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Development of a Corrosion Model for Prediction of Atmospheric Corrosion of Mild Steel

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Abstract: Corrosion is a naturally occurring phenomenon commonly defined as the deterioration or loss of functions of materials (usually metals) due to the effect of the environmental factors. According to the nature of environment, corrosion can be broadly categorized as corrosion in atmosphere, corrosion in water, corrosion in sea, corrosion in soil etc. Among these types, corrosion of steel in atmosphere is a problem of great interest. Since steel is the most extensively used structural material in industry, and it is well accepted fact that the cost of material deterioration in an atmospheric environment is enormous. Corrosion of metal in atmosphere is inevitable but is controllable with the aid of proper corrosion management systems. For the implementation of a proper corrosion management system it is necessary to study the corrosive nature (corroivity) of the operation environment of a material. Development of a relationship between corrosivity and environmental variables such as relative humidity, temperature, salinity etc. which is known as Corrosion modeling is widely used method use for the evaluation of corrosivity of atmosphere. This paper describes the work carried out to formulate a model for the prediction of corrosion of mild steel under Sri Lankan atmospheric conditions. For this purpose, a model was proposed which is based on published literature on corrosion modeling. The proposed model was calibrated by the data obtained from field exposure tests which were conducted in four different locations in Sri Lanka. The chi-square goodness of fit test has been used to find out the performance of model. The model showed good performance with goodness of fit at 95% significance level. Finally, the model was validated with different set of data and the prediction performance of this model shows a good capability on forecasting of the rate of corrosion of mild steel in different atmospheric conditions in Sri Lanka.

Keywords: Corrosion Model, Atmospheric Corrosion, Mild Steel Corrosion, Weight Loss

1. Introduction

Most materials experience some kind of interaction with a large number of diverse environmental conditions and often such interactions impair materials' usefulness due to its reaction with the environment, [1]. Therefore, the working environment is the most predominant factor that determines the corrosion of a material. According to the nature of environment corrosion can be broadly categorized as corrosion in atmosphere (atmospheric corrosion), corrosion in water, corrosion in sea, corrosion in soil etc. Among these types, corrosion of steel in atmosphere is a problem of great interest since steel is the most extensively used structural material in industry and it is well accepted fact that the cost of material deterioration is enormous. Almost one-half of corrosion cost is due to the corrosion of steel in the atmosphere [2]. Therefore, it is possible to make a great saving by being concerned about prevention from atmospheric corrosion. However, it should be noted that the importance of mitigating corrosion is not just saving money but also it contributes to prevent corrosion related a failures and ensure reliability and minimize risk.

Most of the time the calculated corrosion cost quantifies only the financial penalty but this alone does not cover the entire cost of corrosion to the society. Like other natural hazards such as earthquakes or severe weather disturbances, corrosion can cause dangerous and expensive damages to everything such as pipelines, bridges, buildings, vehicles and wastewater systems and even home appliances. Unlike weather-related disasters, there are time-proven methods known as 'corrosion management' to prevent and control corrosion that can reduce or eliminate its impact on public safety, the economy, and the environment. Better corrosion management can be used to implement preventive strategies in non-technical and technical areas. For the implementation of preventive strategies against corrosion in technical areas it is necessary to study the corrosive behavior of operation environment of materials. For the assessment of the corrosive nature of the atmosphere several methodologies and strategies are available. Among them corrosion modeling is one of the most popular method.

Corrosion models have been developed for a multitude of situations using a great variety of methodologies. For scientists and engineers who are involving in corrosion technology, those models have become an essential tool for the selection and life prediction associated with the introduction of new materials or processes. In this context, developing those models is an accepted method of representing current understandings of reality.

It is well known fact that the corrosion of metals in atmophere depends on many environmental factors. The corrosion damage mainly depends on Exposure Time (t) and climatic factors such as Relative Humidity (RH), Temperature (T), Sulphur compounds (SO_X), Nitrogen compounds (NO_x), Salinity (Cl^-ions), Time of Wetness (TOW) and the presence of some other constituents such as air born particles, ozone, carbon dioxide etc. [3]. Therefore, it is possible to understand the aggressiveness of atmosphere for corrosion by determining these environmental factors. In another words, it would be possible to develop an equation or model to determine the corrosion loss in terms of time and other atmospheric variables.

There are many research activities conducted all over the world for the formulation of models for atmospheric corrosion. Many researchers have taken different approaches and obtained empirical relationships between corrosion loss and atmospheric variables [4, 5, 6, 7, 8, 9, 10, 11, 12, 15, 16, and 17]. Most of these models can be used only for specifically defined locations or with certain limitations. That means these models are not representation of general corrosion model for all environmental conditions.

During last few decades there were considerable development in construction industry in Sri Lanka and the use of steel for construction purposes is highly increased. Therefore, the need of environmental assessment is essential requirement for the selection and maintenance of steel structures such as bridges, towers, building etc. For these purpose several environmental assessments in local regions were conducted for specific reasons but these were not use for any development of corrosion models.

Due to above mentioned reason this work was started with the objective of developing a corrosion model which can be used to predict the corrosion rate of mild steel in Sri Lanka. This report describes the process undertaken to develop such an atmospheric corrosion model for plain carbon steel (mild steel) and the process involves firstly the field exposure program which was conducted in different locations in Sri Lanka that represent different environmental conditions. Secondly, a corrosion model was proposed which will be based on the power law and published literature. Constant of power equation are function of atmospheric variables such as temperature, relative humidity, and salinity etc.

Finally, fit the data obtain from field exposure test and find out the constants of the model by computer based mathematical iteration process based on the theory "minimizing percentage least square". Then the model was tested for goodness of fit and the values of model constants were validated by set of data obtained in different three locations in Sri Lanka.

2. Methodology

(1) Field exposure test

Initially field exposure tests were conducted in four locations in Sri Lanka namely;

a) Colombo (Urban)
b) Kolpetty (Marine)
c) Peradeniya (Rural-Wet)
d) Anuradhapura (Rural -Dry)

As indicated, these locations represent four different environmental conditions. Mild steel samples with dimensions 150X100X2mmand having chemical composition as shown in table 1 was used for this study.

Table 1. *Chemical Composition of Mild Steel Specimens.*

Material	Chemical Composition [%]				
	C	S	Mn	Si	P
Mild Steel	0.14	0.02	0.50	0.25	0.01

Specimens were prepared as per the method described in ISO 8565 and fixed on exposure rack at an angle 45° as shown in figure 1. The exposure program was conducted over 24 months. During the exposure period three specimens were picked up from each site by two-month time interval. The specimens were cleaned and determined the mass loss as per the method given in ISO 8407 [14]. The atmospheric variables such as temperature, humidity and rain fall of each location were recorded in one-month time intervals which were obtained from the data available at the Department of Meteorology Sri Lanka. The sulphur dioxide and chloride deposition rates were determined by means of passive sampling and the wet candle method respectively as given in ISO 9225[13].

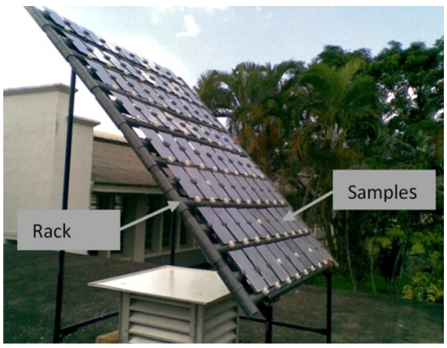

Figure 1. *Field Exposure Rack.*

The average values of data obtained from exposure test was calculated as per the method described below and tabulated in table 1. As an example Average relative humidity during the period of ‘t ‘months was calculated as follows;

$$(RH)_t = \frac{\sum_{n=1}^{t}(RH_n)}{t} \quad (1)$$

Where; RH_n- Average relative humidity of the n[th]month

$(RH)_t$- Average relative humidity during the period of t months

In the same way average value of Temperature $(T)_t$ Chloride deposition rate $(Cl)_t$, Sulphur deposition rate $(S)_t$, and rainfall $(RF)_t$during the period of t months were calculated.

Table 2. *Field Exposure Data.*

Data No.	Location	Duration [month]	Average Humidity $(RH)_t$[%]	Average Temperature $(T)_t$ [°C]	Average Chloride Content$(Cl)_t$[mg/ m^2.day]	Average Sulphur Content$(SO_2)_t$[mg/ m^2.day]	Average Rain Fall$(RF)_t$[mm]	Total Mass loss[g/m^2]
1	Urban	2	81.25	28.55	102.50	22.50	123.40	84.66
2	Urban	4	80.75	28.40	95.00	24.25	141.25	175.32
3	Urban	6	80.58	28.21	87.50	20.67	133.10	210.46
4	Urban	8	79.69	27.89	84.38	20.25	137.18	288.72
5	Urban	10	79.95	27.84	82.00	20.90	175.17	362.72
6	Urban	12	79.83	27.96	85.00	21.17	166.03	426.24
7	Urban	14	80.07	28.05	89.29	21.29	159.55	462.26
8	Urban	16	80.50	28.05	90.63	21.63	182.56	485.43
9	Urban	18	80.69	28.00	90.56	20.78	181.29	506.24
10	Urban	20	80.25	27.93	89.75	20.40	175.92	518.34
11	Urban	22	80.20	27.87	89.32	20.41	171.58	526.32
12	Urban	24	80.42	28.09	90.63	20.50	188.80	542.36
13	Rural-wet	2	84.00	25.15	0.00	0.00	212.50	58.66
14	Rural-wet	4	84.88	24.70	0.00	0.00	151.50	80.23
15	Rural-wet	6	83.33	24.55	0.00	0.00	132.17	102.45
16	Rural-wet	8	82.81	24.83	0.00	0.00	126.88	121.43
17	Rural-wet	10	82.05	25.03	0.00	0.00	108.20	135.43
18	Rural-wet	12	81.88	25.05	0.00	0.00	106.67	155.34
19	Rural-wet	14	82.14	25.09	0.00	0.00	136.07	182.34
20	Rural-wet	16	82.84	25.00	0.00	0.00	162.31	210.65
21	Rural-wet	18	82.94	24.86	0.00	0.00	165.94	246.54
22	Rural-wet	20	83.03	25.02	0.00	0.00	161.85	266.54
23	Rural-wet	22	82.95	25.68	0.00	0.00	166.00	284.32
24	Rural-wet	24	82.94	24.97	0.00	0.00	161.42	299.62
25	Marine	2	79.69	27.96	275.00	12.50	135.67	271.33
26	Marine	4	79.95	28.05	300.00	13.75	500.75	498.53
27	Marine	6	79.83	28.05	308.33	15.33	355.50	678.32
28	Marine	8	80.07	28.00	316.25	17.00	314.13	820.25
29	Marine	10	80.50	27.93	308.00	17.90	322.80	898.53
30	Marine	12	80.69	27.94	305.83	20.00	287.83	1045.68
31	Marine	14	80.25	28.04	294.29	20.14	266.14	1254.26
32	Marine	16	80.20	27.54	288.75	19.94	267.44	1366.11
33	Marine	18	80.42	28.60	294.17	19.89	247.56	1597.34
34	Marine	20	80.45	28.12	297.25	19.85	241.80	1684.56
35	Marine	22	80.76	27.75	295.23	19.86	232.95	1786.50
36	Marine	24	81.02	27.68	302.92	20.25	234.29	1832.32
37	Rural -Dry	2	77.75	28.98	0.00	0.00	110.50	31.12
38	Rural -Dry	4	76.25	29.48	0.00	0.00	55.25	64.89
39	Rural -Dry	6	74.92	29.68	0.00	0.00	40.67	84.16
40	Rural -Dry	8	75.44	29.61	0.00	0.00	118.00	110.32
41	Rural -Dry	10	77.60	29.00	0.00	0.00	178.00	132.41
42	Rural -Dry	12	78.58	28.57	0.00	0.00	171.58	154.23
43	Rural -Dry	14	78.54	28.69	0.00	0.00	169.36	176.45
44	Rural -Dry	16	78.47	28.69	0.00	0.00	151.81	190.00
45	Rural -Dry	18	78.08	29.24	0.00	0.00	148.44	201.54
46	Rural -Dry	20	77.63	28.96	0.00	0.00	134.05	210.68

(2) Development of model structure

It is well accepted that therate of corrosion can be expressed in the form ofpower equation shown in equation 2.

$$C = Kt^n \quad (2)$$

Where C is the loss of weight due to corrosion and t is the exposure time which is the primary factor that determines the basic rate of corrosion. The initial corrosion loss observed during the first unit time of exposure is described by K, while n is a measure of the long-term decrease in corrosion rate or pasivation of materials which is directly dependent on the metal, the physical–chemical atmospheric conditions and the exposure conditions [3].

Therefore, this equation can be used to any location by defining appropriate K and n values as a function of atmospheric variables of particular location.

$$n=f\,(TOW, Cl^{-}, SO_2, T, etc.) \quad (3)$$

$$K=f\,(TOW, Cl^{-}, SO_2, T, etc.) \quad (4)$$

To propose a corrosion model thatsuitable for sri lankan atmospheric conditon above ideahas been selected as the primary concept and sevaralother existing corroion models, which were already published, were alsoreviewed. Among those models the corrosion model poublished byDawn E. Klinsmith [4] was identified as a one of best corrosion model that could be applicable to Sri Lankan atmospheric conditions. This corrosion model basically adheres to the features of power equation and it avoids many of drawbacks in other published corrosion models.

The model proposed by Klinsmith [4] is given below;

$$Y = At^B\left(\frac{TOW}{C}\right)^D\left(1+\frac{SO_2}{E}\right)^F\left(1+\frac{Cl}{G}\right)^H e^{J(T+T_0)} \quad (5)$$

Where,
Y-mass loss due to corrosion
T-Time
TOW-Time of wetness
SO_2-Sulphur deposition rate
Cl-Chloride deposition rate
T-Temperature
A, B, C, D, E, F, G, H, J and T_0– Constant

Although this model has shown good performances in many cases, when consider the Sri Lankan atmospheric conditions the rain fall is one of main factor that can be influenced the outdoor metal corrosion because it has been reported that comparatively high rainfall in every part of the country throughout the year and the effect of rain on atmospheric corrosion damage are somewhat ambiguous. While providing electrolyte effect for corrosion and rain can influence in beneficial manner by diluting harmful corrosive surface species [3]. Therefore, when consider the Sri Lankan atmospheric condition parameter of Rain fall (RF) has to be added to the model. In addition to that relative humidity is the main factor that determine the time of wetness (TOW). In general practice TOWis defined as the *time duration in which relative humidity more than80% and the temperature is higher than the 0°C[1]*. When the Sri Lankan atmospheric condition is considered the relative humidity everywhere in the country is always nearly 80% or more. Therefore, whole exposure time of metals in atmosphere is equal to time of wetness. Further, the value of relative humidity determines the amount of moisture deposit on the metal surface and it has a significant effect on the corrosion rate. Therefore, the authors have decided that it is reasonable to replace TOW by RH in the equation no.5 and *the constants A and C in equation 5 has been reduced to constant A in equation 6{(A/C^D) =A}*. Then the modified equation of the proposed corrosion model will be as follows;

$$Y = At^B(RH)^D\left(1+\frac{SO2}{E}\right)^F\left(1+\frac{Cl}{G}\right)^H\left(1+\frac{RF}{K}\right)^L e^{J(T+T0)} \quad (6)$$

(3) Determination of constants of model structure.

For the determination of constants of the model equation software based mathematical iteration method was used. In this exercise the iteration involves the fallowing steps .

1. The systematic substitution of all possible combination of numerical values which are within the pre identified range to the model.
2. Determination of root mean squire error (RMS Error) value for each combination according to the equation 7 given below.
3. Select the combination which gives the minimum RMS Error value and meaningful values to model constants as the best combination.

$$RMS\ Error = \sqrt{\frac{\Sigma(C_{actual} - C_{calculated})^2}{C_{calculated}}} \quad (7)$$

Where, $C_{calculated}$: Corrosion loss calculated by equation 6 for a given combination of model constant C_{actual}: Corrosion loss from field exposure data

(4) Validation of corrosion model

The exposure program of two sites (Colombo and Peradeniya)was continued for another one year and mass loss data were obtained after completing the 36th month. Then the actual mass loss was compared with the mass loss that calculated by the model in order to find out the prediction performance of the model. In this process it was assumed that the variation of atmospheric variables follows the same pattern as in previous year. Therefore, for the calculation of forecasted mass loss the average values of atmospheric variables in first year were used.

3. Results and Discussion

Following combinations of values were obtained for model constants.

A=6.82B= 0.78D=0.07E= 93F=0.31

G= 158H= 1.70J=0.023K= 150L= 0.18T_o= 7.3

By substituting above values to the equation (6) the fallowing equation can be obtained. According to this equation it is possible to determine the corrosion losses in different Sri Lankan environmental conditions.

$$y = 6.82t^{0.78}RH^{0.07}\left(1+\frac{SO2}{93}\right)^{0.31}\left(1+\frac{Cl}{158}\right)^{1.70}\left(1+\frac{RF}{150}\right)^{0.18} e^{0.023(T+7.3)} \quad (8)$$

The statistical method chi-square goodness of fit test was used to find out the performance of model calibration and the figure 1 shows the chi-square distribution of model's output. According to the chi square analysis the model shows good performance with goodness of fit in 95%significance level. This is in reasonably acceptable level or in another word; the values obtained for the model constant are acceptable by means of goodness of fit.

The table 3 shows the comparison of two set of exposure data with forecasted data that was used for the validation of the model. The maximum percentage deviation of forecasted value from the actual value is max. 6% (Table 2) and this is a considerably acceptable value. Therefore, this result is an evidence to determine that the prediction performance of this model shows a good capability on forecasting of corrosion loss.

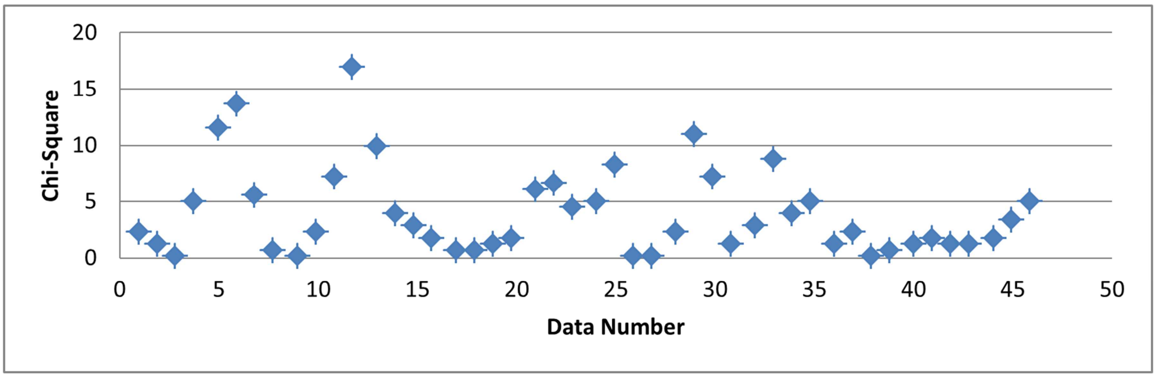

Figure 2. *Chi- Square Distribution of Model Output.*

Table 3. *Comparison of Forecasted Corrosion Loss with Actual Corrosion Loss.*

Location	Duration[months]	Actual Corrosion Loss [g/m^2]	Forecasted Corrosion Loss[g/m^2]	Variation [%]
Colombo	36	840.2	891.2	6.0
Peradeniya	36	382.4	401.5	4.9

'Relative Importance Analysis' was conducted for independent variables (i.e. atmospheric variables) of the developed model by means of change of corrosion loss per unit variation of each atmospheric variable. The table 4 shows that the percentage relative importance of each variable under selected three different atmospheric conditions (1, 2, 3). For the convenience of comparison, three environmental conditions were selected so that chloride deposition rate was varied when other environmental conditions remain unchanged. According to the results given in table 4 it was observed that the contribution of each variable to total corrosion loss depends on the atmospheric condition and in this case temperature is the most important factor that determines the corrosion loss while rain fall is the least important factor.

Table 4. *Percentage relative importance of atmospheric variables under different environmental conditions.*

	Average Humidity $(RH)_t$[%]	Average Temperature$(T)_t$[°C]	Average Chloride Content$(Cl)_t$[mg/ m^2.day]	Average Sulphur Content$(SO_2)_t$[m g/m^2.day]	Average Rain Fall$(RF)_t$[mm]
Relative Importance (%) under Atmospheric condition (1) (RH =80, T=24, Cl=25,SO_2=13, RF=270)	2.37	63.41	25.36	7.69	1.17
Relative Importance (%) under Atmospheric condition (1) (RH =80, T=24, Cl=160, SO_2=13, RF=270)	2.65	71.05	16.37	8.61	1.31
Relative Importance (%) under Atmospheric condition (1) (RH =80, T=24, Cl=300, SO_2=13, RF=270)	2.80	74.81	11.94	9.07	1.38

4. Conclusion

Various types of corrosion models have been developed in different part of the world by multitude of methodologies. Most of these models produce reasonable outcomes with certain limitations and conditions. In the same way the model developed in this project shows good performance and its applicability is limited to the areas of calibration data obtained and areas that have similar environmental conditions. When Sri Lankan atmospheric conditions were considered it was observed that there is no large diversity of environmental conditions in different part of the country and the areas that field exposure program conducted represent many environmental conditions in the country. Therefore, it is possible to use this model with an acceptable accuracy in every part of Sri Lanka. However more accurate result can be obtained by calibration and validation of model by more data from more field exposure programs.

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