04109yrs). The curves are indicative of an exponential decay rate of the metal substrate with time. This might be caused by desorption of hydrogen gas on the substrate, fall in acidic level pH, of the medium (since this was not maintained all the experiment) and the surface conditions of the substrate which were ignored during the experiment.

Deviations

Comparative analysis of the corrosion rates precisely obtained from experiment and derived model shows that the model-predicted values deviated from experimental results. For instance, the model predictions deviate from experimental data by 2.414%, 3.845%, 5.533% and 6.339% at pH3, pH4, pH5 and pH6 respectively. The deviation ΔC_r, of model-predicted corrosion rate from the corresponding experimental result was obtained using the relation,

$$\Delta C_r = \left(\frac{C_r - C_{rm}}{C_r}\right) \text{x } 100\%$$

(7) where C_r and C_{rm} are experimental and model predicted corrosion rates (mm/yr) respectively. The deviation was evaluated using Microsoft Excel version 2008.

These deviations are attributed to the fact that the effects of the surface properties of the mild steel which played vital roles during the corrosion process were not considered during the model formulation. Also, the acidity level of the test medium which was not maintained all through the experiment, may account for these deviations. Maximum tolerable deviations which are less than 7%, translating to over 42% operational confidence level for the derived models as well as over 0.42 reliability response coefficient of corrosion rate to the collective operational factors affecting it are indicative of the derived model. Based on the foregoing, it is strongly believed and admissible that the derived model can give reliable and suitable predictions of corrosion rates in high acidic medium following the high and intolerable deviations obtained at pH of 6.

Correlations

The evaluated correlations based on the coefficients of determination R^2 are shown in Table 2.

Table 2 Comparison of correlations between corrosion rate and exposure time evaluated from experiment and model-predicted results

pH	Exp. data	Mod. predicted data
3	0.906	0.999
4	0.949	0.995
5	0.993	0.999
6	0.996	0.999

The evaluated correlations indicate that the derived model predictions are significantly reliable and hence valid, considering its proximate agreement with results from actual experiment at the different acid point, pH.

Conclusion

Mild steel corrosion rate in HCl acid was predicted based on its exposure time and acid point, pH of the corrosive medium using a non-linear corrosion rate model. The derived model is two- factorial as it is dependent on two input factors: exposure time and acid point, pH. A good agreement between the predicted and actual corrosion rates was observed. Deviational analysis indicates that the maximum tolerable deviation of model-predicted corrosion rate from the corresponding experimental value is less than 7%. The derived model can be used to predict the corrosion rates in terms of the prevailing corrosion control process parameters within the ranges of studies for mild steel.

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